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STUDY OF THE ELECTROSTATIC FIELD AND
CHARGE DISTRIBUTION IN A VORTEX SEEDED WITH DUST

DISSESSATION

Presented in Partial Fulfillment of the Requirements for
the Degree Doctor of Philosophy in the Graduate
School of The Ohio State University

By

John William Daugherty, B.S.M.E., M.S.M.E.

* * * * * *

The Ohio State University
1972

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c  airfoil chord
v  vane chord
D_o  airfoil drag
D_o  orifice diameter
d  distance downstream of airfoil trailing edge
d  particle diameter
E  energy flux from jet
E  modulus of elasticity
E  electric field strength
E^1  electric field strength near blade leading edge
E_o  ambient electric field
F  \frac{(q/m_p)(r_o/r)}{(E_o/F)}
F  \frac{3\pi\mu d/m_p}{\text{(see page 205)}}
F_d  drag force
F_e  electrostatic force
h  vane thickness
h  pulse height (see page 18)
I  moment of inertia
I  turbulence level
I_c  charging current
i  probe current
K  gain of electronic system
K_m  constant of proportionality (see page 17)
K_c  constant of proportionality (see page 18)
k  constant (see page 18)
k  Boltzmann's constant
L_o  characteristic length
1_d  the Debeye length
1    rotor span
M    momentum flux from jet
M_{R}  rolling moment
m_p  particle mass
m    particle mass flow rate
N    number of rotor blades
n    particle density
n    frequency distribution of pulse heights
P    rolling angular velocity
P    pressure
P    polarization
p    dipole moment
Q    volume flux from jet
q    dynamic pressure = \frac{1}{2} \rho v^2
q    charge per particle
R    measured rainfall rate
R_i  radius to the i-th vorticity contour
r    radial distance from vortex center
r_c  radius of the vortex core
r_o  injection radius of particles
S    vane planform area
T    absolute temperature
T  torque
\dot{t}  blade thickness
t  time
\mathcal{U}_\infty  free stream fluid velocity
u  local fluid velocity in x-direction
\mathbf{u}_p  particle velocity in radial direction
\mathbf{u}^l  perturbation velocity in x-direction
V  volts
V  free stream velocity
\mathbf{V}_p  particle volume
\mathbf{V}  local fluid velocity in y-direction
\mathbf{V}  local jet velocity
\mathbf{V}_p  particle velocity in tangential direction
\mathbf{V}_o  exit velocity of jet
W  free stream velocity in direction of trailing vortex
w  local fluid velocity in Z-direction
\mathbf{w}_p  particle velocity in Z-direction
x  distance from jet exit
\mathbf{x}  coordinate direction
\mathbf{x}_{T.E.}  distance downstream of airfoil trailing edge
\mathbf{y}  coordinate direction
\mathbf{y}  distance normal to jet axis
\mathbf{y}  distance from vane neutral axis
\mathbf{Z}  coordinate direction
\mathbf{Z}  distance downstream from airfoil trailing edge
Greek Letters

\( \alpha \) airfoil angle of attack
\( \Gamma \) circulation
\( \Gamma_c \) circulation in the vortex core
\( \Gamma_0 \) circulation determined from Prandtl-Glauert analysis
\( \varepsilon_0 \) permittivity of free space
\( \varepsilon_r \) relative permittivity
\( \varepsilon_o \) bending strain
\( \theta \) angular position in trailing vortex
\( \mu \) viscosity
\( \nu \) kinematic viscosity
\( \rho \) density
\( \rho_p \) particle density
\( \sigma \) constant
\( \sigma_o \) bending stress
\( \tau \) shear stress
\( \phi \) constant = \( N \Omega^3 \hat{t} \) (see page 29)
\( \phi \) velocity potential
\( \psi \) stream function
\( \Omega \) angular velocity
\( \omega \) vorticity
Subscripts

\( m \)  mean value
\( o \)  initial conditions and value obtained from Prandtl-Glauert analysis
\( r \)  radial component
\( T.E. \)  trailing edge
\( x \)  \( x \)-component
\( y \)  \( y \)-component
\( z \)  \( z \)-component or axial component
tangential component

Superscripts

*  - nondimensional quantities
CHAPTER I
INTRODUCTION

1.1 Introductory remarks

Static charge buildup on aircraft has always been a nuisance with regard to in-flight transmission and reception of radio messages. In the case of a helicopter, static charge buildup is a severe problem because it also presents a personnel and material handling hazard. An individual loading sling loads from a hovering helicopter becomes an integral part of the discharge path for the static charge on the surface of the helicopter. The resultant discharge causes violent shocks to the unloading personnel; and in situations where the stores are flammable or explosive, arcing from the helicopter to these stores can result in fires and/or explosions.

Due to the hazard associated with electrostatic charging of helicopters, studies have been carried out to determine means of eliminating or dissipating of this build-up charge. These studies resulted in the installation of an active discharging system on many U.S. Army helicopters (51). Definitions of the charge-generating mechanisms are still nebulous. There have been attempts to credit the large deposits of static charge on helicopters to ions in the engine exhaust gases, to contact charging (tribo-electrification) occurring when suspended particles in the air (water droplets,
I mist, dust, snow flakes) impact the surface of the helicopter, and to movement of the helicopter through varying electrostatic fields present in the atmosphere. There still remains the question of why the charge deposition is always additive. In the case of exhaust gases from the engines, where ions of both positive and negative polarity are present, what fundamental mechanism causes only ions of the same sign to be deposited on the surface of the helicopter?

A fundamental aspect of the fluid field associated with the flight of a helicopter, which does not occur with fixed wing aircraft, is that the trailing vortices shed from each rotor tip flows downward in a helical path and bathes the surface of the helicopter. The trailing vortices shed from the tips of fixed wing aircraft, flow downstream and eventually become dissipated in the atmosphere.

1.2 Problem Statement

The purpose of this research is to study the charge-generating and separation capabilities of a trailing vortex system and to determine if the trailing vortex system can create a stable electric field and if so to determine the parameters which control the strength of this field. A secondary purpose for this work is to develop a vortex probe capable of measuring the vorticity from trailing-vortex systems in a rotating system; i.e., a hover stand. The data obtained from an experimental analysis of decaying vortex system will be useful to other investigators studying causes of vortex breakdown, investigating similarity relationships for describing
vortex decay, and for developing methods of reducing the magnitude of the rotational velocities present in the vortex. The last area of research is becoming very important due to the flight hazard wing tip vortices from jumbo jets present to smaller craft following in their wake.

1.3 Outline of Investigation

An experimental program was initiated to measure the strength, geometry, and charging capabilities of a trailing vortex produced due to lift on a differential airfoil. This airfoil was placed in the test section of a low-turbulence, subsonic wind tunnel. To measure the rotational velocities present in the trailing vortex system, a non-rotating type vortex meter has been designed and fabricated. To calibrate this probe, a calibration system has been designed and built that is capable of rotating the vortex probe to 30,000 R.P.M. To accurately position the vortex probe in the wind tunnel, a traversing mechanism has also been designed and built. Servo-operated, this device is operated remotely from a control panel and can position the probe in a plane normal to the flow accurately to 0.05 of an inch. Modification of the digital counter activating cams affords an even greater degree of locatability. To seed particles into the flow field and to obtain a homogeneous mixture, a particle feed system has been designed and built. This device is capable of seeding particles into the flow field in such a way as
to simulate helicopter landing zones with regard to dust and if desired, moisture concentration. To remove the seed particles from the tunnel exhaust flow, a filter system was designed and constructed; it is 99% efficient for removal of particles greater than 50 micron in diameter. A miniature electric field mill (17) was used to measure the electric field in the seeded flow. An impact probe was developed which was used to map the particle density distribution throughout the flow field.

Experimental measurement of the trailing vortex geometry and strength was made throughout a plane normal to the flow direction at several locations downstream of the trailing edge of the airfoil. Measurements made with the electric field mill and density probe were made at the same locations as the vortex measurements. This permitted comparison of flow field geometry versus electrostatic charging.

A simple mathematical model of the trajectories of the seed particles in the trailing vortex system was programmed for an IBM 360 digital computer. Electric field effects and vortex strengths measured in the experimental portion of this study were included in the mathematical model. Particle trajectories of several particles entering the vortex at the same location aft of the airfoils but at different radii were studied to determine if particles within a vortex interacted as the vortex travelled downstream from the airfoils.
CHAPTER II
HISTORICAL BACKGROUND AND REVIEW

The first section of this review discusses the study of trailing vortex systems generated by airfoils. These studies began in the 1920’s and have continued up to the present. Visualization studies will be briefly surveyed; then, considerable discussion of techniques and equipment used to obtain quantitative measurements of vortex geometry and decay is presented.

To review, in detail, all the previous work on the subject of trailing vortex systems shed from airfoils is unnecessary since the primary interest to the present study is the geometry of the trailing vortex as it travels downstream from the trailing edge of the airfoil. The geometry of a trailing vortex system has been studied by visualization techniques and by making pressure and/or velocity measurements throughout the vortex. Only a few results of visualization studies will be reviewed here for the benefit of the reader. The interested reader may consult the References for a more complete listing of the work accomplished through visualization studies; (i.e., 1, 4, 7, 8, 14, 16). Similarly, only those works describing the measurements of the velocities and/or pressures in the trailing vortex system which have a direct relationship to the present study will be reviewed here. Other papers giving qualitative
and quantitative results of vortex measurements are listed in the References for the reader, (18, 20, 28, 36, 37 and 41). The primary concern of this first section is a review of vortex measurements achieved through the use of some type of vortex meter. Papers which give details about the design, calibration, use, and results obtained with rotating and non-rotating vorticity meters will be discussed at length.

The second part of this review concerns electrostatic charging. The topics picked for review here are an attempt to provide a basis for the premise investigated in this work. The evidence of electrostatic charging that occurs in meteorological rotational flows (tornadoes, dust devils) and rotational flows created artificially in the laboratory (swirl flows) directed the present investigation to the trailing vortex system shed by the rotor tips as a significant charging mechanism in helicopters. Thus, this section of the review discusses the types of probes used to monitor electrostatic charging in particulate flows citing the essential details in their design, followed by a detailed discussion of electric field breakdown in a swirling flow. Since the primary purpose of this work is to study the fundamental mechanisms of rotary wing aircraft charging a discussion of charging which occurs in airborne helicopters is presented.

The present work is a study of charge separation characteristics in a trailing vortex system, which to the author's knowledge, has not been previously attempted. Hence, only those papers on elec-
trostatic phenomena which aid the present investigation will be discussed in detail. Other works related to static electricity effects in aircraft and atmospheric phenomena are cited in the References for the reader.

2.1 Trailing Vortices -- Visualization Studies

Since the day Prandtl published his famous lifting line theory (48, 49, and 50), experiments have been performed in an attempt to verify qualitatively and quantitatively the theory. The earliest works were primarily attempts at visualizing the formation and decay of vorticity shed from blunt bodies and infinite wings by using millet seeds and a water table. Some typical results of flow visualization studies employing smoke are shown (56, 54). Photographs of smoke traces at several locations downstream of a lifting wing in a subsonic flow show the rapid rolling up of the shed vortex sheet into two trailing vortices (56). These photographs also show that at a distance of approximately two chord lengths aft of the trailing edge of the airfoil, the major portion of the shed vortex sheet has become concentrated in the two trailing vortices. Reference (54) shows similar vortex patterns trailing downstream from the tips of rotor blades.

A good example of flow visualization employing a tuft-grid is shown in Reference (36). This visual study was carried out showing the effect of angle of attack and tip shape on vorticity for a rectangular airfoil and a variety of wing tip geometries over a range of angle of attack. There are also photographs of the tuft-grid pattern at varying distances downstream from the airfoil with a standard tip. These tuft-grid studies indicate that the trailing vortex from a rectangular wing has a radius of approximately 2 inches at several downstream locations -- from 1.5 inches aft of the airfoil to 14 inches aft of the airfoil.
2.2 Vorticity Meter Studies

Attempts at quantitative measurements of the vorticity in a trailing vortex system dates back at least as far as 1950 (59). In (27), a rotating device called a vortometer is described, and sample data presented. The vortometer consists of a small circular cylinder free to rotate about an axis perpendicular to the axis of the cylinder when placed in a flow field with the axis of rotation aligned in the free-stream direction. Rotational velocity data is presented in (27) which was obtained with a 1 inch-long vortometer in a vortex core trailing downstream from a triangular wing of a 42-inch span and aspect ratio 2.0. The airfoil was at a 14° angle of attack, and the measurements were made in a transverse plane 11.2 inches downstream of the trailing edge. The rotational speeds of the vortometer were measured with a stroboscope. The results are plotted in the form of contour lines of constant rotational speed. By means of visual observations, it was found that away from the center of the vortex core, the rotational speed decreased to zero, reversed direction, and attained a relatively small negative value; then it decreased to zero again. A more recent and sophisticated design of a rotating type vorticity meter is discussed in Reference (32). The following description of the probe is taken from Reference (37):

The vortex probe consists of four, unpitched vanes mounted on a hub attached to a shaft supported between two jeweled bearings. A small light is shone through a window in the shaft onto a small photocell. In order to reduce windage losses, the window was filled with a polished clear plastic, and the clearance between the shaft and the housing was made as large as was feasible. For windtunnel model tests, the diameter of the vanes was 3/8 in. The rotational velocity of the vanes is measured by
counting electronically the voltage pulses from the photocell. Ideally, the vanes rotate with an angular velocity equal to half of the fluid vorticity. In practice, the angular velocity is slightly different from this because of the finite size of the vanes and the friction in the system.

Calibration of the probe is described in detail in Reference (32); hence, just a brief discussion will be presented here. The entire probe is rotated in a subsonic wind tunnel. The spinner R.P.M. is plotted against probe R.P.M. at various tunnel speeds. The efficiency of the vorticity meter is obtained from these plots. Increasing the free stream velocity (i.e., tunnel speed), increased the probe efficiency. The variable speed motor used for the calibration provided a maximum probe speed of about 5,000 R.P.M. It was stated (32) that the probe measures speeds in excess of this value; and the question is raised as to the behavior of the calibration curves above 5,000 R.P.M. A blade element analysis of the rotating vanes indicated that the torque sensed by the meter vanes is proportional to both the free stream velocity and probe R.P.M. The rotating type vorticity meter will give true values of vorticity only in a linear vorticity field due to its finite size. The meter actually records the average value of the vorticity measured by the spinner.

Data acquired with this probe is given in (36) and (37). Figures 1 and 2, taken from (37), show measured vorticity contours behind a model wing and a full scale wing at several downstream stations. The model wing is symmetrical, rectangular, and set at a 12° angle of attack. The specifications on the airfoils of the full scale wing are given in Table 1 of Reference (37). Reference (36) presents vorticity data taken downstream of a rectangular wing with several types of wing tips, for
Fig. 1: Vorticity contours for the 1/12 scale 0-1 aircraft wing. (37)

V = 75 MPH
\( \alpha = 12^\circ \)

Fig. 2: Vorticity contours for the full-scale 0-1 aircraft. (37)
several angles of attack, and at several downstream positions. These results illustrate the effect of altering the tip shape on the rolling up of the vorticity, which is to retard the rolling up and reduce the tangential velocity.

Reference (40) discusses the design of a non-rotating vorticity meter consisting of four instrumented blades mounted on a steel shaft (Figure 3). The blades are considered as wings of small aspect ratio in rolling motion. The strain in the blades is found to be dependent on the thickness and material of the vanes and the square of velocity of the fluid in which the probe operates. The probe calibration was performed by placing it in a uniform flow field parallel with the free stream. The probe was spun at various speeds, and the signal from the strain gages mounted on the blades is passed through the slip rings to a voltmeter and power supply. Only one vane was instrumented and due to difficulty with the slip ring assembly, calibration was not completed.

The probe was used in only one wind tunnel test. The position of the vortex filament was stated to be obtained within 1/10th inch with this probe. A velocity map was obtained using a velocity field probe described in Reference (61). The velocity map and vortex location as determined with the vortex probe, are shown in Figure 4.
Fig. 3: NASA Type Non-rotating Vortex Meter (40)
FIGURE: 4: Flow Field Downstream of Wing Trailing Edge (40)
This review of existing vortex probes indicates that a vortex probe capable of making absolute vorticity measurements is not available commercially. It was also found that the calibration techniques employed with vorticity probes are inadequate, due primarily to slip-ring noise. One objective of this work is the design of a vortex probe capable of measuring vorticity directly, without recourse to correction factors, and capable of operation under g-loading, and also improvement of the technique for calibration of vortex probe through elimination of the slip-ring noise.

A detailed discussion of the advantages and disadvantages in the design, calibration, and operation of the rotating and non-rotating vortex meters and the data obtained through their use will be given in section 3.2. The remainder of this section will review electrostatic measuring devices and some of the data obtained with these devices.

2.3 Electrostatic Probes

The electrostatic probes reviewed in this section are those that are similar in design and operation to those used in the experimental phase of the present work. Emphasis of this review will be on the details of design and operating characteristics of each probe.

2.3.1 Conical Impact Probe

In Reference (5), a probe is described which, when inserted into a particulate flow, acquires an electric charge caused by the
impingement of the particles upon it. An attempt is made to relate this charge to the flow of particles and to use the probe as a means of measuring the flux of fuel in a pulverized fuel feed pipe.

The measuring head, on which the charge collected, was set at the end of a tubular brass stem with the axis of the head perpendicular to the stem, Figure 5.

![Diagram of Conical Impact Probe]

Fig. 5: Conical Impact Probe

The probe head is insulated from the stem by Araldite epoxy and connected by a coaxial lead to a d.c. amplifier. The stem of the probe and the screening of the coaxial lead were both grounded.

An AVO model 1388 A.D.C. amplifier was used in conjunction with a potentiometric recorder to measure the probe current. A Coulter counter was used for determining the size distribution of the particles.

The calibration of the probe was performed in a two-inch pipe. Flow velocities up to 65 ft./sec. were maintained by two centrifugal fans in series. The large difference in probe current, occurring when the probe is placed upstream and downstream of the fans,
prevented absolute calibration of the probe. The authors thought the increased charging of the particles on passing through the fans might be due to collisions of the particles with the fan. They questioned this premise due to the fact that there was no sign reversal upstream or downstream of the fan.

2.3.2 Ball Probe

An electrostatic ball probe is described in Reference (55). The ball probe utilized the principles of triboelectrification; i.e., solid particles become charged due to impact with the wind tunnel walls. Therefore, a probe of a given cross section inserted into the flow stream will pick up charge at a rate proportional to the mass flow. In the design of the ball probe, effort was made to maintain a high resistance to ground by use of glass sleeving to insulate the lead to the steel ball from the hypodermic needle tubing serving as the probe shaft. The probe requires at least a $10^{11}$ ohm resistance so as not to shunt the signal to ground. This required careful washing with distilled water and acetone after the stainless steel ball was soldered to the inner conductor. Resistance of $10^{13}$ ohm was maintained following this washing procedure. The current produced by impact of the particles against the ball is fed directly into a Keithly 6-10-R electrometer. The ball probe is used to measure the mass flow distribution in a particulate flow. For a narrow size range of particles, the mass flow of solid particles
is given by

$$\sum_{p} C_{p} = K_{m} i$$

(2.1)

where $i$ is the probe current due to the impacting particles.

The constant of proportionality $K_{m}$ is dependent upon the probe diameter, and the average charge to mass ratio is induced on the particles by impacting with the walls. For a given mass flow distribution, $K_{m}$ is constant; and the probe current, measured at each radius times $K_{m}$, gives the mass flow distribution at that radius.

2.3.3 Cylindrical Probe

A cylindrical electrostatic probe is described in Reference (10). The cylindrical probe operates on the same principle as the ball probe. In comparison to the ball probe, where the impact velocity of the particles against the ball is nearly that of the mean flow, the velocity of impact of the particles in the inside of the cylindrical probe is that of the velocity of random motion of particles sustained by the turbulent motion of the air. The cylindrical probe affords a larger amount of charge transfer per impact than the ball probe. This is due to the sliding of the particles along the inner wall of the probe. The cylindrical probe is also used to measure mass flow distributions.

The outer surface was painted with an enamel in order to increase the resistance to ground. The cylindrical probe current
times a proportionality constant $K_c$ is equal to the mass flow. 
The proportionality constant $K_c$ is a function of the probe geometry 
and average charge to mass ratio of the particles. Detailed analysis 
of the ball probe and cylindrical probe proportionality constants 
have been carried out in Reference (13b).

2.3.4 Particle Charge Probe

A particle charge probe is described in Reference (39). The 
probe is made of a thin stainless steel tubing (no. 15 hypodermic 
needle) with a glass sleeve located inside a similar but larger 
tube which acts as a shield. The gas particle suspension enters the 
probe through a small aperture, flows inside the needle tubing and 
is ultimately led to a miniature particle separator inside a cathode 
follower unit. Each entering-charged particle induces on the inner 
tube a charge of magnitude equal to the charge it carries; thereby 
a voltage pulse on the probe is created. The authors stated that 
collisions of the particle with the tube wall or the separator would 
result in a charge transfer but would not create an additional 
pulse or alter its magnitude. The voltage pulses from the probe are 
fed into the grid of an electrometer tube of the cathode follower 
and then, via a pre-amplifier and pulse amplifier, to a scalar with 
pulse-height discriminator. The pulse height $h$ at the scalar is 
related to the charge $q$ on the particle by

\[ q = ch/K \]  

(2.2)
where $K$ is the over-all gain of the electronic system and $c$ is the input capacitance of the probe assembly. By counting the number of pulses at different discriminator levels, an integral spectrum curve is plotted. By differentiation of the integral curve, the frequency distribution of the pulse heights $n$, which is the charge distribution of the particles, is obtained.

### 2.3.5 Electric Field Meters

A brief discussion of electric field meters is given here to provide background for a later section dealing with a recent design of a new field meter. Electric field meters of the type considered here employ electrostatic induction to provide a signal which may be amplified and monitored by a suitable device; i.e., plotter, meter. The inductor is a rod, or vane, rotated on a driven shaft about its center in a plane parallel to the direction of the electric field. The inductor has charges induced on it due to its movement through the electric field. The inductor is partially shielded such that a charge variation is induced which is a function of the shielding and the frequency of rotation of the inductor. The inductor rod is highly insulated and connected to the grid of a vacuum tube with a very high resistance between the grid and the ground.

The inductor system may be operated in two fundamentally different ways depending on the relaxation time of the electric circuit between the grid and ground as compared to the period of
rotation of the inductor. If this relaxation time is long, the system is particularly adapted for a system employing alternating current. If the relaxation time is short, most of the induced charge will be conducted to the ground through the high resistance. This current is rectified by a synchronous switch and a simple direct current electric field meter results. A detailed review of both types of field meters is given in Reference (23).

2.4 Electrostatic Charging In Swirling Flows

The ability of a rotational flow to act as a charge generating and separation device is verified by the work discussed in Reference (30). A supersonic swirling air flow was created by the use of swirl vanes located at the inlet to a supersonic nozzle. The amount of swirl imparted to the flow could be varied by changing the pitch angle of the vanes. The exhaust of the nozzle passed through a transparent dielectric cylindrical duct. The air entering the system was drawn from the laboratory and contained varying amounts of water vapor, depending on prevailing atmospheric conditions. It was noted that during some experimental runs, the water vapor would condense upon exiting the nozzle and due to the swirling motion of the flow be carried to the walls of the cylindrical duct. Subsequently, there would occur a glow discharge which appeared to be confined to the center line of the duct. Further study of this glow discharge and the conditions affecting it, resulted in the following observations (30).
-- At low specific humidities, the measured charging current was uniform suggesting that the charging is due to particles with large mass-to-charge ratios, whose motion could not be affected appreciably by electric fields.

-- It appeared that the glow discharge is maintained by an intermittent build-up and neutralization of negative space charges in the interior of the duct.

-- When the dielectric duct was replaced by one made of a conducting material, no luminescence was observed.

-- The glow was more intense near an axial Mach number of two than at lower and higher Mach numbers. The conclusion drawn from this work is that the rotational flow acts as a charge separating mechanism, depositing the heavier positively charged particles on the walls of the duct and concentrating the smaller negatively charged particles in the core of the vortex.

2.5 Electrostatic Charging of Helicopters

The hazards of static buildup on helicopters were mentioned briefly in the introduction. To illustrate the seriousness of this problem, one has only to refer to a publication by M.E. Rodgers (51) where it is reported that rescue operations were being jeopardized by the frequent electrical shocks received by winchmen and survivors. In some cases severe shocks had been experienced, and concern was expressed about the possible consequences to survivors in poor physical condition. Attempts to provide conductive paths
through the winchmen's clothing proved largely ineffective, and trailing wires for earthing purposes represented greater hazards than the static buildup under certain conditions.

The various mechanisms leading to static electrification of helicopters in flight have been cited in References (51) and (9). These mechanisms are precipitation charging, spray electrification charging by induction, and charging from engine exhaust gases. In Reference (58), the main rotor blades of helicopters are said to be the chief contributors to the electrostatic charge on helicopters. The remainder of this paragraph will be devoted to discussing the details of these charging mechanisms.

1. Participation charging -- occurs when charge-carrying particles, such as dust, water droplets, snow flakes or ice crystals strike some part of the helicopter's surface. The charging currents depend upon the space charge density, intercepting surface area, and velocity of impact.

2. Spray Electrification -- occurs due to the shattering of the surface liquid film of water droplets on impact with some part of the helicopter surface. The shattering of the droplet causes the electrical double layer to break and results in separation of parts having dissimilar charges.

3. Charging by induction -- occurs due to the helicopter passing through regions of varying electric field. The absolute charge on the helicopter remains relatively unchanged while the po-
4. Charging from the engine-exhaust gases takes place due to the thermally generated ion pairs in the combustion chamber of jet engines. If ions of either polarity preferentially recombine, the remaining charges of like sign will yield a charging current.

An experimental program designed to measure the charging due to the main rotor blades is described in Reference (58). Under clear air conditions (no snow, dust, sand, rain, etc.) the electrostatic charging currents due to the main rotor blades were relatively small (-20 nanoamperes) compared to the helicopter's total current (+2 to +3 microamperes). Under contaminated conditions (dust), the rotor blades were major contributors of electrostatic charging currents. The static electricity, associated with the helicopter under clear air conditions, was thought to be due to charging currents from the engines.

The mechanisms by which the charge is generated and deposited on the helicopter is not discussed in Reference (58). However, a noticeable change in generated current was observed to occur when ice, which initially coated the main rotor blades, gradually eroded from the blades during rotation. The reason for the increase in current was believed due to the difference in the dielectric constant between the ice and the blade.

A recent paper (51) presents charging currents derived from the engine power unit and rain precipitation. The contention that
engine charging is one mechanism of helicopter charging is based on noticeable increase in the voltage levels of one particular model helicopter (MK4 Whirlwind) when the Pratt and Whitney piston engine was replaced by the Gnome 1,000 gas turbine (MK 10 Whirlwind).

The potentials and charging currents, measured on different helicopters in clear air conditions, are given in Tables 1 and 2.

**Table 1.** Aircraft Potentials Measured On Different Helicopters at RAE Farnborough in Clear Conditions (Reference 51).

<table>
<thead>
<tr>
<th>Type of Helicopter</th>
<th>Number of Readings</th>
<th>Voltage Reading - kV</th>
<th>Maximum</th>
<th>Minimum</th>
<th>Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>Whirlwind 10</td>
<td>5</td>
<td></td>
<td>30.7</td>
<td>23.3</td>
<td>28.8</td>
</tr>
<tr>
<td>Wessex 2</td>
<td>5</td>
<td></td>
<td>1.1</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>Wessex 1</td>
<td>5</td>
<td></td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>Whirlwind 1</td>
<td>5</td>
<td></td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
</tr>
</tbody>
</table>
Table 2. -- Charging Data Measured on Different Helicopters In Singapore In Clear Air Conditions (51)

<table>
<thead>
<tr>
<th>Aircraft Type</th>
<th>No.</th>
<th>Height Above Ground (Ft.)</th>
<th>Time Since Last Earthed (Sec)</th>
<th>Charging Current (μA)</th>
<th>Voltage (kV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wessex 5</td>
<td>XS-517</td>
<td>20</td>
<td>90</td>
<td>+0.05</td>
<td>6</td>
</tr>
<tr>
<td>Belvedere</td>
<td>XG-457</td>
<td>20</td>
<td>60</td>
<td>+0.4</td>
<td>+2.0</td>
</tr>
<tr>
<td>Belvedere</td>
<td>XT-468</td>
<td>20</td>
<td>120</td>
<td>0.05</td>
<td>3</td>
</tr>
<tr>
<td>Whirlwind 10</td>
<td>XR-458</td>
<td>20</td>
<td>90</td>
<td>+0.65</td>
<td>+42</td>
</tr>
<tr>
<td>Whirlwind 10</td>
<td>XR-458</td>
<td>22</td>
<td>90</td>
<td>+0.70</td>
<td>+48</td>
</tr>
<tr>
<td>Whirlwind 10</td>
<td>XR-458</td>
<td>20</td>
<td>90</td>
<td>+0.6</td>
<td>+51</td>
</tr>
<tr>
<td>Whirlwind 10</td>
<td>XK-988</td>
<td>22</td>
<td>120</td>
<td>+0.6</td>
<td>+52</td>
</tr>
<tr>
<td>Whirlwind 10</td>
<td>XK-988</td>
<td>20</td>
<td>120</td>
<td>+0.6</td>
<td>+55</td>
</tr>
<tr>
<td>Whirlwind 10</td>
<td>XR-479</td>
<td>20</td>
<td>120</td>
<td>+0.6</td>
<td>+46</td>
</tr>
<tr>
<td>Whirlwind 10</td>
<td>XR-479</td>
<td>20</td>
<td>180</td>
<td>+0.6</td>
<td>+46</td>
</tr>
<tr>
<td>Whirlwind 10</td>
<td>XR-479</td>
<td>20</td>
<td>300</td>
<td>+0.6</td>
<td>+40</td>
</tr>
<tr>
<td>Whirlwind 10</td>
<td>XR-485</td>
<td>20</td>
<td>90</td>
<td>-</td>
<td>+43</td>
</tr>
<tr>
<td>Whirlwind 10</td>
<td>XR-485</td>
<td>20</td>
<td>90</td>
<td>-</td>
<td>+48</td>
</tr>
</tbody>
</table>
Charging currents also increased significantly with fuel flow rate, as shown in Figure 6. A significant change in the charging current occurs when the fuel flow rate increases above 250 lb./hr.

![Diagram showing current versus fuel flow rate]

**Fig. 6: Current Versus Fuel Flow Rate**

The suggested explanations for this increase in charging current with fuel consumption are:

1. When the fuel consumption reaches a critical value (\(\sim 250\) lb./hr.), thermal equilibrium conditions exist between the carbon particle and flame temperature within the reaction zone and ionization occurs leaving the carbon particles positively charged.

2. More positively charged particles reach the duct walls by diffusion than negative ones.

This paper also presents data on charging currents of helicopters in rain storms. The initial data was taken while attempting to measure engine charging currents in rain.
The results indicate that, in quiet or steady rain, negative charging currents were almost always measured and magnitudes rarely exceeded $\pm 2.0 \mu A$. In showers or thunderstorms, rain current magnitude and polarity could change rapidly. Recorded currents on a whirlwind MK 10 with an all-up-weight (AUW) of 8,000 lb. ranged from $-100 \mu A$ to $+60 \mu A$.

In attempting to explain the charging currents on helicopters in rain, it was decided that further study should be carried out. This conclusion was reached when rain precipitation currents overshadowed engine charging. There were several tests when low currents were measured in heavy rain, also changes in polarity and magnitude of currents which could not be related to rain intensity.

Additional testing during the thunderstorm season in Singapore yielded the following conclusions:

1. Precipitation charging currents, measured on different helicopters hovering in identical conditions, are related by the ratio of their respective all-up-weights, Table 3, on the following page.
Table 3.-- Comparison Between Ratios of All-Up-Weight and Measured Charging Currents For Different Aircraft (51)

<table>
<thead>
<tr>
<th>Type of Helicopter</th>
<th>Ratio of All-Up-Weights</th>
<th>Ratio of Measured Charging Current</th>
</tr>
</thead>
<tbody>
<tr>
<td>Belvedere/Whirlwind</td>
<td>2.6/1</td>
<td>2.5/1</td>
</tr>
<tr>
<td>Belvedere/Wessex</td>
<td>1.5/1</td>
<td>1.4/1</td>
</tr>
<tr>
<td>Wessex/Whirlwind</td>
<td>1.7/1</td>
<td>1.7/1</td>
</tr>
<tr>
<td>Whirlwind/Whirlwind</td>
<td>1.15/1</td>
<td>1.14/1</td>
</tr>
</tbody>
</table>

NOTE: Whirlwind 7700 lb.
1. Whirlwind 6700 lb.
2. Highest currents occur in heavy rain associated with high ambient electric stresses.
3. Maximum charging recorded on a whirlwind (AUW=8,000 lb.) were ±100μA.
4. The charging current is dependent upon the field gradient.

The basic charging mechanism was concluded to be the induced charges on the tiny water filament just prior to separation from the main drop (due to impaction with the rotor blade) which are imparted to the air. Those droplets, which do not become recap-
tured by the air-frame constitute a net charging current of opposite polarity.

The principle of induction charging attributed to Adkins (2) was used to obtain quantitative values of charging with the results.

1. Charge released due to drops splashing onto the upper surfaces (which nearly approximated the test conditions of Adkins) were calculated using Adkins' empirical formula.

\[ I_c = 2.15 \left(10^{-q}\right) E R^{1.23} \]  \hspace{1cm} (2.3)

For values of \( E=100\text{V/cm}, R=100\text{mm/hr} \) and \( \text{Area} = 25\text{m}^2 \), the current is \( I_c = 0.0016 \mu\text{A} \).

2. Charge generated, due to impact with the leading edge of the rotor blade, is determined from the expression

\[ I_c = 2 \left(10^{-15}\right) A \phi E^1 R^{0.68} \]  \hspace{1cm} (2.4)

which is similar in form to Adkins' expression. Here \( A \) is a constant of proportionality determined empirically for a given target surface. This constant relates the quantity of charge released/unit of impact energy/unit of field strength.

\( \phi \propto N \Omega^3 t l^4 \) and is constant for a given helicopter at a given AUW. (\( N \) is number of rotor blades; \( \Omega \) is angular velocity; \( t \) is blade thickness; and \( l \) is rotor span.) \( E \) is the field strength at
the impact point, which can be very high due to curvature of the blade leading edge; hence, it is assumed that $E^1 = 10E$.

$R$ is the measured rainfall rate.

Since it is assumed that the parameter does not differ widely from blade to blade, different helicopters hovering in identical conditions for $E$ and $R$ should be related by the ratio of their respective $\phi$ constants. This comparison is shown in Table 4.

Table 4. -- Data Showing Agreement Between Ratios of Blade Constants, $\phi$ and AUW, for Different Helicopters (51)

<table>
<thead>
<tr>
<th>Type of Helicopter</th>
<th>Ratio of Blade Constants</th>
<th>Ratio of AUW (empty)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Belvedere/Whirlwind</td>
<td>2.14/1</td>
<td>2.45/1</td>
</tr>
<tr>
<td>Belvedere/Wessex</td>
<td>1.26/1</td>
<td>1.42/1</td>
</tr>
<tr>
<td>Wessex/Whirlwind</td>
<td>1.7/1</td>
<td>1.72/1</td>
</tr>
</tbody>
</table>

Using the value of $A=6 \times 10^{-8}$, as found by Adkins (for rain drops falling on a flat plate in still air), a charging current of $I_c = 57 \mu A$ is obtained. (Assumed values of $E=100V/cm$ and $R=100mm/hr$ are used.) True values of $A$ for a helicopter are expected to be 10 times greater than the Adkins value; hence, it is stated that the expression for $I_c$ will predict the high charging currents measuring the rain precipitation.
The significance of the data is based on the static hazard the aircraft presents when charged to the voltages they attain. Tables 1 and 2 show that voltages of 30-50 KV are regularly occurring and represent energies in excess of 0.5 Joules at the upper limit.

The conclusion drawn from this paper, which is directly related to the present work, is the direct increase in charging currents with increase in AUW, Tables 3 and 4. The Whirlwind 1 and Whirlwind 2 helicopters have the same blades and tip speed. The added AUW requires more lift to be generated by the weighted helicopter; therefore, more vorticity is shed from the rotor tips. Assuming the trailing vortex contributes to charge separation (and also, is a charge generator), the additional current may be related directly to the increase in the flow of vorticity over the body of the helicopter.
CHAPTER III
TEST EQUIPMENT

3.1 Introduction

This section of this paper describes briefly the experimental equipment employed in the measurement of the vorticity contours, the electric field contours, and the particle density contours. Most of the equipment discussed in this section was designed and fabricated specifically for the experiments to be performed during the course of this study. Inclusion of all the specific details relating to the design and operation of this equipment would tend to obscure the more important part of this work which is the experimental results obtained with the air-bearing vortex probe, the electric field meter, and the particle impact probe.

The three instruments mentioned above are the most important pieces of equipment used in this work; hence, they are discussed in detail. The theory behind the vortex probe is outlined, and the details of their design is discussed; clarified, where possible with drawings and photographs. The results of the calibration of the vortex probes are presented. All the electric field sensing devices and particle distribution probes used in the course of this work are discussed. The design of the particle density probe used to obtain the final density contours is discussed in detail.
This chapter gives the essentials of details of the experimental apparatus used to establish a trailing vortex system and in the measurement of the vorticity, electric field, and particle distribution at various locations in this vortex system. Specific details, dimensions, operating procedures and drawings of the equipment is presented in appendices.

3.2 The Flow System

The equipment required to produce the seeded flow field and the trailing vortex system are a subsonic wind tunnel into which a differential airfoil is mounted, a particle feed system, and a filter system. A brief discussion of this equipment is presented here. Complete details, drawings and photographs of this equipment is given in appendices.

3.2.1 Wind Tunnel and Differential Airfoil

A low-turbulence subsonic wind tunnel was used to obtain a flow field for the experimental tests. The wind tunnel is 45 feet long from inlet to the end of the turning box located at the tunnel exit and has the capability of developing test section velocities of 187 ft./sec. The test section is 10 feet long with a 2 x 1.5 ft. cross section and is constructed of wood coated with non-pigmented varnish for dielectric properties. The trailing vortex system is generated in the wind tunnel through the use of a differential airfoil. A differential airfoil is two airfoil sections of equal span length and chord
with which are mounted tip-to-tip across the wind tunnel test section. The airfoil sections are positioned so that the angle-of-attack of one section is equal and opposite to that of the other. The airfoils are supported in the wind tunnel at their quarter-chord position by a steel support rod positioned 2 feet aft of the contraction section exit. (See Appendix A.1). Attached to the support rod, external to the wind tunnel are angle-of-attack indicators. When installed, the angle-of-attack indicators mate with the airfoil and permit the angle of attack to be varied during operation of the wind tunnel. The differential airfoil is used in this work because it produces a stable vortex whose position in the wind tunnel test section is independent of the flow velocity, the airfoil angle of attack, and the distance aft of the airfoils. Details of the wind tunnel and the flow calibration are presented in Appendix A.1.

3.2.2 Particle Feed System

The wind tunnel flow field was seeded with particles which are blown against the wind tunnel inlet screen by a nozzle. The particles are stored in a spring-loaded hopper capable of holding 50 pounds of particles. The hopper is equipped with a dial indicator to indicate the flow rate of particles from the hopper. The particles are drawn from the hopper by a venturi located beneath the hopper. The spout of the hopper is connected to the throat of the venturi. Air passing through the venturi mixes with the particles and carries them to a mixing chamber in the back on the nozzle.
The nozzle, which directs the particles against the wind tunnel inlet screen, consists of a cylindrical mixing chamber section, a converging-diverging section, and a hollow sting running down the center of the nozzle. At the end of the sting is mounted a deflecting cone. The mixing chamber receives the mixture of air and particles from the venturi and also unseeded air from the primary air supply. This mixture is exhausted through the converging-diverging section toward the wind tunnel inlet.

A third air-supply line is attached to the hollow sting. Air passing down the sting is exhausted through jets located in the base of the cone. The main purpose of the cone is to reduce the core velocity of the nozzle exhaust. The air jets at the base of the cone help to shape the nozzle exhaust plume. Details, drawings, and photographs of the particle feed system are included in Appendix A.2. The determination of the nozzle length, size, and contour is discussed in Appendix A.3.

3.2.3 Filter System

The wind-tunnel flow exits into a large turning box which directs the flow of air and seed particles up toward the laboratory ceiling. A system, to filter the particles from the flow without creating a severe pressure drop, was necessary to prevent the particles from blowing throughout the laboratory. Secondly, it is desirable to reuse the particles, due to their cost, and to avoid unwanted particle size variations. The particles are obtained from a local
plastic manufacturer in 50-lb. bags, and the particle size distribution can vary considerably from bag to bag.

Several filter systems were considered prior to selecting the system used. Systems considered were standard throw-away furnace filters, reusable-industrial filters, cyclone separators, and enclosures. The disadvantages of these systems are cost, not being able to recover the trapped particles for additional tests. Additional tests required additional equipment and long time-delays between tests; and with heavy particle loadings, the pressure drop would increase rapidly.

The system, finally selected, is a large 18-ft. high, 12-ft. diameter, filter bag which is made of cotton flannel. The advantages of this system are: low-cost, ease of maintenance; and the easy recovery of the particles for reuse in testing.

At the open end, the filter bag is tapered to a 56-inch, rectangular opening which fits snugly over the top of the turning box. The bottom three feet of the filter bag is reinforced to prevent tearing. The top of the bag has hanger straps with grommets. A 3-inch cuff, with a rope insert, was attached to the open end. The bag is suspended from a circular hoop which together is raised to the ceiling of the laboratory by cable and winch.

The pressure drop through the filter bag can be represented by (44):

$$\Delta P = k \mu v$$

(3.1)
where \( k \) is a constant dependent upon the fabric

\( \mu \) is the viscosity of the fluid in centipoises.

\( V \) is the velocity in feet per minute.

The value of \( k \) for 10 oz./sq.yd. cotton flannel with a chain twill weave is 1.59 (44). For the test conditions in this work, the pressure drop through the filter bag was calculated to be 1.38 inches of water. After installation, the measured pressure drop was 0.5 inch of water. The difference between the measured and actual value of pressure drop is probably due to the difference in the dimensions of the system used to make the experimental correlation and the filter bag; i.e., a 3-inch diameter tube as compared to a 12-foot diameter bag. The inside of the filter bag has a heavy nap which traps the particles and retards the filling of the fabric pores. After each test run, the bag is agitated to shake the particles from the nap. The particles drop into the turning box where they are vacuumed up and returned to the hopper for reuse. A picture of the inflated filter bag is shown in Figure 7.

3.3 Vortex Probes

3.3.1 Introduction

Two vortex-sensing probes have been designed and fabricated for the measurement of the vorticity in the trailing vortex system. These probes are capable of determining the geometry and magnitude of rotation of a trailing vortex by traversing a plane normal to the
axial direction of the vortex; (i.e., normal to the wind tunnel axis).
Details about the fluid flow geometry were obtained to verify that the differential airfoil does produce a stable trailing vortex system, to assist in the interpretation of the electrostatic charging data, and also to substantiate the electrostatic charging patterns obtained. An additional reason for development of the vortex probe is that, in the future, they are to be used in a rotating system where they will be subjected to high $g$-loadings.

Two types of vortex probes were considered in this work, rotating and non-rotating. The rotating type probe ideally rotates at the same angular velocity as the rotating fluid (31, 36). This has not been achieved due to bearing friction losses. The non-rotating type vortex meter senses the rotation of the fluid by means of stress in a sensing element. The sensing element is instrumented with strain gages. The output signal from the strain gages (either in millivolts or frequency) corresponds to a stress in the sensing element due to twist which is caused by the rotating fluid acting on the probe vanes. The problems associated with the non-rotating type vortex meter had been hysterisis of the sensing element (causes the zero point to shift during a test) and variations due to cooling of the sensing element, since the strain gages are exposed to the flowing stream. The airbearing vortex probe discussed later in this paper is a non-rotating type probe with no hysterisis or thermal errors.

In order that the details of the probe designs and the advantages and disadvantages of each type of probe be understood, the theory behind vortex probes will be reviewed and details regarding construction, calibration and operation of each type probe will be discussed.
3.3.2 Rotating Vortex Meter -- Theory

The rotating vortex meter (36, 31, 32, 39) is based on the relationship between rotation of a fluid at a point and the vorticity of the fluid at that point. In the analysis of the deformation of a fluid element, it can be shown that the fluid element is subjected to both a rotation and an angular displacement (29). The average rates of rotation (counterclockwise rotation is defined as positive) about the three coordinate axis are:

\[
\Omega_x = \frac{1}{2} \left( \frac{\partial w}{\partial y} - \frac{\partial v}{\partial z} \right) \\
\Omega_y = \frac{1}{2} \left( \frac{\partial u}{\partial z} - \frac{\partial w}{\partial x} \right) \\
\Omega_z = \frac{1}{2} \left( \frac{\partial v}{\partial x} - \frac{\partial u}{\partial y} \right) 
\]  

(3.1)

These components of rotation are similar to the components of a vector, designated by mathematicians as curl of a vector \( \vec{V} \), where the components of \( V \) are \( U, V, W \), such that

\[
\text{Curl } \vec{V} = \left( \frac{\partial w}{\partial y} - \frac{\partial v}{\partial z} \right) \hat{i} + \left( \frac{\partial u}{\partial z} - \frac{\partial w}{\partial x} \right) \hat{j} + \left( \frac{\partial v}{\partial x} - \frac{\partial u}{\partial y} \right) \hat{k} 
\]

(3.2)

Therefore, the rotation of a fluid element about an appropriate axis of rotation is

\[
\vec{\Omega} = \frac{1}{2} \text{Curl } \vec{V} 
\]

(3.3)
The vorticity vector is then defined as twice the rotation, thus,
\[ \omega = 2 \Omega = \text{Curl} \, \nabla \]
where
\[ \omega_x = \frac{\partial w}{\partial y} - \frac{\partial v}{\partial z} \]
\[ \omega_y = \frac{\partial u}{\partial z} - \frac{\partial w}{\partial x} \]
\[ \omega_z = \frac{\partial v}{\partial x} - \frac{\partial u}{\partial y} \]

Since the vorticity of the fluid is just twice the rotation of the fluid, a measurement of the rotation of the fluid throughout the flow field also gives the vorticity distribution throughout the flow field. To determine the circulation, recourse must be made to the definition of velocity potential and Stokes' theorem.

The circulation \( \Gamma \) is defined as the line integral of the velocity around a closed contour. Mathematically, the line integral of the velocity around a closed curve \( C \) is the sum of the products of the elemental length \( dl \) of the curve and the corresponding component of velocity tangent to the curve. For the closed curve \( C \), the circulation is represented by the integral
\[ \Gamma \equiv \oint_C V \cos \alpha \, dl \] (3.5)
where \( \alpha \) = the angle between the element \( dl \) and the component of velocity tangent to the curve. In vector rotation this may be written as:
\[ \Gamma \equiv \oint_C \vec{V} \cdot d\vec{l} \] (3.6)
where \( \vec{V} \) represents the vector velocity and \( \vec{l} \) the vector radius from any fixed radius. If \( u, v, \) and \( w \) denote respectively the velocity components in
the x-, y-, and z-directions the Cartesian form of equation (3.6) becomes

\[ \Gamma = \oint (u\,dx + v\,dy + w\,dz) \]  \hspace{1cm} (3.7)

Consider the two dimensional case where

\[ V\cos\alpha\,dl = u\,dx + v\,dy \]

The velocity potential φ is defined by the relations

\[ u = \frac{\partial \phi}{\partial x} \quad \text{and} \quad v = \frac{\partial \phi}{\partial y} \]

Thus the line integral of velocity can be written as

\[ V\cos\alpha\,dl = \frac{\partial \phi}{\partial x}\,dx + \frac{\partial \phi}{\partial y}\,dy = d\phi \]

\[ \int_A^B (u\,dx + v\,dy) = \phi_B - \phi_A \]  \hspace{1cm} (3.8)

The line integral along path A to B can be interpreted as a change in the velocity potential.

Using Stokes' theorem, the contour integral can be transformed into a surface integral (for convenience, two dimensional cartesian coordinates are used here).

\[ \Gamma = \oint_C (u\,dx + v\,dy) \]  \hspace{1cm} (3.9)

\[ = \iiint_C \left( \frac{\partial v}{\partial x} - \frac{\partial u}{\partial y} \right) \, dx\,dy \]

By comparing the last integral with the components of the velocity vector, the circulation can be written
\[ \oint = \iint \omega_z \, dx \, dy \quad (3.10) \]

The significance of this expression is that the circulation around any contour is the integral of the vorticity over the area enclosed by the contour. Now the vorticity at a point was defined as twice the rotation at that point; therefore,

\[ \oint = \iint 2 \Omega_z \, dx \, dy \quad (3.11) \]

This expression is the mathematical relationship upon which the rotating type vortex meter is based. The rotating vortex meter is used to obtain a map of the rotation throughout the flow field. The circulation of the fluid within this region is obtained by integration of the vorticity (or twice the rotation) over the flow field area. References (32, 36, 37) present typical data obtained using rotating type vortex meter.

A final comment is necessary in regard to the relationship

\[ \omega = 2 \Omega = \text{Curl} \vec{V} \quad (3.12) \]

which states that the vorticity of the fluid element is twice the rotation of the fluid element. For this statement to be absolutely correct when applied to rotating vortex probes, the dimensions of
the probe must be vanishingly small; i.e., represent a point. This end is achieved by making the vanes of the probe small compared to the size of the vortex which is being measured. In (32), it is shown that, for a ratio of probe span to vortex span of 0.1, the error due to the finite size of the probe is negligible.

3.3.3 Non-rotating Vortex Meter -- Theory According to McMahon

A non-rotating vortex meter has also been used in the measurement of the vorticity in the trailing vortices downstream of an airfoil. This type of vortex meter measures the amount of strain experienced by the vanes of the meter due to the rotation of the fluid. Strain gages are mounted on the vanes of the meter and give a measure of the amount of rotation (or vorticity) in the fluid. To determine the relationship between the strain in the vanes of the vortex meter and the rotation of the fluid, the meter vanes are analyzed analogous to wing experiencing rolling motion (40). The torque delivered to the meter vanes, due to the rotating flow field, can be determined from a damping in roll analysis. The resistance of a wing to rolling is expressed in terms of the damping-in-roll parameter, $C_{\alpha p}$, which according to slender body theory is:

$$C_{\alpha p} = -\frac{\pi}{32}AR$$  \hspace{1cm} (3.13)
The rolling movement experienced by a vane of the meter is

\[ M_R = q S b C_\lambda \]  \hspace{1cm} (3.14)

where \( q = \frac{1}{2} \rho v^2 \)

- \( S \) = vane plan form area
- \( b \) = vane span
- \( v \) = velocity of fluid (near probe vane)

Since

\[ C_p = \frac{dC_\lambda}{d\left(\frac{Pb}{2V_\infty}\right)} = \frac{-\pi R}{32} \]  \hspace{1cm} (3.15)

where \( V_\infty \) = the free stream velocity
- \( P \) = rolling angular velocity

\[ C_\lambda = \frac{-\pi R}{32} \left( \frac{P b}{2 V_\infty} \right) \]  \hspace{1cm} (3.16)

and

\[ M_R = q S b \left( \frac{-\pi R}{32} \right) \left( \frac{P b}{2 V_\infty} \right) \]  \hspace{1cm} (3.17)

where \( R = \frac{b^2}{S} \)

The bending stress of one vane is determined from

\[ \sigma_b = \frac{M_R y}{I} \]  \hspace{1cm} (3.18)
where $M_0 = M_R$.

$\bar{y} =$ distance from the neutral axis

$I =$ moment of inertia

For a vane of span $b/2$, chord $c$, and thickness $h$

$\bar{y} = \frac{h}{2}$

$I = \frac{ch^3}{12}$

The relationship between the maximum stress in bending and the maximum strain in bending is

$$\varepsilon_B = \frac{\sigma}{E}$$  \hspace{1cm} (3.19)

where $E$ = modulus of elasticity.

Combining equations (3.18, 3.19) after substitution and simplification, the strain in one vane can be expressed as

$$\varepsilon_B = \frac{M_0 \bar{y}}{E I}$$  \hspace{1cm} (3.20)

Using equation (3.17), McMahon obtains equations for strain in the vain

$$\varepsilon_B \propto \left( \frac{b}{c h^2} \right) \left( \frac{\rho v p}{\rho v E} \right)$$  \hspace{1cm} (3.21)

or he writes

$$\varepsilon_B \propto \left( \frac{1}{h^2} \right) \left( \frac{v}{E} \right)$$  \hspace{1cm} (3.22)

Where $V$ is the velocity of the fluid as defined above. McMahon then fabricated and tested a non-rotating meter based on these principles.

If one considers the expression for strain euqa.(3.22),
The strain in each vane is a function of the thickness of the vane, the material properties of the vane, and the velocity field in which the vane is positioned. The advantages and disadvantages of both meters will now be cited and sample data obtained with each meter reviewed. This data will be compared against Lamb's theory of vortex decay.

3.3.4 Comparison of Rotating and Non-rotating Vortex Meters

The advantage of the rotating type vortex meter is that the rotation of the fluid at a point is obtained directly from the rotating vanes of the meter, whereas the non-rotating type vortex meter measures the torque delivered by the fluid to fixed vanes. The rotating type meter suffers in accuracy due to bearing friction and inertial effects. Both meter types are in error due to their finite size (i.e., they are not really points in the flow field) and both meters yield results dependent upon free stream velocity. Neither meter has been calibrated with complete accuracy due to difficulty in maintaining a known pure rotational flow field (36). The rotating meter is inaccurate when located in other than a linear vorticity field (32). The non-rotating type of meter should yield satisfying measurements regardless of the variation of the vorticity field (i.e., as long as the torque limits of the meter are not exceeded).

The rotating meter has been used in both wind tunnel and free flight tests (37); whereas, the non-rotating meter has been used
for only one wind tunnel test. The data, obtained through the use of these meters, will be reviewed and compared against existing data of vortex decay, (36, 41, 43) and data obtained from the present experimental tests.

3.3.5 Design of Vortex Probes

To determine the shape and rate of decay of the trailing vortex as it moves downstream from the differential airfoil, it is necessary to use some type of vortex meter. After a review of existing vortex meters, it was decided to build a non-rotating vortex meter similar to the meter discussed in Reference (40). It was decided to build this type of meter since it appeared capable of operating in a high-g environment. Some time after initiating the design and fabrication of the non-rotating type of vortex meter, and becoming more familiar with the problems associated with it, a completely new idea in vortex meter design was conceived. The new design had none of the disadvantages associated with existing vortex meters; therefore, a prototype model was fabricated for immediate use. The new vortex meter employs air bearings from whence it got its name of the air bearing vortex meter. The detail of the design and fabrication of each meter is discussed here; and data obtained with the meters will be discussed in a later section.

3.3.5.1 Non-rotating Vortex Meter

A non-rotating type of vortex meter (consisting of a hollow steel shaft, a probe head, and four instrumented vanes) was con-
Structured to measure the vorticity in the trailing vortex system. The shaft and vanes are made of stainless steel; the probe head is made of brass.

The shaft, Figure 8, of the non-rotating vortex probe, is 6.70 inches long. The outside diameter of the shaft is 0.375 inches and the bore of the shaft is 0.125 inches. One end of the shaft has been threaded to receive the probe head. The shaft has been slightly tapered toward each end, starting with a maximum diameter of 0.375 inches at the middle of the shaft and reducing down to 0.371 inch-diameter at each end. The tapered shaft was polished to provide smooth bearing seats for the support bearings.

The two support bearings are installed on the shaft with a slight press fit; and due to the taper in the shaft, each bearing must be installed from each end of the shaft. When the bearing mounts are bolted in place, the support bearings are seated firmly on the tapered shaft preventing any lateral movement of the shaft when it is rotated.

At a point 0.375 inches from the unthreaded end of the shaft, the shaft has been turned down an additional 0.020 inch over a width of 0.18 inch. When the shaft is installed, in either the calibration device and/or the probe holder of the positioning device, the set screw which holds the shaft in place, makes contact with the shaft at this point. When screwed into the recess in the shaft, the set screw prevents the shaft from laterally sliding.
Fig. 8: Probe - Front and Side Views
The probe head, Figure 8, consists of 3 parts:

- the probe head-base
- the probe-head vanes
- the strain gages

The probe-head base is a partially hollow brass hemisphere cylinder 0.375 inches in diameter. The length of the hemisphere cylinder is 1.25 inches, and its bore is 0.125 inches. The 0.125 inches hole extends from the base of the cylinder, a distance of 1.25 inches. A 0.125-inch-threaded-hole has been made in the center of the hemisphere along the axis of the probe head. The stem, upon which the four vanes are mounted, screws into this hole. Drilled into the hemisphere, are four 0.0625 inch diameter holes spaced 90 degrees apart on a 0.125 inch radius. These holes are drilled on an angle so they intersect with the bore of the cylindrical portion. The four leads from the strain-gage bridge pass through these holes. The base of the probe head has been threaded so it can be screwed on the probe shaft.

The probe-head vanes are cut out of 0.002 inch-thick, stainless steel shimstock. The vanes are 0.5 inch wide and 1.0 inch long; the longer side is aligned parallel to the axis of the probe. The four vanes are mounted perpendicular to each other in slits milled in a 0.125-inch, diameter-brass stem. The stem is 1.885 inches long. The vanes are mounted 0.25 inches from the tip of the stem. Each vane has two 0.125 inch holes punched in it. The holes are located on the long axis of each vane close to the stem which holds the vanes. The
leads from the strain gages, mounted on the vanes, are passed through these holes.

The strain gages, used to monitor the strain in the vanes were Baldwin-Lima-Hamilton SR-4 general purpose gages. The actual designation of the gages is FAE-06G-256-ES. These gages have a 0.17-inch overall width and a 0.06 x 0.06-inch grid. The grid material of the gages is constanta(Copper-nickel alloy), and the backing material is polymide. The resistance of each gage is 120 ±0.2 ohms.

The strain gages were bonded to the vanes at the midpoint of the longer dimension and adjacent to the stem. The vane is basically a cantilevered beam which has its maximum strain at the point of restraint which, in this case, is near the stem of the probe head. The gages are mounted using RTC epoxy.

Only two of the vanes were instrumented and had gages attached to them at both sides of two mutually perpendicular vanes. There are two reasons why all four vanes are not instrumented. First, the F.M. transmitter, used in conjunction with the vortex probes, is single channelled; i.e., the transmitter can only transmit the signal of one Wheatstone bridge; and secondly, the choice of two mutually perpendicular vanes is based on the mathematical expression for vorticity, which in cartesian coordinates is:

\[ \vec{f} = -\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} \]  \hspace{1cm} (3.23)

With the gages located on mutually perpendicular vanes, one vane
gives a measure of $\frac{\partial u}{\partial y}$ and the other vane a measure of $\frac{\partial v}{\partial x}$.

The strain gages are connected in the usual Wheatstone bridge pattern — short leads of 28-gage wire are used to wire the four gages; these small leads pass through the holes in the vanes and are soldered to the strain-gage tabs. Four long leads are also soldered to the strain-gage tabs, (the four corners of the wheatstone bridge) and they pass through the four holes in the probe-head base and down the center of the shaft. These four leads are attached to the terminals of the transmitter. The assembled probe, mounted in its support bearings, is shown in Figure 9; Figure 10 shows an unassembled view.

3.3.5.2 Air-bearing Vortex Meter

The air-bearing vortex meter consists of the following: the probe body, the shaft and vanes, two air bearings and two aluminum spacers, the sensor and sensor mount, o-rings, set screws and tapered pins, and the probe end cap. Detailed drawings of the probe and the various pieces which, together make up the probe, are given in Figures 11-13. The assembly drawing, Figure 11, illustrates how the probe body is assembled. To complete the assembly of the probe, first the shaft is inserted into the probe body. The sensor mount, with the sensor in place, is placed into the probe end cap. The shaft is then pinned to the sensor, and the probe body threaded into the probe-end cap.
Fig. 9: Non-rotating Vortex Probe - Assembled

Fig. 10: Non-rotating Vortex Probe - Unassembled
Fig. 11: Air Bearing Vortex Probe—Assembly Drawing
Fig. 12: Probe Body Detail

Scale: Full  Date: 9 June 1970
Drwg:No: 2  Drwg: By F. Lux
Fig. 13: End Cap & Sensor Mount
The novel aspects in the design of this probe is the use of air bearings to support the shaft and type of sensing element employed to monitor the torque on the shaft. The air-bearings are purchased from the DICO-Bearing Specialty Co., Boston, Massachusetts. The air-bearings, model No. LB-12, have a sapphire, hard, porous bronze inner liner which is surrounded by an aluminum shell. When air is fed under pressure to the bearing through a port in the aluminum shell, it is forced through thousands of tiny pores in the porous bronze liner. The shaft riding in the bearing is then floated in the air, flowing through the air bearing. The friction on the shaft, as it rotates, is due to the viscosity of the air layer between the shaft and the bronze liner; it is essentially zero.

The probe can be operated with one or two air bearings installed, the determining factors being the accuracy of bearing alignment and the straightness and length of the shaft. The following paragraph gives a brief description of the procedure followed in assembling the probe for one bearing operation and describes the path by which the air makes its way to the air bearings from an external air supply.

Prior to assembly, the air-bearing shaft and probe body are cleansed with acetone. Referring to Figure 11, the front o-ring, which has a slightly larger O.D. than the 0.5-inch diameter bore of the probe body, is forced into place within the probe body. This is followed by the air bearing and another o-ring. The air-
bearing is placed into the probe body with the air inlet port in line with the air passage in the probe body. To check on the location of the air bearing port, relative to the air passage in the probe body, the set screw in the probe body that is in line with the air inlet port of the air bearing is removed. By looking into this passage, the alignment of the air bearing can be checked. With the air bearing aligned properly, the large aluminum spacer is placed into the probe body. Care is taken to insure that the holes in the spacer line up properly with the exhaust holes in the probe body. The air inlet plug is inserted next, followed by the small spacer, again taking care to line up the holes in the spacer with those in the probe body. Set screws are threaded through the probe body into the last spacer and hold the entire assembly in place. A set screw is threaded into the unused air passage at the base of the probe body. The tapered pin is removed from the shaft and the shaft inserted into the probe body.

The sensor mount with sensor are placed in the probe end cap. A special device, Figure 14, which holds the sensor assembly, is used to place the sensor assembly in the probe end cap. This device passes over the sensor and presses onto the larger (0.5 inch) boss at the base of the sensor mount. The leads from the sensor are passed through two holes in the base of the end cap. Keeping tension on the leads, the sensor is placed into the well of the probe end cap. The sensor mount is rotated slightly at the bottom of the well until it
Fig. 14: Cylinder Holder Used to Install Vortex Probe Sensor In The Vortex Probe End Cap
Fig. 15: Air-bearing Vortex Probe --
Installed In The Positioning Device In The Wind Tunnel
locates itself on two set pins protruding from the base of the well. With the sensor assembly properly in place, the shaft is pinned to the sensor and the probe body screwed into the well. The probe is now assembled for use, Figure 15.

The air for the air bearing enters through the base of the end cap. A threaded copper tube, attached to the air supply, is screwed into the port in the base of the end cap. Air enters this port and flows into a circular groove in the probe end cap. The base of the sensor mount has two circular grooves, top and bottom, on the same radii as that of the probe end cap. Four holes in the base of the sensor mount, intersecting the grooves, allow the air to flow from the passage between the sensor mount and end cap into the groove on top of the base of the sensor mount. A similar groove in the base of the probe body allows air to flow about in the passage formed by the base of the sensor mount and probe body into the passage(s) in the probe body. The air then travels down the passage(s) in the probe body and into the air bearing(s). The air exit from the air bearings and exits from the probe through the exhaust ports in the probe body.

The advantages of the air-bearing vortex meter over existing vortex meters are:

1. It is frictionless. When air is supplied to the probe, the shaft is floating in air; therefore, no corrections are needed
for bearing friction losses. To verify that the shaft is supported in frictionless bearings, the shaft was unpinned from the sensor and permitted to float freely in the air bearings. During rotating of the probe body, the shaft remained stationary.

2. It has interchangeable parts. The sensor and shaft of the air-bearing vortex meter can be replaced by removing the tapered set pins. The vanes can be removed by sliding them out of the slots milled in the end of the shafts. The air bearings do not cause loss of calibration from lack of lubrication as do bearings used in rotating vortex meters.

3. The sensing element is out of the flow field. In difference to the non-rotating type vortex meter with the strain gages mounted on the vanes, the vanes of the air-bearing probe are contained within the probe body. There is no cooling effect due to the flow field. There is no need to correct the readings obtained from the air-bearing vortex meter due to windage effects on the electrical leads. Constant temperature operation is obtained from the exhaust air from the air bearings.

4. Probe never needs to be lubricated and should not lose calibration due to friction.

5. Probe should be capable of operation in a high-g environment; e.g., in a rotating system.

6. New calibration technique permits calibration over a much greater range of angular velocity due to elimination of slip ring noise.
3.4 X-Y Positioner

The x-y positioner is an electromechanical device capable of locating probes accurately within the wind tunnel test section. The x-y positioner locates the probes in a plane aft of the airfoil trailing edge. The positioning device is moveable and can be positioned at any point in the wind tunnel test section. The probe support hub of the device is capable of supporting any and all of the instruments used in the course of this work.

A cam-operated counting system describes the position of the probes relative to the wind-tunnel test section walls. Alteration of the cam affords positioning accuracy of better than 0.01 inch. Separate power trains drive the probe support vertically or horizontally.

Due to the large pressure drop associated with the x-y positioning device when placed in the wind tunnel flow, the test section velocity was reduced to 110 ft./sec. To increase the magnitude of the test section velocity, an inlet bell and aft diffuser were fitted to the positioning device. The combination of the inlet bell-position-diffuser reduced the turbulence in the flow due to the positioning device and resulted in an increase in the test section flow velocity to 149 ft./sec. Details, drawings, and photographs of the x-y positioning device are given in Appendix A.4

3.5 Vortex Probe Calibration Device

To calibrate the vortex probes, a mechanical system capable of
rotating the probes at angular velocities varying from 0 to 30,000 R.P.M. was built. The calibration device consists of a plate onto which are mounted bearing supports, the vortex probe being calibrated, an aluminum canister which contains a telemetry system and a variable speed D.C. motor capable of angular velocities up to 35,000 R.P.M. The system is designed with interchangeable hubs so it can be used to calibrate both the Four-vane vortex probe and the Air-bearing vortex probe.

The vortex probes are mounted on two precision ball bearings. The four-vane probe fits into a conical hub which screws onto the calibration canister. The air-bearing probe screws into a specially designed air-bearing which, in turn, screws into the calibration canister. The aluminum journal rides in a brass bearing which is grooved to permit the passage of air into the air-bearing probe and to reduce galling between the journal and the bearing surface. The alignment of the aluminum journal in the brass bearing is maintained by alignment of a large roller bearing located at the midpoint of the canister.

The aluminum canister has a thin phenolic disc about its circumference located near the aft end of the canister. The outer circumference of this disc has been grooved to hold the antennae wire from transmitter located inside the canister.

The electric signal from the strain gage sensors of the vortex probes are delivered to a small transmitter located inside the
the aluminum canister of the calibration device. The signal from the sensors are converted to an F.M. signal which is transmitted to a stationary F.M. receiver positioned near the calibration device. The change in the stress level of the sensors, due to the torque of the fluid, result in a variation of the frequency of the transmitted signal. The power for the transmitter is supplied by a rechargeable 12-volt battery. Both the F.M. transmitter and the battery are cylindrical in shape and are located within the aluminum canister. Details, drawings and photographs of the calibration device are given in Appendix A.5. Details about tuning the transmitter and obtaining a signal has been given in Appendix A.6.

3.6 Vortex Probe Calibration Procedure and Results

3.6.1 Calibration Procedure

The calibration of the vortex probes is carried out by rotating the vortex probe in a uniform flow which is attained in the low-turbulence, subsonic, wind tunnel facility. The rotation of the probe causes torque to be produced on the vanes which causes a change in stress in the sensor. This change in stress changes the frequency of the radio signal being transmitted from the calibration system to a receiver located outside the wind tunnel. This frequency is visually displayed on an oscilloscope or monitored with a digital frequency counter. The probe is rotated over a range of angular velocities, and a plot of frequency versus angular velocity is obtained. The assembly of the calibration device (in preparation for
calibration of a vortex probe), the hookup and operation of the associated electronic equipment, and other details associated with the operation of the calibration device are given in Appendix A.7.

3.6.2 Results of The Vortex Probes Calibration

Two non-rotating type vortex probes were designed and fabricated for use in this work. The first probe fabricated for use (Section 3.3.5.1, Figure 8.) is similar to a probe discussed in Reference (40). The calibration results of this probe indicated that the instrumented vanes of the probe had little flexibility. Thus, the probe had minimum sensitivity. This probe was used to measure the vorticity at several locations downstream from the trailing edge of the airfoil. The raw vorticity data obtained with this probe indicated a similar flow pattern at each downstream position; however, to resolve the data into vorticity contours is at best questionable. More study on this probe and interpretation of the results obtained with this probe are required.

The second non-rotating probe designed and fabricated for use in this work is a completely new design, and the results of its calibration are discussed in the next section.

3.6.2.1 Air-bearing Vortex Probe Calibration

The results of the vortex probe calibration is a plot of frequency change versus revolutions per second (rps). This plot is used to convert the recorded frequency readings, obtained as the vortex probe traverses from point to point in the trailing vortex system, to values of rps. Calibration tests were run in still air (V=0) and
in the wind tunnel test section, where the flow velocity was 135 fps. The original data, obtained from each calibration test is plotted in Figure 16. The spread of the data points at zero rps is due to variation in the zero setting of the transmitter. The line drawn through the data points for the tests 2, 3, and 6 suggests that there is no effect of flow velocity on the calibration of the vortex probe. To reduce the original data points to a common base, the frequency at each test speed (rps) is subtracted from the zero speed frequency of that test run. The results are shown in Figure 17 as a plot of frequency change versus rotational speed. In Figure 17, the three data points at 130, 143, and 162 rps (represented by ▲ in Figure 16) have been omitted since a check of the transmitted signal at these points showed that there was a great amount of noise present. As the rotational velocity of the probe was reduced from a maximum of 200 rps, frequency readings were taken at 154 and 145 rps respectively. During the recording of these readings, the signal remained free of noise and, as can be seen in Figure 16, they agree with the trends indicated from other test runs.

The curve drawn in Figure 17 is the mean of all the data points. The data points were fit to a second order polynomial, but the resultant coefficients gave delta frequency values too low at low values of rps and delta frequency values too high at high values of rps. The reason for this discrepancy can be seen when the data's plotted on a log-log plot in Figure 18. The slope of the data from
Air Bearing Vortex Probe Calibration Results
Aug. 10, 1970

Fig. 16

Frequencies - cps

Test #1 V=0
Test #2 V=135 FPS
Test #3 V=135 FPS
Test #4 V=135 FPS
Test #5 V=0
Test #6 V=0

RPS
Fig 17 Air Bearing Vortex Probe Calibration Results
Aug. 10, 1970

- Test #1 V=0
- Test #2 V=135 FPS
- Test #3 V=135 FPS
- Test #4 V=135 FPS
- Test #5 V=0
- Test #6 V=0
Fig 18 \( \Delta \text{Freq vs RPS} \)

Vortex Probe

Aug 10, 1970

DOTTED LINE
Slope = \( \frac{280}{180} = 1.55 \)

SOLID LINE
Slope = \( \frac{280}{160} = 1.75 \)
the log-log plot varies from 1.55 to 1.75, which indicates that an exponent of 2.0 in the expression \( Y = a x^n \) (\( Y = \Delta \text{FREQ.} \) and \( X = \text{Rps} \)) does not correlate the data. Using the form \( Y = a x^n \), and taking the value of \( n = 1.65 \) from the log-log plot, it can be determined by substitution of data points into the expression \( Y = a x^{1.65} \) that the value of the constant "a" which correlates well over the entire range of test velocities (rps) is \( a = 0.065 \). The curve drawn in Figure 17 was obtained using the expression \( \Delta \text{FREQ.} = 0.065 \text{(rps)}^{1.65} \). The calculated standard deviation is 12.435.

A theoretical analysis of the probe would follow the damping-in-roll analysis as outlined in 3.2.3. It was shown that the stress in the blades is proportional to the square of the velocity of the fluid in which the probe is placed. The analysis did not take into account any real fluid effects such as boundary layer buildup and separation from the blades or wake interference from blade to blade.

The results of the calibration of the vortex probe indicate that the free-stream velocity has negligible effects on the frequency versus rps plot. This was also indicated by the damping-in-roll analysis from (40). The calibration curves, presented in (40), showed considerable variation due to doubling the free stream velocity and a very slight effect due to rotational velocity. This is probably due to the manner in which the lead wires are positioned relative to the probe vanes. Since the strain-gage leads lay on the surface of the blades, rotational effects should be minimal; whereas in this position, the leads are subject to the full force of the dynamic pressure.
The data from the air-bearing vortex probe was reduced to values of rps using the curve in Figure 17. A comparison of the results with other data and theory is given in section 4.2.

3.7 Test Particulates

The particulates, used for seeding the flow, are poly-vinylchloride, (PVC) pellets, and sand. The poly-vinyl-chloride pellets were used to seed the wind tunnel flow for most of the experiments to avoid excessive wear of the equipment. The physical properties, particle size distribution and other details of the seed materials, as specified by the supplier, are listed. The particle size distribution, as specified by the supplier, is compared against the distribution obtained from a sieve analyses run during this study.

3.7.1 Poly-vinyl-chloride (PVC-pellets)

The PVC pellets are spherical in shape, white in color and chemically inert. The physical properties are:

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spec. Gr. (resin)</td>
<td>1.4</td>
</tr>
<tr>
<td>Bulk density</td>
<td>0.47 - 0.58 gm/cc</td>
</tr>
<tr>
<td>Vol. resistivity</td>
<td>$10^{14}$ ohm/cm</td>
</tr>
<tr>
<td>Thermal cond.</td>
<td>1.3 BTU/FT. -°F</td>
</tr>
<tr>
<td>Dielectric constant</td>
<td>3.7</td>
</tr>
<tr>
<td>Specific Heat</td>
<td>0.25 cal/gm - °C</td>
</tr>
</tbody>
</table>

The results of a sieve analysis for three samples of PVC as supplied and the results obtained during the course of this study are given for comparison in Table 5.
Table 5 -- PVC Sieve Analysis Results

<table>
<thead>
<tr>
<th>Sieve Size (Microns)</th>
<th>Supplied Distribution % Retained</th>
<th>Measured Distribution % Retained</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Test #1</td>
<td>#2</td>
</tr>
<tr>
<td>420 µ</td>
<td></td>
<td></td>
</tr>
<tr>
<td>250 µ</td>
<td></td>
<td></td>
</tr>
<tr>
<td>210 µ</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>177 µ</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>149 µ</td>
<td>9</td>
<td>41</td>
</tr>
<tr>
<td>105 µ</td>
<td>45</td>
<td>40</td>
</tr>
<tr>
<td>100 µ</td>
<td>15</td>
<td>6</td>
</tr>
<tr>
<td>74 µ</td>
<td>12</td>
<td>3</td>
</tr>
<tr>
<td>50 µ</td>
<td>19</td>
<td>9</td>
</tr>
</tbody>
</table>

The results of the sieve analysis, performed during the course of this work, indicates an average particle size much larger than suggested by the supplier. The importance of an accurate particle size distribution is obvious when considering that the number of particles for a given mass flow varies inversely as the cube of the particle diameter. The average particle diameter of the PVC pellets was found to be 200µ. 
3.7.2 #120 Petro Sand and #3 Glass

The #120 Petro Sand and #3 glass granules are generally spherical although the surface is very rough. The physical properties of these two materials could not be obtained from the supplier but the materials are 99.9% silicon dioxide; thus, the physical properties of SiO₂ should suffice for engineering calculations. The particle distribution for each material, as suggested by the supplier and the distribution obtained from a dry sieve analysis during this work, is given in Table 6.

Table 6 — Particle Distribution of the 2 Sands / #120 and #3

<table>
<thead>
<tr>
<th>Sieve Size (Microns)</th>
<th>% Retained #120 Sand</th>
<th>% Retained #3 Glass</th>
</tr>
</thead>
<tbody>
<tr>
<td>841 µ</td>
<td>1.2</td>
<td>1.2</td>
</tr>
<tr>
<td>580 µ</td>
<td>10.0</td>
<td>10.0</td>
</tr>
<tr>
<td>420 µ</td>
<td>Trace</td>
<td>1.27</td>
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<tr>
<td>280 µ</td>
<td>0.50</td>
<td>30.5</td>
</tr>
<tr>
<td>250 µ</td>
<td>8.90</td>
<td>53.00</td>
</tr>
<tr>
<td>200 µ</td>
<td>6.60</td>
<td>20.0</td>
</tr>
<tr>
<td>177 µ</td>
<td></td>
<td>7.20</td>
</tr>
<tr>
<td>149 µ</td>
<td>40.00</td>
<td>7.0</td>
</tr>
<tr>
<td>105 µ</td>
<td>38.20</td>
<td>1.5</td>
</tr>
<tr>
<td>74 µ</td>
<td>12.80</td>
<td>18.75</td>
</tr>
<tr>
<td>50 µ</td>
<td>1.90</td>
<td>2.57</td>
</tr>
</tbody>
</table>
The average particle diameter of the #120 Petro sand and the #3 glass were found to be 150\(\mu\) and 350\(\mu\) respectively.

It must be emphasized that the particle diameters, determined from sieve analysis tests, carried out by this writer, are from only one test per particle sample. A more accurate particle distribution would be obtained by performing a set-sieve analysis. This procedure was attempted with a PVC sample but, since these particles float and stick together in water, the accuracy of the resulting distribution is questionable.

3.7.3 Particle Distribution At A Typical Helicopter Landing Zone

One object of this research effort is to simulate the conditions, with regard to dust loading of a typical helicopter landing zone, (52) gives the results from measurements of the dust concentration and particle size distribution of particulates recirculated through the rotor of a hovering helicopter at a typical helicopter landing zone. The results taken from (52) for a typical landing zone, (The Phillips Drop Zone), is shown in Figure 19 from which can be seen that the mass flow rate of dust near the rotor tip in the Phillips Drop Zone is 15-25 mg/cu. ft., which corresponds to a mass flow in the wind tunnel of 0.9-1.5 lb/min. The particle size distributions at the Phillips Drop Zone are plotted in Figure 20 along with the results obtained from the sieve analyses performed in this work. The PVC pellets and #3 glass have particle size distributions similar to that in the Phillips Drop Zone. The particle size distribution for the #120 sand falls between that of the terrain and the distribution obtained at a one-foot hover height.

3.8 Electrostatic Sensing Device

This section of this paper describes the various instruments used
NOTE: Data represents average concentration measured at 1-foot hover height.

Fig. 19: Dust Distribution - Phillips Drop Zone (52)
Fig. 20: Typical Particle Size Distribution as a Function of Elevation, Sample Station 5, Phillips Drop Zone (52).
and results obtained from them in attempts to measure the electrostatic charge on the individual particles and/or the electric field set-up by the swirling particles in the trailing vortex. A difficulty, associated with using these instruments, was the lack of knowledge about the order-of-magnitude of electric field levels, voltage gradients and charging rates to be expected. Without knowledge of field strengths and particle density distribution, it's possible that these instruments were not used properly when making the initial electrostatic measurements. Other probes that were considered for the electric field and particle charge measurements are discussed in Appendix D.

3.8.1 A leaf electroscope was used, which consists of a flat steel support and a thin metal vane*. The vane was free to pivot about a rod, located at the midpoint of the support. The center lead of a length of co-axial cable was attached to the leaf electroscope support. The co-axial shield was connected to the ground. The other end of the co-axial cable, Figure 21, at various locations in the seeded trailing vortex system downstream from the trailing edge of the airfoils. The probe was positioned in the center of the vortex core, at the edge of the vortex core and outside the influence of the vortex. The leaf electroscope showed no evidence of charge occurring in the swirling flow.

To determine the magnitude of the electric field necessary in the vicinity of the probe to cause deflection of the leaf of the electroscope, the probe was positioned midway between two large parallel plates. One plate was grounded. The other plate was connected to a variable voltage

*Courtesy of Mr. Fluck, Ohio State University's Physics Department
Fig. 21: Leaf Electroscope
supply. A voltage of 12,000 volts was applied to the top plate before the leaf of the electroscope began to deflect. Neglecting fringing effects, this corresponds to an electric field strength of 20,000 volts per meter (the plates are 2 feet apart).

After observing the results of the parallel plate test, it was decided that the leaf electroscope used for the test did not have sufficient sensitivity. A goldleaf electroscope was purchased, Figure 22. The results the electric field measurements obtained with this instrument were also negative.

The leaf electroscope was used in tests which verified that the plastic PVC pellets will become charged due to contact with the airfoils. An airfoil set at a large angle of attack was supported with its trailing edge several inches above a piece of aluminum foil. Particles were dropped onto the surface of the airfoil. The particles slid and/or rolled over the surface of the airfoil and dropped onto the aluminum foil, the leaf of the electroscope deflected indicating that the particles had become charged through contact with the airfoil.
Fig. 22: Gold Leaf Electroscope
3.8.2 Electric Field Mill

An electric field mill was constructed (17) which is used to measure the electric field distribution in a plane normal to the wind tunnel flow. The electric field meter sensor consists of a set of fixed conductive vanes and a second set of vanes, geometrically similar to the first, which are grounded. The grounded set of vanes is positioned directly above the conducting vanes on an insulated shaft which prevents charge flow from one set of vanes to the other. The rotating vane periodically shields and exposes the insulated probe to the electric field in which the field meter has been placed.

The field meter used in this work was modified so it could operate in the seeded flow field in the wind tunnel. A grounded cone was attached to the field mill sensor in front of the rotating vane. This cone deflects the particles away from the conducting plate of the field mill sensor.

The sensor plate output of the field mill was connected to a model 610C Keithley electrometer. The electrometer functioned as a pre-amplifier and impedance matching device. The output of the Keithley electrometer then passed through a high-low band-pass filter to an amplifier. The output of this amplifier was then monitored with a digital counter for statistical analysis and a light-beam oscillograph for continuous recording of the field mill signal.

The electric-field mill probe was inserted into the x-y positioning device, and the output from the sensor recorded as it traversed vertically through the trailing vortex. Vertical traverses
were run at several horizontal locations in the vortex. The field mill was also used to determine the statistical distribution of voltage pulses recorded at discrete locations in the vortex. A drawing of the electric field mill is shown in Figure 23.

3.9 Electrostatic Density Probes

To determine the density distribution of particles throughout the wind tunnel flow field, several types of density measuring probes were considered for this work. A review of the published literature on the subject of electrostatic density probes resulted in the fabrication of several probes similar to those described in References (10, 24, and 39). The probes and initial results, obtained with them, will be discussed in this section.

3.9.1 Cylindrical Probes

Cylindrical probes, Figure 24, were fabricated similar to the probe discussed in Reference (10). The inside diameters are 0.25 inch and 0.50 inch respectively. The inner surface is a brass sleeve, 0.010 inch thick. The probe body is plastic, 0.125 inch thick. During initial tests, the plastic body retained static charge which influenced the output from the probes. To eliminate this charge buildup, the outside of the probes were painted with conducting paint and connected to ground.

The cylindrical probes were to be used as current-monitoring devices as discussed in Reference (10). To calibrate the probes,
Figure 23—Field Mill Design (17)
Fig. 24: Cylindrical Density Probes

Fig. 25: Particle Charge Sensor and Amplifier
a particle feed system was set up to drop spherical plastic particles through the probes at a known mass flow rate. The particles tended to pack which reduced their ability to flow through the small spout of the feed system. It was difficult to control the stream of particles exiting from the spout so that they flowed through the probe. Many of the particles entering the probe adhered to the inner wall of the probe.

Due to the particles packing and adhering to the inside wall, its use in this work was questionable. The cylindrical probes were used to check the capability of several amplifiers under consideration for this work. To eliminate the problem of particles adhering to the walls of the inner surface of the cylindrical probe, water droplets were used in place of the plastic pellets. The water droplets were used because the rate at which they passed through the probe could be controlled. The droplets induce discrete pulses of current in the probe corresponding to the passage of each droplet through the probe. The probe output was connected to one of several amplifiers being considered for use in this work. In this way, the capability of each amplifier could be evaluated.

3.9.2 Particle Charge Sensor

A duplication of the particle charge sensor discussed in (45) was fabricated. A picture of the probe and preamplifier are shown in Figure 23. The principle of operation of this probe is that an initially uncharged particle strikes the probe tip, becomes charged, and then flows past the probe body. The moving charge induces a current in the electrode structure of the probe.
The electrode structure is a cone-capped cylinder at the probe tip as shown in Figure 28. The current pulse has a non-zero value only when the particle is passing over the gap between the conical cap and the grounded cylinder of the probe body. Due to small signal currents induced in the probe by impinging particles, it was necessary to incorporate a preamplifier within the probe structure. The circuit diagram of this preamplifier was presented in Reference (45). A duplicate preamplifier was built for the present work but never functioned as described in Reference (45), and exhibited excessive circuit noise. The cause for this is still unknown.

3.9.3 Ring Probe

The results from the cylindrical probe calibration attempts suggested a modification to the cylindrical probe which will be discussed in this section. The cylindrical probe was capable of monitoring the individual drops of water as long as they did not strike the inner probe surface. When this happened, the drop adhered to the wall and intercepted succeeding drops passing through the probe. Eventually, the opening of the probe filled with water and created a short circuit between the inner surface and the grounded outer surface.

To circumvent the problem caused by the water droplets filling the end of the cylindrical probe, the inner conducting sleeve was segmented into two sleeves located on each side of a sensing washer. The two inner sleeves were connected to ground. The inside diameter of the sensing washer was slightly larger than the inside diameter
of the sleeves to prevent the particles passing through the probe from contacting the washer. When assembled, the magnitude of the output noise of this probe, due to internal shorting, exceeded the output signal induced by the water droplets.

3.9.4 Impact Probe

The results of the previous designs of electrostatic density probes indicated that, with the particulates used in this work, probes which require the passage of particles through them, are susceptible to clogging. The observations of the output obtained from the tests of the water droplets through the ring probe indicated that the amplification system being employed had excessive electronic noise and lacked the necessary amplification. The water droplets tests indicated that a discrete pulse could be induced by a charged particle passing through a conductor. However, the signal to noise ratio, i.e., the height of the voltage pulse induced as the droplet passed through the conductor to the background output voltage, was very low and often negligible. During these tests it was observed that when a droplet struck the conductor, a measurable pulse was always produced. To avoid the problem of probe clogging and to insure that the probe would have the maximum sensitivity a probe similar to the ball probe, discussed in Chapter 2 (10), was selected as the probe to be used for measuring the particle density distribution in the trailing vortex. The impact probe used in this work was a small brass cylinder, 0.125 inches in diameter and 0.1875
inch long. These dimensions were chosen based on the necessity of keeping the probe sufficiently small to minimize disturbances to the flow field and to permit local measurements yet the probe had to be large enough to intercept particles in regions of minimum particle density, such as the vortex core.

The brass cylinder was soldered to the center wire of a co-axial cable. The wire shield of the coaxial cable within 0.5 inches of the probe tip was removed and the shield connected to ground. The probe lead was also connected to ground. A $10^7$ ohm resistor was inserted into the probe lead between the probe tip and ground. Particles impacting the probe cause a current to flow through the resistor which results in a voltage pulse across the resistor. Each voltage pulse is amplified by an amplifier with a 20 mega-ohm input impedance and an over-all gain of 1,000. The output of the amplifier is connected to a digital counter which records the individual pulses and displays the running total. The background noise level of the amplifier is less than a microvolt. The amplifier is contained within a grounded metal case to eliminate pickup of stray signals. The amplifier circuit is shown in Figure 26.
3.9.4.1 Calibration of the Impact Probe

The impact probe was initially tested in the exhaust of a small nozzle, Figure 27. Particles are introduced upstream of the nozzle and through impacts with the duct walls becoming charged. To increase the probability of particle impacts prior to exiting from the nozzle, pieces of screen were placed in the duct to increase the turbulence and increase the probability of particles impacting the duct and/or the screens. The approximate number of particles per sample is determined from the sample distributions. The weight of each sample used in these calibration tests was 0.2 gm. As a check on the number of particles per sample a ring probe which was soldered to the impact probe was located at the exit of the nozzle. The diameter of the circular loop was slightly larger than
Fig. 27: Particle Density Probe Calibration
the exit diameter of the nozzle. The particles were introduced into the calibrations system over a 4.0 minute time interval. Eighteen samples of each of the three particulates were used for these tests.

The total number of particles sensed by the ring probe was monitored by a digital counter. Histograms of the results of these tests are shown in Figures 28, 29, and 30. The mean value and standard deviation of the recorded pulses for the eighteen samples of each material has been calculated and is indicated on the figures. The results of these tests indicate the number of particles per sample sensed by the ring probe agrees with the number calculated using the measured distribution for the PVC pellets and is more than 50% low for the #3 glass and #120 sand samples. The error between the number of particles sensed by the ring probe and that calculated from the distributions of the sand samples is probably due to low charge levels residing on the sand particles. The sensitivity of the digital counter is set so it will not count the particulate impurities in the exhaust air stream. If this voltage setting is above the level of the voltage pulses caused by some of the impinging sand particles, the total recorded number of particles per weighted sample will be less than the number calculated from the distribution. Two sieve analyses tests were performed on the #120 sand. The results for the second test have been given in Table 6. The results for the first test were discarded since the weight of the sample tested was larger than recommended by standard practice. However, it is signifi-
Particle Count Histogram - PVC
Ring Probe Results

- Mean Value: 72000
- Standard Deviation: 5270

- PVC Pellets
  - 0.2 Gm Samples
  - Calculated: 73036

Vet Sieve Analysis

Impact Probe Results

- Mean Value: 45220
- Standard Deviation: 4050

- PVC Pellets
  - 0.2 Gm Samples

FIGURE 28
Particle Count Histogram - #3 Glass

Ring Probe Results

<table>
<thead>
<tr>
<th>Frequency of Occurrence</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
</tr>
<tr>
<td>6</td>
</tr>
<tr>
<td>5</td>
</tr>
<tr>
<td>4</td>
</tr>
<tr>
<td>3</td>
</tr>
<tr>
<td>2</td>
</tr>
<tr>
<td>1</td>
</tr>
</tbody>
</table>

Mean Value = 5650
Standard Deviation = 500

#3 Glass
0.2 Gm Samples
Calculated = 13636
Dry Sieve Analysis

Impact Probe Results

<table>
<thead>
<tr>
<th>Frequency of Occurrence</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
</tr>
<tr>
<td>6</td>
</tr>
<tr>
<td>5</td>
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<tr>
<td>4</td>
</tr>
<tr>
<td>3</td>
</tr>
<tr>
<td>2</td>
</tr>
<tr>
<td>1</td>
</tr>
</tbody>
</table>

Mean Value 3562.5
Standard Deviation = 416

#3 Glass
0.2 Gm Samples

 Recorded Counts Per Sec x 10^-2

FIGURE 29.
Particle Count Histogram - #120 Sand

Ring Probe Results

- Mean Value: 27830
- Standard Deviation: 2260

#120 Sand
- 0.2 Gm. Samples
- Calculated: 59238

Dry Sieve Analysis

Impact Probe Results

- Mean Value: 15530
- Standard Deviation: 1250

#120 Sand
- 0.2 Gm. Samples

Recorded Counts Per Sec. x 10^{-3}

FIGURE 30:
cant that the number of particles calculated using the distribution obtained from the first sieve analysis differs by less than 1,500 particles from the number of particles sensed by the ring probe.

The circular wire was removed from the cylindrical probe tip and the cylindrical impact probe was then positioned 0.5 inches from the nozzle exit in line with the nozzle exhaust. The pulses induced in the probe due to particles impacting the probe and particles passing close to the probe surface were recorded. Histograms of the results of these tests are also shown in Figures 31, 32, and 33. The mean value and standard deviation of the measurements are indicated in each figure. The results of these tests are used in determining the effective diameter of the probe $D_{\text{EFF}} = D_{\text{ACT}} (\text{No. from Dist/No. From Counter})^{\frac{1}{2}}$. Since particles passing close to the probe induce pulses in the probe, the region of measurement for the probe is larger than the geometric diameter of the probe. The results of these tests indicate that the effective diameter of the probe is 0.252 inches for PVC pellets and #3 glass particles and 0.239 inches for the #120 sand particles.
3.10 Co-ordinate Systems

There are three sets of reference coordinates which will be used in the discussion of the experimental results. These coordinate systems are the airfoil coordinates referenced to the trailing edge of the airfoils; the traverse coordinates, referenced to the center of the wind tunnel test section, and the cylindrical coordinate system used in the mathematical model and referenced to the vortex center. The z-axis of the airfoil coordinates coincides with the center of the wind tunnel test section and approximately with the center of the vortex. The three sets of coordinates are shown in Figures 31-33.

There is reference made in some of the electric field distribution data to numbered horizontal and vertical locations. For example, Figure 45 was obtained at a horizontal location 10 and vertical locations ranging from 120 to 30. These designations were obtained when reference was made to the counts indicated on the digital counters of the control panel. The probe holder of the positioning device was brought to a point in the test section 5 inches from the floor and 5 inches from the north wall. The counters were then set to zero. As the probe moved vertically or horizontally across the wind tunnel test section its location was indicated by the counts registered on the digital counters, each count corresponding to 1/13 of an inch. Due to difficulty, with the counting system, they occasionally had to be re-zeroed at different locations in the test section. Thus, the probe location was always referenced to the wind tunnel centerline and the test section coordinate system was used in presenting the electric field contours. The wind tunnel centerline is at the position 40-horizontal and 60-vertical. Hence, the point 27 and 73 is 1 inch left and 1 inch above the centerline. The test section is 1.5 ft. by 2.0 ft.
Figure 31: Airfoil Coordinates

Figure 32: Traverse Coordinates (Center of Test Section 0,0)

Figure 33: Cylindrical Coordinates Used in the Math Model
CHAPTER IV
EXPERIMENTAL RESULTS

4.1 Experimental Procedure

The experimental measurements obtained during the course of this work were obtained in three separate phases. The first phase of testing dealt with obtaining the vortex data. The second phase of testing resulted in the electric field distribution. The third and last phase of testing was to obtain the particle density distribution. All the results discussed in this section regarding electric field measurements and density distributions are for PVC seed particles only.

The vortex probe was used to measure the vorticity distribution at several locations aft of the airfoil trailing edge. The probe is mounted in the x-y positioner aft of the airfoils. The probe is moved to the wind tunnel center line which coincides approximately with the vortex center. Frequency readings are taken over ten second intervals. At least two and often three frequency readings were taken at each point. The probe is repositioned at various locations in a plane normal to the wind tunnel flow. After recording the frequency readings at the desired locations in the vortex, the probe is then moved far from the vortex, but not into the
wind tunnel boundary layer, and a background reading obtained. To make a vorticity map at another location aft of the airfoils, the tunnel must be shut down. Then the x-y positioner is repositioned at the desired location aft of the airfoils, and the vortex probe repositioned on the wind tunnel center line. The tunnel flow velocity is brought back up to the desired velocity and, as previously outlined, frequency readings recorded at various locations in a plane normal to the flow. To locate the probe at each new position downstream necessitated shutting down the wind tunnel flow. This procedure permitted verification of the statement that the position of a trailing vortex shed from a differential airfoil is independent of the airfoil angle of attack, the flow velocity, and the distance aft of the airfoil. Vortex data was obtained for two flow velocities and two angles of attack at various locations downstream from the airfoils.

The electric field meter tests were performed after the vorticity measurements were completed. The electric field measurements were made at five transverse locations in the plane of the trailing vortex. The field meter was positioned at a transverse location, then continuously moved vertically through the vortex; the output of the field meter was recorded continuously on a light-beam oscillograph. The field meter was then positioned at five vertical locations over which the continuous trace was taken. At each vertical location, the magnitude of the electric field was monitored statistically. The output
of the field meter was connected to a digital counter with a variable voltage threshold. By varying the counter threshold level, the voltage pulses below a specified level do not register on the counter. The results of the statistical measurements are plotted on probability graph paper and from this plot the mean field strength is obtained.

The particle density distribution was the last phase of the experimental tests. The particle distribution was measured without airfoils in the wind tunnel. The mass flow indicated by the particle density probe was compared against the known mass flow from the particle feed system. The particle density probe was then used to map the density distribution throughout the trailing vortex at several locations aft of the trailing edge of the airfoil. Photographs of the variation of the probe voltage output with time (due to particles impacting the probe) were taken from an oscilloscope. These photographs were used to determine the average charge per particle.

4.2 Vortex Probe Results

The vortex probe results are shown in Figure 34 through 42. The center of the wind tunnel is at 0-horizontal and 0-vertical. The results are plotted as lines of constant angular velocity, which is equal to half the vorticity. Figures 34 - 38, recorded when the tunnel flow velocity was 135 fps, show the vorticity from the 0012 differential airfoil set at $\alpha = 7^\circ$ angle of attack rolling up into a single trailing vortex less than three chord lengths downstream. The vorticity patterns at each position downstream illustrate why the differential airfoil is used for this work. Although the wind tunnel
Fig. 34: Angular Rotation Contours

0012 Airfoil \( \alpha = 17^\circ \)

V = 135 FPS

Z = 1.5 Inches

Sept. 17, 1970

Transverse Distance ~ Inches
FIGURE 35: Angular Rotation Contours - KPS
Angular Rotation Contours—RPS

0012 Airfoil
V=135 FPS
Sept., 15, 1970

Transverse Distance ~ Inches

Fig. 36: Angular Rotation Contours—RPS
Fig. 37: Angular Rotation Contours—RPS
Fig. 36: Angular Rotation Contours ~ RPS
Fig. 39: Angular Rotation Contours ~ RPS

$\theta = 6^\circ$ DEG
$V = 15$ FPS
0023 Airfoil
March 27, 1971
Fig. 40: Angular Rotation Contours ~ RPS
Fig. 41: Angular Rotation Contours ~ RPS

0012 Airfoil
March 25, 1971

N = 23 Inches
\( \alpha_C = 7^\circ \) DEG.
V = 115 RPS

Core Velocity 2:2-RPS
= 1120 RPM

Transverse ~ Inches

Vertical ~ Inches
Fig. 42: Angular Rotation Contours ~ RPS
flow was stopped completely from test to test, the vortex location and geometry was not noticeably altered. Verification of this statement is possibly due to an oversight in setting up the test equipment. Throughout these tests, the left-half of the differential airfoil was accidently set at a slightly larger angle-of-attack than the right-side half. The result of this misalignment is evidenced by a faster rolling up of the individual vortices on the left side of the airfoil. Figures 34, 35 and 36 indicate that close to the airfoil the vortices from the individual airfoils do not roll up smoothly into one trailing vortex. A portion of the vorticity shed from the left airfoil breaks away from the main trailing vortex but becomes reabsorbed within three chordlengths of the airfoil. The misalignment of the airfoils is probably the reason the vorticity shed by the right-hand airfoil is initially so dispersed. At a distance 6 inches aft of the trailing edge of the airfoil, where the shed vorticity appears to be concentrated about two individual vortex cores, the vorticity shed by the right-hand airfoil begins to roll up rapidly, becoming concentrated in one trailing vortex.

The vorticity measurements downstream of the 0012 differential airfoil at +7 degrees angle of attack were repeated with the wind tunnel flow at 115 fps. Vorticity contours were taken at three locations aft of the airfoil trailing edge; z=6 inches, 12 inches and 24 inches. Care was taken to insure that the airfoils were set at equal and opposite angles of attack. They were then bolted in place to prevent their moving when the other equipment in the wind tunnel was being shifted about.
The results of these tests are shown in Figures 39, 40 and 41 as contours of constant rotational velocity. A similar plot is shown in Figure 42, which shows rotational velocity contours 12 inches aft of the airfoil trailing edge with the airfoils set at 12 degrees. The wind tunnel flow velocity was 115 fps.

These contour plots indicate that the geometry of the vortex is well defined as close as 12 inches aft of the airfoils. The contours at 12 inches aft for a 12° angle of attack show the increase in vorticity with increasing angle of attack. The consistency of the rotational velocity contours verify that the differential airfoils produce a stable vortex whose position in the wind tunnel test section is independent of the angle of attack, the flow velocity, and distance downstream of the airfoils. To extract quantitative information from the rotational contours requires the application of Stokes' theorem. The area between contour lines were measured using a planimeter. The angular velocity $\Omega_i$ in each area was taken to be the average between the two enclosing lines of constant angular velocity. An equivalent circularized radius for each of the irregular areas $A_i$, is obtained by summing the areas from the first to the $i$th, dividing by $\pi$ and taking the square root of the result. The tangential velocity corresponding to each circularized radius is found from Stokes' theorem which states:

$$\int \mathbf{V} \cdot d\mathbf{l} = \iint \mathbf{V} \times \mathbf{V} \cdot dA = \iint \mathbf{V} \cdot dA$$

In Ref. (29) it is shown $\omega = 2 \Omega$. From the figures of the angular rotation contours, the lines of constant speed are assumed to be circles, with an average radius $r_i$. The tangential velocity along this circle is represented by an average velocity $V_i$. The line integral can be approximated by

$$\int \mathbf{V} \cdot d\mathbf{l} \approx V_i \cdot (2\pi r_i)$$
An approximation for the surface integral can be written as follows:

\[ \iint \vec{\omega} \cdot d\vec{A} = \sum_{j=0}^{j=i} 2 \bar{\Omega}_j (\Delta A_j) \]

where \( \Delta A_j = A_j - A_{j-1} \)

and \( \bar{\Omega}_j = \frac{\Omega_j + \Omega_{j-1}}{2} \) the mean rotational speed of the fluid enclosed within \( \Delta A_j \). Hence, combining these expressions

\[ \nu_i (2\pi r_i) = \sum_{j=0}^{j=i} 2 \bar{\Omega}_j (\Delta A_j) \]

or

\[ \nu_i = \frac{1}{2r_i} \sum_{j=0}^{j=i} 2 \bar{\Omega}_j (\Delta A_j) \]  \hspace{1cm} (4.1)

Figure 43 presents a plot of tangential velocity plotted against radial distance for each of the angular velocity maps, Figs. 39-42. The plot of tangential velocities for \( \alpha = \pm 7^\circ \) indicates that the vortex decays slowly as it travels downstream. A comparison of the profiles from this work at \( \alpha = 12^\circ \) \( Z = 12'' \) and profile from (36) for \( \alpha = 12^\circ \) \( Z = 30'' \) is shown in Figure 43. The data from (36) has been corrected for probe friction and windage losses.

The radial coordinate, at which the maximum tangential velocity occurs, is arbitrarily designated the radius of the vortex-core. Using these values of core radius, the total circulation strength of the rotational fluid enclosed inside the above-defined core radius, \( \Gamma_c \), is computed again using Stokes' theorem,

\[ \Gamma_c = 2\pi \nu_c = 4\pi \left[ \Omega_1 (\Delta A_1) + \Omega_2 (\Delta A_2) + \ldots \right] \]

\[ \ldots + \Omega_j \pi (r_c^2 - r_j^2) \]  \hspace{1cm} (4.2)
Tangential Velocity Profiles
0012 Airfoil
V=115 FPS

- Lambs Solution $\alpha=12^\circ$ with $\gamma=7.83(10^{-4})$Ft$^2$/Sec.
- $Z=6''$ $\alpha=\pm7^\circ$
- $Z=12''$ $\alpha=\pm7^\circ$
- $Z=23''$ $\alpha=\pm7^\circ$
- $Z=12''$ $\alpha=\pm12^\circ$
- $Z=30''$ $\alpha=\pm12^\circ$ (Ref.36)

FIG. 43: RADIAL DISTANCE INCHES
The results obtained from this calculation are:

\[ \begin{align*}
\alpha &= \pm 7 \text{ DEG.} & Z &= 6 \text{ in.} & r_c &= 0.8 \text{ in.} & \Gamma_c &= 30.4 \text{ ft.}^2/\text{sec.} \\
\alpha &= \pm 7 \text{ DEG.} & Z &= 12 \text{ in.} & r_c &= 1.15 \text{ in.} & \Gamma_c &= 40.3 \text{ ft.}^2/\text{sec.} \\
\alpha &= \pm 7 \text{ DEG.} & Z &= 23 \text{ in.} & r_c &= 1.30 \text{ in.} & \Gamma_c &= 51.1 \text{ ft}^2/\text{sec.} \\
\alpha &= \pm 12 \text{ DEG.} & Z &= 12 \text{ in.} & r_c &= 1.20 \text{ in.} & \Gamma_c &= 67.0 \text{ ft}^2/\text{sec.}
\end{align*} \]

A check on the tangential velocity profiles can be now formulated using Lamb's solution for the decay of a viscous vortex.

Using the value of the core radius and velocity from Figure 43 (which was determined experimentally) this expression can be used to determine the value of time \( t \), required in equation 4.3. This value of \( t \) then fixes the solution of all other unknowns. The profile obtained from equation 4.3 is similar to the experimental results for the case \( \alpha = \pm 12 \), \( Z = 12 \) inches, when an eddy viscosity equal to 5 times the laminar viscosity is used in Equation 4.3, see Fig. 43. A similar result was obtained from the theoretical results of (43). The difference in the results of this work as compared with (36) will be discussed in Sec. 5.1. The airbearing vortex was calibrated by rotating the probe about its axis in a non-rotating flow field. The torque
sensed by the probe is the same as if the probe were placed in a rotational flow field in which the velocity varied directly with radial distance from the point of rotation. The probe axis coincides with the center of fluid rotation. In this flow field the vortex probe gives an absolute measurement of vorticity.

In a nonlinear flow field, the vortex probe measures the average vorticity sensed by the four vanes of the vortex probe. It is not possible to calibrate the vortex probe in a non-linear flow since the amount of vorticity in the flow field is unknown. However, a qualitative estimate of the accuracy of the vortex probe can be made as outlined in (3). In a linear flow field the axis of the probe is at a point where the absolute vorticity is equal on opposing blades. Thus the vortex probe gives an accurate measure of the vorticity in the fluid. If the velocity field is concave downward the probe measures less than the absolute vorticity since the vorticity on opposing blades is unequal and the total vorticity is less than in a linear flow field. If the velocity field is concave upward the vorticity measurement would be greater than the absolute vorticity. The above statements can be verified by drawing a plot of vorticity versus radial distance. Then compare the area under the curve between radii separated by the width of the probe vane with the probe located in each of the above mentioned flow fields. The results of the analysis presented (32) showed that if the radius of the vane of the vortex-probe less than 0.2 inch the error in the measured vorticity is negligible. The vanes of the air-bearing vortex probe are 0.15"; hence, no corrections were made to the measured vorticity.
4.3. Electric Field Meter Results

The electric field meter was installed in the x-y positioner. The sensing plate of the meter was positioned at the desired location aft of the trailing edge of the airfoil. Electric field data was taken at \( Z=12 \) inches and \( Z=24 \) inches. In each case, the angle of attack of the airfoils were set at \( \pm 7 \) degrees and \( \pm 12 \) degrees. When the meter was located in the proper axial position, it was then positioned at the desired horizontal and transverse location with the x-y positioner. The wind tunnel flow was then brought up to speed and the particle feed system turned on. The electric field meter then traversed a vertical path through a portion of the vortex, beginning 3.5 inches above the vortex center line and ending 3.5 inches below. The field meter was then traversed intermittently vertically upward over the same path. At six locations spaced vertically across the vortex (4.0 and 1.5 inches above, at the center, 1.5 and 2.5 inches below) the electric field meter output was monitored statistically. Due to the limited capacity of the particle feed system, the flow of particles was stopped as the meter was repositioned between statistical readings and during transverse movement of the meter. It was necessary to shut down the wind tunnel flow completely several times during the mapping of the electric field in order to collect the particles and refill the particle-feed hopper.

The flow field in the absence of the airfoils was traversed vertically with the electric field meter at five horizontal locations
across the wind tunnel test section. Visual observation of the oscillograph traces for these traverses indicated a slight decrease in the electric field level near the south wall of the wind tunnel test section. The mean amplitude from these traces was taken to be 0.8 to 1.0 inch which corresponds to an electric field of 1,000-1,350 volts/meter.

The output signal of the electric field meter is fed into a Keithley electrometer which amplifies the signal by a factor of 100. The output signal of the Keithley is passed through a band-pass filter, through a second amplifier with a gain of 100, and finally to the oscillograph or the digital counter. The oscillograph is used for obtaining continuous traces. The digital counter is used during the statistical monitoring of the electric field. The output traces of the oscillograph for the test conditions $\alpha = \pm 7^\circ$ and $z = 24$ inches is shown in Figure 44. The distribution of the voltage pulses at each of the locations, where statistical readings were recorded, has been drawn on the traces. To obtain the distribution curves, the per cent of the voltage pulses above a specified threshold level is plotted versus threshold voltage on probability graph paper. Then for a specified threshold voltage (marked along the abscissa) pass vertically on the plot to the straight line. The value of "per cent of total voltage counts" is then read from the ordinate axis. The electric field data for $\alpha = \pm 7^\circ$, $z = 12$ inches, plotted on probability graph paper, is shown in Figures 45, 46, 47, and 48. The mean value of electric
field is obtained from the probability plots. The threshold voltages corresponding to the mean values of electric field are indicated along the absissa of the plot. These values of threshold voltage are then used to obtain the displacement (voltage pulse amplitude) from Figure 49.
FIGURE 44a

ELECTRIC FIELD METER OUTPUT

0012 Airfoil
  = 7 DEG.
  Z = 23 inches
  PVC Pellets
  \dot{m} = 1.67 lb/min.
  Data: 3/23/71
Vert. +4.0 in. to -2.0 in.
Horiz. = 1.75 in. to +1.75 in.
FIGURE (44b)

ELECTRIC FIELD METER OUTPUT

No Airfoil
PVC Pellets
\( \dot{m} = 1.67 \, \#/\text{min.} \)
Date 2/18/71
Vert +4.0 in. to -4.0 in.
Horiz. +3.0 in. to -3.0 in.
PVC PELLETS

Date 3/24/71
\( \alpha = \pm 7^\circ \)
Z = 12 Inches
Horizontal Location -10

Mean Values

100
120
80
60

100
does 3/24/71
\( \alpha = \pm 7^\circ \)
Z = 12 Inches
Horizontal Location -10

\( \bullet \) Vertical - 120
\( \blacksquare \) - 100
\( \circ \) - 80
\( \triangle \) - 60
\( \square \) - 40
\( \diamond \) - 30

Fig 45 Threshold Voltage in Volts
PVC PELLETS

% of Total Voltage Pulses

Date: 3/24/71
α = ± 7
Z = 12 inches
Horizontal Location = 20

○ Vertical - 120
■ - 100
△ - 80
□ - 60
□ - 40
◇ - 30

MEAN VALUES

Fig 46 Threshold Voltage in Volts
Fig 47 Threshold Voltage in Volts
Fig. 48 Threshold Voltage in Volts

Date: 3/24/71

\( \alpha = \pm 7^\circ \)

Z = 12 Inches

Horizontal Location 40

- Vertical: 120
- 100
- 80
- 60
- 40
- 30

Mean Values
ELECTRIC FIELD MILL

DISPLACEMENT - VOLTAGE CURVE

Fig. 49: Threshold Voltage Volts Peak To Peak
Using this value of displacement, the electric field strength is obtained from Figure 50.

The electric field data and the voltage distribution curves for $\alpha = \pm 7^\circ$, $Z=23$ inches is shown in Figures 51 through 65. Plots of the per cent of voltage pulses versus threshold voltage for $\alpha = \pm 12^\circ$, $Z=12$ and $\alpha = \pm 12^\circ$, $Z=23$ inches are shown in Figures 66 through 70. Voltage distribution curves have not been presented for all the test conditions cited; however, they can be obtained from the probability plots. The mean values of electric field for the three test conditions considered in this work have been plotted and electric-field contours drawn as shown in Figures 71, 72 and 73. Figures 71 and 72 show the electric-field contours for the test conditions $\alpha = \pm 7^\circ$ and $Z=12$ inches and 23 inches respectively. Figures 73 shows the electric field contours for $\alpha = \pm 12^\circ$ and $Z=12$ inches.

The complete electric-field contours (Figures 71, 72 and 73) were obtained by linear interpolation between the locations where the electric field measurements were made. The dotted portions of the contours were added on the basis of trends indicated by the other contours.
Fig. 50: Electric Field Strength (Volts/Meter) vs. Displacement (inches)

ELECTRIC FIELD MILL CALIBRATION CURVE
PVC PELLETS

Date 3/23/71
\( \alpha = \pm 7^\circ \)
\( Z = 23 \text{ Inches} \)
Horizontal Location -10

% of Total Voltage Pulses

Fig. 51: Threshold Voltage in Volts
March 23, 1971
\( \alpha = 7^\circ \)
\( Z = 23'' \)
Horizontal = 10
Vertical = 30

![Graph](image)

March 23, 1971
\( \alpha = 7^\circ \)
\( Z = 23'' \)
Horizontal = 10
Vertical = 40

![Graph](image)

**Fig. 52:** Electric Field in Volts / M
March 23, 1971
\[ \alpha = 7^\circ \]
\[ Z = 23'' \]
Horizontal - 10
Vertical - 60

PVC PELLETS

Fig. 53: Electric Field in Volts/M
March 23, 1971
$\alpha = 7^\circ$
$Z = 23''$
Horizontal - 10
Vertical - 100
PVC PELLETS

Electric Field in Volts/M

Fig. 54: Electric Field in Volts/M
March 23, 1971
$\alpha = 7^\circ$
$Z = 23''$
Horizontal - 20
Vertical - 120
PVC PELLETS

**Fig. 56:** Electric Field in Volts / M

Voltage Pulses in Counts/sec.

Electric Field in Volts / M

Voltage Pulses in Counts/sec.

Electric Field in Volts / M
March 23, 1971
$\alpha = 7^\circ$
$Z = 23''$
Horizontal - 20
Vertical - 80
PVC PELLETS

Fig. 52: Electric Field in Volts/M
March 23, 1971
\[
\begin{align*}
\alpha &= 7^\circ \\
Z &= 23'' \quad \text{Horizontal - 20} \\
&\text{Vertical - 30} \\
PVC PELLETS
\end{align*}
\]
Date 3/23/71
α = ±7°
Z = 23 inches
Horizontal Location - 30
- Vertical - 120
- - 100
- - 80
- - 60
- - 40
- - 30

**Fig. 59**: Threshold Voltage in Volts
March 23, 1971
\( \alpha = 7^\circ \)
\( Z = 23'' \)
Horizontal - 30
Vertical - 120
PVC PELLETS

**Fig. 60:** Electric Field in Volts/M
March 23, 1971

$\alpha = 7^\circ$

$Z = 23''$

Horizontal - 30°

Vertical - 80°

PVC PELLETS

Fig. 61: Electric Field in Volts/M
March 23, 1971
\( \alpha = 7^\circ \)
\( Z = 23'' \)
Horizontal - 30
Vertical - 40
PVC PELLETS

**Figure 62: Electric Field in Volts/M**
PVC PELLETS

Date 3/23/71
\( \alpha = \pm 7^\circ \)
\( Z = 23 \text{ Inches} \)
Horizontal Location -40

\( % \) of Total Voltage Pulses

Vertical - 120
- 100
- 80
- 60
- 40
- 30

Fig. 63: Threshold Voltage in Volts
March 23, 1971
\( \alpha = 7^\circ \)
\( Z = 23'' \)
Horizontal - 40
Vertical - 120

**PVC PELLETS**

**Electric Field in Volts/M**

**Voltage Pulses in Counts/sec**

**Fig. 64:** Electric Field in Volts/M
March 23, 1971
\( \alpha = 7^\circ \)
\( Z = 23" \)
Horizontal - 40
Vertical - 40
PVC PELLETS

Fig. 65 Electric Field in Volts/M
Fig. 66: Threshold Voltage in Volts

Date 4/2/71
α = ± 12
Z = 12 Inches
Horizontal Location - 20
- Vertical - 70
- 60
- 50
- 40
- 30
- 80

Mean Values

% of Total Voltage Pulses vs. Voltage
Fig. 67: Threshold Voltage in Volts
PVC PELLETS

% of Total Voltage Pulses

Date 4/2-71

\( \alpha = \pm 12^\circ \)

\( Z = 12 \text{ Inches} \)

Horizontal Location 40

- \( \bullet \) Vertical - 70
- \( \square \) - 60
- \( \bigtriangleup \) - 50
- \( \bigtriangledown \) - 40
- \( \bigcirc \) - 30

\( 99.99 \)

Threshold Voltage ~ Volts

Fig. 68:
PVC PELLETS

Date 4/1/71
\( \alpha = \pm 12 \)
\( Z = 23 \) Inches
Horizontal Location 20

- Vertical - 100
- 80
- 60
- 40
- 20

MEAN VALUES

Fig. 69: Threshold Voltage in Volts
PVC PELLETS

Date 4/1/71
α = ±12
Z = 23 Inches
Horizontal Location 30
• Vertical
■ - 80
○ - 60
△ - 40
□ - 30

MEAN VALUES

99.99
99.9
99.8
99
98
97
96
95
94
93
92
91
90
80
70
60
50
40
30
20
10
0

% of Total Voltage Pulses

0 2 4 6 8 10 12 14
Fig. 70: Threshold Voltage in Volts
Fig. 71: Horizontal Distance in Inches
Electric Field Distribution Volts/M
0012 Airfoil
\( \alpha = +7 \) Degrees
\( z = 12 \) inches
Fig. 72 Horizontal Distance in Inches
Electric Field Distribution Volts/M
0012 Airfoil
\( \alpha = +7 \) degrees
\( Z = 23 \) inches
Electric Field Distribution
0012 Airfoil
Φ = +12 degrees
Z = -12 inches

(Figure 73)
Particle Density Distribution

The particle density probe is inserted into the probe holder of the x-y positioner. The probe was then located four feet from the test section inlet. The wind tunnel flow was brought up to speed and the particle feed system turned on. The particle density probe was traversed vertically and horizontally in a plane normal to the wind tunnel flow. At each location, the number of particles impacting the probe was recorded over two ten-second intervals. The average reading was then taken as the particles per second passing that point in the wind tunnel.

The result of these measurements are shown in Figure 74 which is a plot of the particle density distribution without the airfoils in the test section. The particle density distribution, with no airfoils in the test section, indicates a density gradient from the top of test section toward the bottom. This is to be expected due to the gravitational force on each particle. It must be emphasized that the gravitational effect on the particles occurs during the time the particles are leaving the feed nozzle plume and being accelerated in the wind tunnel inlet from a velocity of 13 ft./sec. to a velocity of 115/ft./sec. After the particles enter the test section inlet, the effect of gravity is negligible compared to the drag force due to the flow velocity. The average particle density across the test section is 250 particles per second.
\[ V = 135 \text{ FPS} \]
\[ \dot{m} = 1.67 \text{ lb./min.} \]

**Fig. 74:** Particle Density Distribution
The wind tunnel was shut down and the differential airfoil installed in place. The particle density probe was positioned the desired distance aft of the airfoil trailing edge (either 12 or 24 inches). The wind tunnel velocity was brought up to speed and the particle feed system turned on. The particle density probe traversed vertically and horizontally over a plane aft of the airfoil. The probe is moved to each location, and particle counts are taken twice over ten second intervals. The readings are averaged to give the average particle density at that location in the flow field. The density distribution at \( z = 12 \) and 23 inches aft of the airfoils for \( \pm 7 \) and \( \pm 12 \) degrees angle of attack are shown in Figures 75, 76 and 77. The particle density contours are obtained by linear interpretation between measured values.

The specific pattern, which was traversed by the probe in measuring the particle distribution, was to locate the probe initially at the vortex center. The wind tunnel flow velocity is brought up to speed, and the particle feed system turned on. The particles striking the probe were counted over two ten second intervals, then the probe was moved vertically and horizontally in a path about the core of the vortex on points spaced one-half inch apart. At each location, the particles striking the probe are counted over two ten-second intervals. The probe was moved over this square-cornered spiral path in half-inch increments until all points monitored were two inches or more from the vortex center.
\[ V = 115 \text{ FPS} \]
\[ \alpha = +7 \]
\[ Z = 12 \text{ inches} \]
\[ \text{PVC Pellets} \]
\[ \dot{m} = 1.67 \text{ lb/min.} \]

![Graph: Particle Density Distribution](image-url)

**Fig. 75:** Particle Density Distribution
$V = 115$ FPS
0012 Airfoil
$\alpha = +7$ Degrees
$z = 23$ inches
PVC Pellets
$m = 1.67$ lb/min.

**Fig. 76**: Particle Density Distribution
\( V = 115 \text{ FPS} \)
0012 Airfoil
\( \alpha = +12 \text{ Degrees} \)
\( Z = 12 \text{ inches} \)
PVC Pellets
\( \dot{m} = 1.67 \text{ lb./min.} \)

Fig. 77: Particle Density Distribution
Due to the limited capacity of the particle feed system, the wind tunnel had to be shut down several times during the measurement of the density distribution over the entire plane of the flow field in order to collect the particles and refill the particle feed hopper. Each time this was done, the last monitored point in the flow recounted to insure there was no variation in the particle feed rate or vortex geometry.

4.5 Particle Charge Measurements

The particle density probe was used to determine the charge on the individual particles at several points in the flow field. Electric charge is transferred to the probe by each charged particle impact; i.e., a particle passing within the effective area of the probe as described in Section 3.9.4.1. The amount of charge transferred by each particle depends upon the contact area of the particle relative to the probe, the contact potential across the contact surface, the electrical properties of the particles, the particle size, the velocity of the particle and the density of the gas in which the particles are suspended. The density of the air is assumed to include humidity effects.

The particle density probe was positioned in the vortex center and 2.0 inches from the vortex center. The output of the density probe is displayed on an oscilloscope and photographed. The photographs of particle impacts for $\alpha = \pm 7$, $z = 12$ are shown in Figures 78 through 83. The flow was seeded with PVC pellets with a particle mass flux of 1.67 lb./min. Figure 78 shows the output of the probe located at the vortex center line in the unseeded flow 12 inches aft of the airfoil trailing
Fig. 78: Particle Density Probe Output
\( \alpha = +7 \) Deg. Z=12 inches V=115 FPS
No dust Horiz.-0 Vert.-0
Vertical Scale- 2 volts/cm
Sweep Rate = 5 millisecond/cm

Fig. 79: Particle Density Probe Output
\( \alpha = +7 \) Deg. Z=12 inches V=115 FPS
PVC Pellets \( \hat{m}=1.67 \) lb/min.
Horiz.-0 Vert.-0
Vert-2 volts/cm Sweep=5Millisecond/cm
Fig. 80: Particle Density Probe Output
\( \alpha = +7 \text{ Deg.} \quad Z=12 \text{ inches} \quad V=115 \text{ FPS} \\
PVC Pellets \( \dot{m} = 1.67 \text{ lb/min.} \)
Horiz.-0 Vert.-0
Vertical Scale-2 volts/cm
Sweep Rate-5 millisec/cm

Fig. 81: Particle Density Output
\( \alpha = +7 \text{ Deg.} \quad Z=12 \text{ inches} \quad V=115 \text{ FPS} \\
PVC Pellets \( \dot{m} = 1.67 \text{ lb/min.} \)
Horiz.-0 Vert.-2.0 inches below
Vertical Scale-2 volt/cm
Sweep Rate-1 millisec/cm
Fig. 82: Particle Density Probe Output
\[ \alpha = +7 \text{ Deg.} \quad Z = 12 \text{ inches} \]
PVC Pellets \( \bar{m} = 1.67 \text{ lb/min.} \)
Horiz. 0 Vert. -2.0 in. below
Vertical Scale - 2 volts/cm
Sweep Rate -1 millisec/cm

Fig. 83: Particle Density Probe Output
\[ \alpha = +7 \text{ Deg.} \quad Z = 12 \text{ inches} \]
PVC Pellets \( \bar{m} = 1.67 \text{ lb/min.} \)
Horiz. 0 Vert. -2.0 in. below
Vertical Scale - 2 volts/cm
Sweep Rate -2 millisec/cm
edge. The airfoils are at +7 degree angle of attack. Figure 79 is the probe output at the same location with the flow seeded with PVC pellets. Figure 79 shows one probable particle impact at 2 cm (from the left hand side of the photograph) and possibly two more at 4 cm and 5 cm. Figure 80 shows a trace also taken at the vortex center. The conditions were the same as those of Figure 79. The trace of two probable particle impacts appear at the right side of the trace.

Figures 81, 82, and 83 show traces of the output signal from the particle density probe with the probe positioned 2.0 inches below the vortex center. The test conditions were the same as before. Figure 81 shows what appears to be 4 particle impacts. Figure 82 shows what appears to be 6 particle impacts for identical conditions as Figure 81. Figure 83 shows a trace taken with a slower sweep rate on the oscilloscope. This trace, which is taken over twice the time period as used in Figures 81 and 82, shows what appears to be a minimum of 8 particle impacts.

The particle charge measurements were repeated for the test conditions $\alpha$=12 degrees and $Z$=12 inches. The seed particles were PVC pellets. The particle mass flow in the wind tunnel was 1.67 lb./min. The density probe was located at the vortex center and 2.0 inches below the vortex center.

The results of these tests are shown in Figure 84 through 91. Figures 84 and 85 were obtained with the probe at the vortex center in unseeded flow. The particle feed system was turned on and, with the
Fig. 84: Particle Density Probe Output

$\alpha = +12$ Deg. $Z=12$ inches
No seed Particles
Horiz.-0 Vert.-0
Vertical Scale-2 volts/cm
Sweep Rate-2 millisec/cm

Fig. 85: Particle Density Probe Output

$\alpha = +12$ Deg. $Z=12$ inches
No seed Particles
Horiz.-0 Vert.-0
Vertical Scale-2 volts/cm
Sweep Rate-5 millisec/cm
**Fig. 86:** Particle Density Probe Output
\( \alpha = +12 \text{ Deg.} \) \( Z=12 \text{ inches} \)
PVC Pellets \( m=1.67 \text{ lb/min.} \)
Horiz. -0  Vertical -0
Vertical Scale -2 volt/cm

**Fig. 87:** Particle Density Probe Output
\( \alpha = +12 \text{ Deg.} \) \( Z=12 \text{ inches} \)
PVC Pellets \( m=1.67 \text{ lb/min.} \)
Horiz. -0  Vertical -0
Vertical Scale -2 volt/cm
Sweep rate -5 millisecond/cm
Fig. 88: Particle Density Probe Output
\( \alpha = \pm 12 \text{ Deg.} \) \( z = 12 \text{ inches} \)
PVC Pellets \( \dot{m} = 1.67 \text{ lb/min.} \)
Horiz.-0 Vert.-0
Vertical Scale-2 volts/cm
Sweep Rate-5 millisec/cm

Fig. 89: Particle Density Probe Output
\( \alpha = \pm 12 \text{ Deg.} \) \( z = 12 \text{ inches} \)
PVC pellets \( \dot{m} = 1.67 \text{ lb/min.} \)
Horiz.-0 Vert.-2.0 inches below
Vertical Scale-2 volt/cm
Sweep Rate-2 millisec/cm
Fig. 90: Particle Density Probe Output
\( \alpha = \pm 12 \text{ Deg.} \quad Z = 12 \text{ inches} \\
PVC Pellets \( m = 1.67 \text{ lb/min.} \)
Horiz.-0  Vertical-2.0 inches below
Vertical Scale-2 volt/cm
Sweep Rate -2 millisec/cm

Fig. 91: Particle Density Probe Output
\( \alpha = \pm 12 \text{ Deg.} \quad Z = 12 \text{ inches} \\
PVC Pellets \( m = 1.67 \text{ lb/min.} \)
Horiz.-0  Vertical-2.0 inches below
Vertical Scale-2 volts/cm
Sweep Rate -2 millisec/cm
probe at the vortex center, the traces in Figures 86, 87, and 88 were obtained. Figure 86 indicates possibly one particle impact in the left hand side of the trace. Figures 87 and 88 do not indicate clearly any particle impacts.

The probe was moved 2.0 inches from the vortex core and another set of output traces obtained. These results are shown in Figures 89, 90 and 91. In Figure 89 a trace was made of the probe output with the particle feed system off. And on top of this same trace, the output trace from the probe when the feed system was turned on was made. Figure 89 shows six probable particle impacts. Figures 90 and 91 show two additional traces of particle impacts which occurred with the probe located 2.0 inches below the vortex center. Figure 90 indicates ten possible particle impacts and Figure 91 indicates eight possible particle impacts.

A discussion of the results obtained from the output traces of the particle density probe and the particle charge determined from these traces will be given in Chapter 5.

4.6 Experimental Tests With Sand In Flow Field

Measurements of the electric field, density distribution and particle charge were made in the wind tunnel flow seeded with sand. The procedure for making the measurements is the same as discussed previously for tests run with the wind tunnel flow seeded with PVC pellets. Due to the abrasive characteristic of the sand, only one vertical trace through the core of the vortex with the field meter and density probe was made for each type of sand. The magnitude of the electric field was
analyzed statistically at five locations over which the continuous trace had been run. Particle charge was measured at several locations over the same vertical path through the vortex core. All measurements made with sand in the flow field were taken 12 inches aft of the airfoil.

Two samples of sand were used for these tests, #120 petro sand and #3 glass. Details and specifications regarding the properties of these materials are given in Section 3.8.

A plot of the particle density and electric field strength, 12 inches downstream of the airfoil with the wind tunnel flow seeded with #120 petro sand, is shown in Figure 92. The magnitude of the electric field was measured statistically at five locations on a vertical path through the midpoint of the trailing vortex as shown in Figure 93. The flow velocity is 115 fps with the differential airfoil set at +7 degrees.

Photographs of the density probe voltage output versus time are shown in Figures 94 through 99. The wind tunnel flow field was seeded with #120 petro sand particles. The background level of the probe in the unseeded flow is shown in Figure 94. Figures 95 through 99 show the voltage output at vertical stations 80, 65, 50, 35 and 0. These vertical locations correspond to vertical distances of 2.5 in., 1.15 in., 0, -1.15 in., -3.85 in. on a path taken vertically through the vortex.

A plot of particle density 12 inches downstream from the airfoil with the wind tunnel flow seeded with #3 glass particulates is shown in Figure 100. The magnitude of the electric field was measured statistically at five locations on a vertical path through the vortex. The results of these measurements are plotted on Figure 101. Photo-
Fig. 92: Electric Field and Particle Density

#120. Sand
#012 Airfoil
$\alpha = \pm 7$ DEG.
$z = 12$ inches

198
Centerline of Vortex
% of Total Voltage Pulses

Figure 93: Threshold Voltage in Volts

#120 Sand

\[ d = 1.67 \text{ lb/min.} \]

Date: April 3, 1971

\[ \alpha = \pm 7 \text{ DEG.} \]

Z = 12 Inches

Horizontal Location

- Vertical
- 
- 
- 
- 

MEAN VALUES

50 60 100

40

99.99

99.8

98

90

70

50

30

10

0.5

0.1

0.01

1.0
**Fig. 94:** Particle Density Probe Output

No Dust Particles V=115 FPS
Vert. +4.5 Horiz.=0
0012 Airfoil $\alpha = +7$ DEG. Z=12 inches
Vertical Scale ~ 2 volt/cm
Sweep Rate ~ 10 millisec/cm

**Fig. 95:** Particle Density Probe Output

#120 Sand - V=115 FPS.
Vert. +2.5 Horiz. = 0
0012 Airfoil $\alpha = +7$ DEG. Z=12 inches
Vert. ~ 0.2 volt/cm Sweep ~ 2 millisec/cm
Fig. 96: Particle Density Probe Output
#120 Sand V=115 FPS
Vert. +1.15 Horiz. 0
0012 Airfoil +7 DEG. Z=12 inches
Vert. 0.2 volts/cm
Sweep 2 millisecond/cm

Fig. 97: Particle Density Probe Output
#120 Sand V=115 FPS
Vert. 0 Horiz. 0
0012 Airfoil +7 DEG. Z=12 inches
Vert 0.2 volt/cm
Sweep 20 millisecond/cm
**Fig. 98:** Particle Density Probe Output

#120 Sand  V=115 FPS  
Vert.~1.15  Horiz.~0  
0012 Airfoil \( \alpha = +7 \) Deg.  Z=12 inches  
Vert.~0.2 volt/cm  
Sweep \( \sim 2 \) millisecond/cm

**Fig. 99:** Particle Density Probe Output

#120 Sand  V=115 VPS  
Vert.~3.85  Horiz.~0  
0012 Airfoil \( \alpha = +7 \) DEG.  Z=12 inches  
Vert.~0.2 volt/cm  
Sweep \( \sim 2 \) millisecond/cm
Note: The Results Of The E-Field Measurements Are Not Shown Due To Lack Of Correlation of Data.

Fig. 100: Electric Field and Particle Density
% of Total Voltage Pulses

Date 4/3/71
\( \alpha = \pm 7^\circ \)
\( Z = 12 \text{ Inches} \)
Horizontal Location -20
- Vertical -100
- -60
- -50
- -40
- -0

Mean Values

Fig. 101: Threshold Voltage in Volts
graphs of the density probe voltage output versus time are shown in Figures 102 through 105. To compare these output traces with the probe output, when the flow is not seeded with particulates, see Figure 94. Figure 102 was obtained when the probe was positioned 1.0 inch above the vortex center. Figures 103 and 104 were obtained with the probe at the vortex center and Figure 105 was obtained with the probe positioned 1.0 inch below the vortex center.

The traces from the oscillograph of the output from the electric field meter are shown in Figure 106. The left hand trace was taken with the flow field seeded with #3 glass particles. The right hand trace was obtained with the flow field seeded with #120 sand particles. Both traces were made vertically through the vortex center starting from 4.0 inches above the vortex center to 4.0 inches below the vortex center.
**Fig. 102:** Particle Density Probe Output

#3 Glass  \( V=115\) FPS
Vert. \( \sim +1.0\)  Horiz. \( \sim 0\)
0.012 Airfoil \( \alpha=7\) DEG.  \( z=12\) inches
Vert. \( \sim 0.2\) volts/cm
Sweep \( \sim 20\) millisec/cm

---

**Fig. 103:** Particle Density Probe Output

#3 Glass  \( V=115\) FPS
Vert. \( \sim 0\)  Horiz. \( \sim 0\)
0.012 Airfoil \( \alpha=7\) DEG.  \( z=12\) inches
Vert. \( \sim 0.2\) volts/cm
Sweep \( \sim 10\) millisec/cm
Fig. 104: Particle Density Probe Output
#3 Glass  V=115 FPS
Vert. ~ 0  Horiz. ~ 0"
0012 Airfoil  φ=7 DEG.  Z=12 inches
Vert. ~ 0.2 volt/cm
Sweep ~ 20 millisec/cm

Fig. 105: Particle Density Probe Output
#3 Glass  V=115 FPS
Vert. ~ -1.0"  Horiz. ~ 0"
0012 Airfoil  φ=7 DEG.  Z=12 inches
Vert. ~ 0.1 volt/cm
Sweep ~ 2 millisec/cm
Electric Field Meter Output

0012 Airfoil

\[ \alpha = +7 \text{ degrees} \]

\[ z = 12 \text{ inches} \]

\[ \dot{m} = 1.67 \text{ lb./min.} \]

Vert. +4.0 in. to -4.0 in.

Horizontal Vortex Center

Left

#3 Glass

Right

#120 Petro Sand

Figure (106)
CHAPTER V
DISCUSSION OF EXPERIMENTAL RESULTS

5.1 Air-Bearing Vortex Probe Results

The vorticity contours shown in Figures 34 and 42 illustrate the capability of the vortex probe to make vorticity measurements and verified the statements about a differential airfoil set forth in Reference 26. The vorticity contours shown in Figures 39, 40, 41 and 42 were analyzed in detail since the test conditions at which they were recorded are the same test conditions at which the electric field and particle density measurements were made. Figures 39, 40 and 41 show the vorticity contours at three locations downstream from the differential airfoil at 6, 12, and 23 inches respectively. The flow velocity was 115 f.p.s. and the differential airfoil sections were set at +7° angle of attack. Figure 42 shows the vorticity contours 12 inches aft of the airfoils for the same flow velocity with the airfoils set at +12 degrees angle-of-attack. It should be noted that the magnitude of the vorticity contours are specified in terms of angular rotation and that this value should be doubled to obtain the magnitude of the vorticity.
These maps of vorticity contours indicate the rapid rolling up of the vorticity shed from all portions of the airfoil sections into one trailing vortex. For both the $\alpha = \pm 7^\circ$ and $\alpha = \pm 12^\circ$ cases, the rolling up process is complete at a location 12" aft of the airfoil. In (100) it was stated that for wings of low aspect ratio the vortex sheet may become essentially rolled up into a trailing vortex within a chord length or less of the trailing edge. The chord length of the airfoil used in this work is 9.0". Figures 39 and 40 show that the vortex rolls up completely between 6" and 12" from the trailing edge, which is in agreement with (100). The velocity profiles, corresponding to these vorticity contours, are shown in Figure 43. The tangential velocity for $\alpha = 12^\circ$ is greater than obtained with data taken from (36). This disagreement could possibly be due to the rolling up of vorticity from both airfoil tips into one trailing vortex. The airfoils are purposely aligned so that they are at equal and opposite angles of attack. (The angle of attack is defined as the angle between the airfoil chord-line and the wind tunnel centerline). The vorticity shed from both airfoils has the same sense of rotation. Hence, the rolling up of vorticity from both airfoils results in one trailing vortex. It would appear this vortex should possess a greater amount of circulation than a vortex generated from a single airfoil tip and correspondingly a greater value of peak tangential velocity.

The vortex cores determined from the vorticity measurements of this work are larger than the vortex cores determined in (36). This difference in core size could be due to difference in instrumentation but more likely is due to the mechanism by which the vortex is generated; i.e., due to the combination of vortices from both airfoil tips into one trailing vortex.

According to (56), the ratio of induced velocities at corresponding stations downstream of wings, for wings with similar span loading, is equal to
the ratio of their magnitudes of circulation around the wings in the plane symmetry. Hence, the induced tangential velocity with the airfoils set at $\pm 7^\circ$ using the $\alpha=\pm 12^\circ$ data is (both taken at $z=12''$ aft of airfoils):

$$\frac{V(\alpha=\pm 7^\circ)}{V(\alpha=\pm 12^\circ)} = \frac{\Gamma(\alpha=\pm 7^\circ)}{\Gamma(\alpha=\pm 12^\circ)}$$

(5.1)

The resulting value of induced velocity at $\alpha=\pm 7^\circ$, using the experimentally determined values for $\alpha=\pm 12^\circ$ is $V_1(\alpha=\pm 7^\circ) = 69$ f.p.s. The maximum value of induced velocity for $\alpha=\pm 7^\circ$ was found experimentally to be 70.7 f.p.s.

A dense map of measured values of vorticity is impractical to obtain; therefore, linear interpolation was used between measured points to complete the vorticity contours. Some of the data points along the outer contours of the vortex were 1/2" apart. A small change in the location of a contour line along the outer portion of the vortex has a significant effect on the value of circulation. The tangential velocity profiles, obtained from the experimental data in this work, $\alpha=\pm 12^\circ$ Fig.43, are larger in magnitude in the region outside the vortex core than indicated by the data from (36) and Lamb's theory. This trend is in agreement with that presented in Reference (26) for a turbulent line vortex. To determine if the vortex core was, indeed, turbulent a hot-wire anemometer was used to traverse the core of the
vortex. The result of the horizontal traverse through the vortex is shown in Figures 107 and 108. The flow velocity and turbulence level are plotted against distance across the tunnel. Figure 107 shows the hot wire output with the airfoils set at zero angle of attack. Figure 108 shows the velocity profile and turbulence level when airfoils are set at $\alpha = \pm 7^\circ$. The increase in the turbulence level in the core of the vortex verifies the assumption of a turbulent vortex core made previously in the discussion of the shape of the velocity profiles, as level of turbulence necessary for a vortex core to become turbulent is 3 per-cent or greater (15).

5.2 Electric Field Meter Results

The results obtained with the electric field meter are electric field contours shown in Figures 71, 72 and 73. The one sidedness of the data distribution in Figure 71 was due to an error in setting the digital counters on the control panel. The electric field contours are obtained by linear interpolation between data points. Figure 73 shows electric field contours and also the actual data points. It should be noted that the electric field contours plotted in Figures 71, 72 and 73 are mean values of electric field and that the maximum value of the instantaneous electric field at each point is, of course, larger.

The electric field contours for the conditions $\alpha = \pm 7^\circ$, $Z=12$ inches and $Z=23$ inches are shown in Figures 71 and 72 respectively. The wind tunnel flow was seeded with PVC pellets for which $\dot{m} = 1.67$ lb./min. It
Fig. 108: Hot Wire Anemometer Results

One Screen
At Inlet
Temperature - 72°
Pressure - 29.38 in Hg
March 31, 1970

Distance Across Tunnel - Inches

Turbulence Level - Percent
0 50 75 100

Velocity - FPM
220 180 140 100

Distance Across Tunnel - Inches

Airfoil - Flat Tip
Angle of Attack - 70°
7/4 North
can be seen that the shape of the electric field contours at \( z=12 \) inches are similar to the vorticity contours for a vortex which is not completely rolled up, Figures 34 through 36. The electric field contours at \( z=23 \) inches indicate a weakening of the field strength relative to that at \( z=12 \) inches, in the vicinity of the center of the vortex. This is to be expected since the charge-carrying particles, which are creating the electric field, are moving with time (or axial distance) away from the center of the vortex. This movement of the particles out of the vortex center, is due to the centrifugal force on the particles caused by the fluids rotational motion. It is interesting to note that the electric field intensity at \( z=23 \) inches increases in the upper left-hand region. This indicates that the particles, in this region at \( z=12 \) inches, are still under the influence of vorticity bearing fluid which has not completely rolled up into the trailing vortex. However, this is not in agreement with the vorticity results which indicate that, for the condition \( \alpha = 47^\circ \), the shed vorticity has completely rolled up at a distance \( z=12 \) inches. A possible explanation for this occurrence is that the particle being heavier than air tends to lag slightly behind the fluid due to their inertia and, therefore, roll up into the vortex at a slightly slower rate than the fluid particles.

The magnitude of the electric field at \( z=12 \) inches is plotted against radial distance along rays A, B, C, D and E, Figure 71. The results of these plots are shown in Figure 109. It can be seen from
Electric Field Vs Radius

\[ \alpha = 7 \text{ Deg} \]
\[ Z = 12'' \]

\[ \theta = 90^\circ \]
\[ \theta = 135^\circ \]
\[ \theta = 180^\circ \]
\[ \theta = 225^\circ \]
\[ \theta = 270^\circ \]

Fig. 109: Radial Distance in Inches
these plots that the electric field varies linearly along a radius from the vortex center. The plots also indicate, where the flow has completely rolled up, the electric field distribution is nearly axisymmetric.

The electric field contours for $\alpha = +7^\circ$ at $Z=23$ inches is shown in Figure 72. These contours are similar to what one would expect from flow of charged particles in a free vortex. When the charged particles reach their equilibrium radius, where they are no longer under noticeable influence of the rotating fluid, the particle distribution that should result is one with most of the particles in the outer region of the vortex and progressively fewer particles nearest the vortex center. The individual particles carry electrostatic charge; hence, the electric field would be expected to increase as one moves away from the vortex center.

The electric field contours for $\alpha = +12^\circ$ at $Z=12$ inches, Figure 73, indicate a stronger electric field throughout the area of influence of the vortex than for the case of $\alpha = +7^\circ$ at $Z=12$ inches, Figure 71. Due to the increase in the angle of attack, from $+7^\circ$ to $+12^\circ$, the induced rotational velocities in the vortex are greater. Compare Figures 40 and 42 which are in agreement with Reference (56). The magnitude of the electric field is also greater near the vortex center. The increased rotational velocities, when $\alpha = +12^\circ$, should reduce the number of particles in the vicinity of the vortex core. Apparently, since the
particles carry the charge which, in turn, creates the electric field, there is a charge generation mechanism which is related to the higher included rotational velocities, that increases the amount of charge on each particle as it travels downstream in the trailing vortex.

It has been mentioned previously that the plotted values of the electric field in Figures 71, 72 and 73 are the mean values.

The values are obtained from the statistical analysis of the voltage pulses which, together, yield the electric field reading. The plot in Figure 45 of the per cent of the total voltage pulses versus threshold voltage indicates that, when the electric field meter was located at vertical stations 30 and 40, a mean voltage could not be determined. Figure 46 shows similar results for vertical stations 30 and 40 when the electric field meter is located at the horizontal station 20. Similarly in Figure 47 for a vertical station 30 with the electric field meter located at a horizontal station 30. These locations are in the lower left-hand corner in Figure 71 and appear to be outside the influence of the vortex. This fact indicates that the group of particles (pulses), which added together create the electric field, have a normal distribution of electrostatic charge. Any physical reasoning which would suggest that the particle fields should follow a normal distribution is not readily evident.

5.3 Particle Density Probe Results

The particle density probe results are shown in Figures 74 through 77 as contours of particle density (in particle per second). The back-
ground density recorded with no airfoils in the test section indicates a homogeneous mixture of PVC pellets in horizontal planes within the wind tunnel test section but some stratification from top to bottom of the flow. This vertical density variation is probably due to the low speed at which the particles enter the wind tunnel prior to the acceleration into the wind tunnel test section. A second possibility is that the plume from the feed nozzle may have been directed too low on the wind tunnel inlet screen. A planimeter was used to obtain the area between density contours. Then by taking the average between the two contours bordering each area as the particle density for that area, it was possible to determine the total number of particles passing through the 4" x 4" plane of measurement. The result indicates 301,400 part per second pass through this 4" square. Hence, the number of particles traveling through the entire plane of the 3 ft. sq. test section is 0.8 x 10^7 particles per second. This number compares well against the number of particles being fed into the test section from the feed hopper which is 0.57x10^7. The number of particles from feed system is obtained using an average particle diameter (200μm) obtained from the sieve analysis tests.

The particle density contours for the conditions α = ±7 degrees at Z=12 inches and Z=23 inches are shown in Figures 75 and 77. The contours at Z=12 inches have an appearance similar to Figures 34, 35 and 39 which show the vorticity contours prior to rolling up into one concentrated
vortex. A possible explanation for the shape of these density contours is that given in the discussion of the electric field contours (Section 5.2). The density contours at \( Z = 23 \) inches indicate the vorticity shed from the airfoil sections has completely rolled up. The particle density contours are similar in shape to the vorticity contours obtained when the vortex is completely rolled up, Figures 38 and 41, however enclosing a much larger area. The particle density contours near the vortex center in Figure 76 indicate a slight increase in the density which implies particles are being brought toward the vortex center due to the vortex roll-up. The particle density contours in Figure 77 are for test conditions \( \alpha = \pm 12 \) degrees and \( Z = 12 \) inches. These contours are similar in shape to those of Figure 76. However, they show a definite decrease in the particle density throughout the entire region. This decrease in particle density is expected due to the increase action of the centrifugal force. These contours also indicate that, the vorticity shed from the airfoil, has rolled up more completely in comparison to the contours of Figure 75 for \( \alpha = \pm 7^\circ \).

The variation of the density along radial lines has been plotted versus distance for several angular positions, Figures 110 and 111. The test conditions were \( V = 115 \) f.p.s. PVC pellets, \( \dot{m} = 1.67 \) lb./min. The variation of density is nearly linear, and for the case \( \alpha = \pm 12^\circ \), \( Z = 12 \) inches indicates a small variation with angular position. These results indicate that a model for the flow of particulates in these tests can be assumed axisymmetric.
Density vs. Radial Dist.
α = 7°  z=12 inches
PVC Pellets

- 0 DEG.
- 90 DEG.
- 180 DEG.
- 270 DEG.

Particle Density - Particles/sec

Fig. 110: Radial Distance - Inches

Density vs. Radial Dist.
α = 7°  z=23 inches
PVC Pellets

- 90 DEG.
- 180 DEG.
- 270 DEG.

Particle Density - Particles/sec

Fig. 111: Radial Distance - Inches
The particle density probe was used to measure the amount of charge on individual particles at several locations in the flow field. The charge on individual particles is obtained from the voltage versus time trace of the particle density probe. Since each particle impact causes current to flow through the probe circuit to ground, the charge generating this current can be determined from the following expression:

\[ q = \frac{1}{R} \int_{t_0}^{t} V(t) \, dt \]  \hspace{1cm} (5.3)

To determine how the density probe output trace would look when a particle impacts the probe, it is necessary to consider what occurs when a positively charged particle impacts the probe. As the particle approached the probe, charge begins to flow toward the probe tip. Taking the positive direction upward, the voltage level drops as negative charge flows from ground to the probe tip. At impact (some) of the positive charge is conducted away from the probe tip to ground. This causes a sharp increase in the voltage level of the probe followed by a drop back to its floating potential. The results of such measurements do not give the total charge per particle since the amount of charge given up to the probe tip during impact is dependent upon the characteristics of the impact. A detailed discussion of charge transfer during particle impact is given in Reference (11).
The average values of the charge per particle obtained from this work are shown in Table 7. The listed numbers of charge per particle are obtained by averaging the results from all the indicated impacts on each trace. The ratio of charge to mass is based on a 200\(\mu\) diameter particle. The ratios of charge to mass indicate the particles outside the vortex core carry between twice to six times as much charge as particles in the vortex core. There does appear to be a slight increase in charge on particles for the \(\alpha = +12^\circ\) case versus the \(\alpha = +7^\circ\) case. It was expected that the charge would be generated due to repeated collisions as the particles travel from the core of the vortex to a location outside the influence of the vortex. This is not to say such a phenomena does not occur. There is a possibility this trend may be occurring at downstream positions far from the trailing edge of the airfoil. The difference in tangential velocity between the two cases is only 30\%. Averaging the charge per particle values (outside the core) given in Table 7 gives 5.73 \((10^{-13})\) coulombs for \(\alpha = +7^\circ\) degrees versus 7.77 \((10^{-13})\) coulombs for the \(\alpha = +12^\circ\) case. This is an average increase in charge of 35\%. If this increase in charge is indeed, due to increase rotation in the flow as it appears, it could be the possible explanation to the increase in helicopter charging cited at the end of section 2.5.
<table>
<thead>
<tr>
<th>Fig. No.</th>
<th>Part. Impacts Contour</th>
<th>Part. Impacts Trace</th>
<th>q (coul)</th>
<th>(q/m) coul/kgm</th>
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<td>$4.81 \times 10^{-5}$</td>
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<tr>
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</tr>
<tr>
<td>83</td>
<td>3</td>
<td>8</td>
<td>$9.0 \times 10^{-13}$</td>
<td>$21.7 \times 10^{-5}$</td>
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</tbody>
</table>

$\alpha = \pm 7 \text{ DEG. } Z = 12 \text{ INCHES } \text{ PVC PELLETS } m \approx 1.67 \text{ lb./min.}$

<table>
<thead>
<tr>
<th>Fig. No.</th>
<th>Part. Impacts Contour</th>
<th>Part. Impacts Trace</th>
<th>q (coul)</th>
<th>(q/m) coul/kgm</th>
</tr>
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<tr>
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<td>1</td>
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<tr>
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<td>5</td>
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<td>$10.85 \times 10^{-13}$</td>
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<td>8</td>
<td>$5.6 \times 10^{-13}$</td>
<td>$13.5 \times 10^{-5}$</td>
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</tbody>
</table>

$\alpha = \pm 12 \text{ DEG. } Z = 12 \text{ INCHES } \text{ PVC PELLETS } m \approx 1.67 \text{ lb./min.}$
5.4 Results of Tests With #120 and #3 Glass

The electric field measurements and particle density variations for the #120 petro sand and #3 glass are given in Figures 92 through 106. The electric field profile for the #120 petro sand, Figure 92, shows that the electric field varies from 1,800 volts/m at the vortex center to 2,250 volts/m outside the vortex core. The particle density distribution shows that the particles are being thrown out of the vortex core due to centrifugal force. The particle density distribution indicates a slight stratification of particle density similar to that with PVC pellets in the flow. The electric field is lower than that which occurred with the PVC pellets. This is probably due to the difference in the electrical characteristics of the two materials. The major variation of electric field intensity occurs near the vortex core which is also where the major variation in particle density occurs. This result agrees with that obtained from tests with PVC pellets. The field gradients for the PVC tests were greatest near the edge of the vortex core, Figure 72, where the density gradient is greatest. The electric field gradient in the #120 petro sand is greatest near the vortex core also where the largest variation in density gradient occurs. This pattern tends to verify that the electric field meter is actually measuring the electric field set up by the flowing particles. The electric field measurements for the #3 glass, Figure 101, are not consistent with the electric field results obtained with the other seed particles in the wind tunnel flow field. A look at the particle density profile, Figure 101, shows that the maximum particle density
in the region of the field measurements is 30 particles per second except below the vortex center where 850 particles per second pass the plane of measurement. The #3 glass particle must be so heavy that they are settling toward the bottom of the test section as they travel through the wind tunnel. The statistical analysis of the voltage pulses shows that the voltage level remains nearly constant indicating that most of the particles have not been influenced by the vortex system. A typical oscillograph trace of the electric field meter output is shown in Figure 106. The trace on the left is for #3 glass particulates, that on the right for #120 sand particulates.

The particle density probe traces for the #120 petro sand are shown in Figures 95 through 99. These traces give a good indication of the variation of particle charge with distance from the vortex origin. Notice that the vertical scale is 0.2 volt/m; hence, the charge levels indicated in these photographs are at least an order of magnitude less than for the PVC pellets. Figure 97 shows a trace taken at the vortex center. The density contour indicates at least four particle impacts should be observable in the trace. Two impacts are clearly observable at the left side of the trace and at least at third at 6.8 cm. The average charge per particle, determined from the particle density output traces taken at various vertical positions in the flow, is shown in Table 8 where the Figure numbers correspond to the photographs in the test. The charge per particle for the #3 glass particles could not be determined from the particle density output traces, Figure 102
TABLE 8: AVERAGE CHARGE TO MASS RATIO OBTAINED FROM PARTICLE DENSITY PROBE

\(\alpha = \pm 7 \text{ DEG.} \quad z = 12 \text{ INCHES} \quad \# 120 \text{ PETRO SAND} \quad \dot{m} = 1.67 \text{ lb./min.}\)

<table>
<thead>
<tr>
<th>Fig. No.</th>
<th>Vert. Loc.</th>
<th>Part. Impacts Contour</th>
<th>Part. Impacts Trace</th>
<th>(q \text{ (coul)})</th>
<th>((q/m)\text{coul/lbm})</th>
</tr>
</thead>
<tbody>
<tr>
<td>95</td>
<td>+2.5</td>
<td>4.0</td>
<td>6.0</td>
<td>0.515 ((10^{-13}))</td>
<td>0.455 ((10^{-5}))</td>
</tr>
<tr>
<td>96</td>
<td>+1.15</td>
<td>3.0</td>
<td>3.0</td>
<td>0.30 ((10^{-13}))</td>
<td>0.265 ((10^{-5}))</td>
</tr>
<tr>
<td>97</td>
<td>0</td>
<td>5.0</td>
<td>4.0</td>
<td>0.1925 ((10^{-13}))</td>
<td>0.1705 ((10^{-5}))</td>
</tr>
<tr>
<td>98</td>
<td>-1.15</td>
<td>3.0</td>
<td>6.0</td>
<td>0.315 ((10^{-13}))</td>
<td>0.278 ((10^{-5}))</td>
</tr>
<tr>
<td>99</td>
<td>-3.85</td>
<td>4.0</td>
<td>---</td>
<td>0.3 ((10^{-13}))</td>
<td>0.263 ((10^{-5}))</td>
</tr>
</tbody>
</table>
through 105. The density contours for the #3 glass indicates a maximum of 120 particles per second pass the points where the particle density output traces were taken. To observe two impacts on the output trace requires a sweep rate of 10 millisec per cm. To resolve the time during impact at this sweep rate is impossible, Figure 103.
CHAPTER VI
PARTICLE TRAJECTORIES IN A TRAILING VORTEX SYSTEM

To more fully understand the nature of charged particle motion in a trailing vortex, analyses of the trajectories of particles are presented in this chapter. Initially the motion of uncharged particles will be considered based upon existing theoretical methods. Next the analyses will be extended to include the effects of charge and radial electric field on the motion of the particles.

6.1 Basic Particle Motion Without Electrostatic Effects

This section presents a comprehensive review of prior analyses of particle motion in a vortex. Because knowledge of trajectories is important, the prior work is shown in considerable detail. Following this exposition, calculations of trajectories of particles of interest to this study are presented. Following the approach of Soo (55) and Hirschkron and Ehrich (25), the governing differential equations describing the three-dimensional path of a particle are obtained. The body force considered to be acting is the drag force on each particle due to the relative motion between the particle and the fluid. Gravitational, electrical and magnetic forces have not been included.

The differential equations describing the path of each particle in a Lagrangian reference frame are (assuming an axisymmetric flow field) from Reference (25)

\[
\frac{d\mathbf{u}_p}{dt} - \frac{\mathbf{v}^2}{\rho} = F(u-u_p) \tag{6.1}
\]

\[
\frac{d\mathbf{v}}{dt} + \frac{\mathbf{v}_p \mathbf{u}_p}{\mathbf{r}} = F(v-v_p) \tag{6.2}
\]
\[
\frac{d\mathbf{w}_p}{dt} = F(w - \mathbf{w}_p) \tag{6.3}
\]

where \( t \) represents time, \( u, v, w \) and \( u_p, v_p, w_p \) represent, respectively, the fluid and particle velocities in the radial, tangential and axial directions. The force term \( F(u_i - u_p) \) is the drag per unit mass acting on each particle. In References (55) and (25), the Stokes drag relationship \( F = 3\pi \mu d^2 / m_p \) for a spherical particle was applicable. This relationship will be used in this work as a first approximation. To determine the exact drag expression applicable to particles in the trailing vortex, the relative velocity between the particle and the fluid must be known. Then the appropriate drag law corresponding to this Reynolds number flow about a sphere could be used. Once the particle trajectories and velocities have been determined, using this relationship, its validity can be checked.

To solve the governing equations, the substitution of derivatives \( dr/dt = u_p \) and \( d\mathbf{z}/dt = \mathbf{w}_p \) were made and yield the following set of differential equations:

\[
\frac{d^2r}{dt^2} + \frac{v_p^2}{r} = F(u - \frac{dr}{dt}) \tag{6.4}
\]

\[
\frac{1}{r} \frac{d}{dt}(r v_p) + F v_p = F v \tag{6.5}
\]
The following assumptions are inherent in the derivation of the particle trajectory equations:

1. The presence of the particles does not alter the velocity field of the field.
2. The particles do not come into physical contact, that is, the movement of any one particle is not influenced by the presence of others.
3. The particles are non-deformable spheres.
4. The wall effects may be neglected.
5. The drag force acts always in the direction of the relative velocity vector between the fluid and particle.
6. The effects of Brownian motion are negligible.
7. The Magnus forces are negligible.
8. The gravity force is negligible compared to the drag force.

To obtain a solution to this system of equations, the fluid velocities \( u, v, \) and \( w \) must be known, either expressed as functions of \( r, \theta \) and/or \( z \) or as constants. In References (55), (25), the fluid flow was assumed to be that of a free vortex with vorticity \( \zeta \), with no radial flow and constant axial flow, viz.

\[
\begin{align*}
  u &= 0 \\
  w &= W_0 = \text{constant and } v = \frac{\zeta}{r}
\end{align*}
\]
The initial velocities for the particles were specified at an initial position \( Z_0 \) as the following constants \( u_p(t=0)=u_0 \) and \( \omega_p(t=0)=\omega_0 \).

With these conditions, the governing equations can be written in the following forms

\[
\frac{d^2 r}{dt^2} + f \frac{dr}{dt} = \frac{1}{r} \left[ \frac{C}{r} + \left( \frac{c v_p - C}{r} \right) e^{-Ft} \right] \tag{6.7}
\]

\[
r \frac{d\theta}{dt} = v_p = \frac{C}{r} + \left( \frac{c v_p - C}{r} \right) e^{-Ft} \tag{6.8}
\]

\[
\frac{dz}{dt} = w_p = \omega_0 + \left( \omega_p - \omega_0 \right) e^{-Ft} \tag{6.9}
\]

Prior to solving this system of equations, they are non-dimensionalized and yield the non-dimensional Stokes' parameter \( B=Fr_0^2/C \). The non-dimensional coordinates are \( r^*=r/r_o \) and \( Z^*=Z/r_o \). The radius \( r_o \) is the radial distance from the center of the vortex where the particles are injected into the flow field. The non-dimensional time is given at \( t^*=tC/r_o^2 \). All velocities are non-dimensionalized by dividing by \( C/r_o \). Substitution of these quantities into the (6.7), (6.8), (6.9) yield

\[
\frac{d^2 r}{dt^2} + B \frac{dr}{dt^*} - \frac{1}{r^3} \left[ 1 + (v_p^* - 1) e^{-Bt^*} \right]^2 = 0 \tag{6.10}
\]
This system of differential equations has been solved numerically for various values of the parameter $B = \frac{Fr}{C^2}$. The results taken from Reference (25) are shown in Figures 112 and 113 for the case of zero deviation of injection velocity (i.e., $u = 0$, $v = 0$) and zero injection velocity ($u_p = 0$, $v_p = 0$).

To modify this system of equations so they are applicable to the flow conditions of interest in this study, the equations describing the fluid velocities must be known. The fluid velocities are obtained as outlined in Reference (43). In Reference (43), the equations of motion for an isolated laminar viscous vortex are linearized by assuming that both the rotational velocity and the deficit of longitudinal velocity are small compared to the free stream velocity. The final form of the equations governing the fluid motion are obtained through a small perturbation analysis of a single trailing vortex. The fluid is assumed incompressible, steady, and the flow field to be axisymmetric. With these assumptions, the rotational equation is uncoupled from the longitudinal equation. Each equation of motion
Spiral path, zero deviation of injection velocity

Ref. 25

Fig. 112: Particle Trajectories $V_p(t=0) = V_f(t=0) \chi(25)$
Fig. 113: Particle Trajectories \( (V_p(t=0)=0 / (25) \)
may then be solved independent of the others and the solutions superimposed. After the linearization process is carried out and using the assumptions discussed above the resulting governing equations for the trailing vortex are radial:

\[ \frac{v^2}{r} = \frac{1}{\rho} \frac{\partial p}{\partial r} \]  \hspace{1cm} (6.13)

rotational:

\[ W \frac{\partial v}{\partial z} = \nu \left[ \frac{\partial^2 v}{\partial r^2} + \frac{1}{r} \frac{\partial v}{\partial r} - \frac{v}{r^2} \right] \]  \hspace{1cm} (6.14)

axial:

\[ W \frac{\partial w}{\partial z} = \nu \left[ \frac{\partial^2 w}{\partial r^2} + \frac{1}{r} \frac{\partial w}{\partial r} \right] \]  \hspace{1cm} (6.15)

and continuity:

\[ \frac{1}{r} \left[ \frac{\partial}{\partial r} (ru) \right] - \frac{\partial w}{\partial z} = 0 \]  \hspace{1cm} (6.16)

where \( w = w - w_1 \) the longitudinal velocity deficit.

From the nature of the approximations, the governing equations simulate the vortex some distance from its origin. Thus, the vortex is assumed to be suddenly generated at \( z=0 \) as a free vortex of circulation \( \Gamma \). The boundary conditions are as follows when

\[ z=0 \quad v = \frac{\Gamma}{2\pi r} \quad w=0 \text{ except at } r=0 \]
when

\[ Z = 0 \text{ for } r \text{ large}, \text{ though still small compared with } Z. \]

and as

\[ Z \to \infty \text{ for all } r. \]

The solution to the rotational equation is

\[ v = \frac{\rho}{2\pi r} \left[ 1 - e^{\sqrt{-\frac{wr^2}{4\nu z}}} \right] \quad (6.17) \]

and the solution to the axial equation is

\[ w = \frac{A}{Z} \left[ e^{\sqrt{-\frac{wr^2}{4\nu z}}} \right] \quad (6.18) \]

where \( A \) is a constant. The constant \( A \) is determined by consideration of momentum.

The radial velocity is obtained from the continuity equation. The axial velocity expression is known and, after differentiation and integration, the radial velocity is

\[ u = \frac{-Ar}{2Z^2} \left[ e^{\sqrt{-\frac{wr^2}{4\nu z}}} \right] \quad (6.19) \]

The constant \( A \) is determined from momentum considerations. The drag of the airfoil producing the vortex is used. Since the axial and
rotational velocities are independent of $\Gamma_0$, the expressions for $\omega$ and $u$ are valid for all values of vortex strength $\Gamma_0$. In the limit as $\Gamma_0 \to 0$ the drag of the airfoil, $D_0$, is

$$D_0 = \int_0^\infty \rho (W-w) w 2\pi r dr$$

(6.20)

$$\approx \int_0^\infty \rho W w 2\pi r dr$$

(This is the drag to viscous effects which results in a momentum defect in the wake. The expression for drag is derived directly from the momentum theorem)

Using the expression for the axial velocity, the drag expression is

$$D_0 = 4\pi \rho \gamma A$$

(6.21)

and the constant $A$ is then

$$A = \frac{D_0}{4\pi \rho \gamma}$$

(6.22)

(See Reference 43 for discussion on the inclusion of the induced drag.)

To obtain a description of motion suitable for the case of a particle moving in a trailing vortex in a viscous fluid, Newman's equations (6.17-6.19) for fluid velocities can be combined with the general particle equations of motion (6.1-6.3). Using the same non-dimensionalization procedure as outlined previously, the non-dimensional form of the differential equations governing the particle trajectory are

$$\frac{d^2 r^*}{dt^*^2} + B \frac{dr^*}{dt^*} - r^* \left( \frac{d\theta}{dt^*} \right)^2 = Bu^*$$

(6.23)

*See "Foundation of Aerodynamics", Pg.49, by A.M. Kuethe and J.D. Schetzer
\[
\frac{d^2 \theta}{dt^*} + \frac{2}{r^*} \frac{d\theta}{dt^*} \frac{dr^*}{dt^*} + B \frac{d\theta}{dt^*} = \frac{Bv^*}{r^*} \tag{6.24}
\]
\[
\frac{d^2 z^*}{dt^*} + B \frac{dz^*}{dt^*} = Bw^* \tag{6.25}
\]

where \( C \) is replaced by \( f_0 \) in the non-dimensional parameter \( B \), and all the fluid velocities are based upon Equations (6.17-6.19). Equations (6.23-6.25) are essentially Newman's equations in non-dimensional form.

The differential equation describing the particle motion in the axial direction can be solved explicitly by integrating twice with respect to \( t^* \) to yield

\[
z^* = z_o^* + w_o^* t^* + \frac{1}{B} (w_p^* - w_o^*) [1 - \exp(-Bt^*)] \tag{6.26}
\]

The remaining two second order differential equations must be solved simultaneously in order to determine the complete particle trajectory.

The solution of these differential equations is obtained using a digital computer. The differential equation solving routine employed is Hamming's modified predictor-corrector method. As a check on the accuracy of the solutions, the initial conditions and parameters were altered to duplicate the flow conditions cited in (25). The solutions, obtained from Hamming's modified predictor-corrector routine and those published in Reference (25) which were obtained using a fourth order Runge-Kutta routine, are shown in Figure 114.
Both differential equation-solving routines give the same results for the extreme cases of $Fr_o^2/C=0$ and $Fr_o^2/C\to\infty$. The two routines give different results for the cases $Fr_o^2/C=1.0$ and $0.1$. The difference in the two solutions is due to an error in the derivation of the differential equation governing the tangential velocity in (25). The solutions obtained from Hamming's routine, omitting the factor 2 in the tangential velocity equation and the results given from (25) were in complete agreement for both the case of zero derivation of injection velocity and the case of zero injection velocity. The numerical solutions to the general equations 6.23 and 6.24 for the case of zero deviation of injection velocity are shown in Figures 115 and 116 as plots of non-dimensional radius versus non-dimensional time and angular position. The computer results in Figures 115 and 116 are based.
Fig. 115: Particle Radius vs. Spiral Angle
on particles of 250/μ diameter and 50/μ diameter. The drag force per unit mass $F_f$ for a 250/μ particle is 10 and for 50/μ particle is 250.

The circulation for the two conditions of interest i.e., $\alpha = 7^\circ$ and $\alpha = 12^\circ$, is 10 ft$^2$/sec and 20 ft$^2$/sec, respectively. To study what effect the vortex has on individual particle trajectories, computer solutions were obtained for 250/μ particles injected into the vortex at radii of 0.5 inches and 2.0 inches. This corresponds to values of the parameter $B$ of 0.00034 and 0.1664 for the $\alpha = 7^\circ$ case and 0.00017 and 0.0832 for the $\alpha = 12^\circ$ case. The cases $B=0.174$ and $B=0.087$ correspond to a 50/μ diameter particle being injected into the vortex at a radius of 1.0 inch.

The computed trajectories are also plotted in Figures 117 and 118 as radial distance from the vortex center in inches versus distance downstream in inches. The values of vortex strength and vortex geometry, $\Gamma_0$ and $r_0$, measured with the vortex meter were used in the numerical computation of the particle trajectories. The computed trajectories start at a point corresponding to 12 inches downstream from the airfoil trailing edge.

The important result obtained from the computed trajectories is that particles initially near the vortex center are thrown out of the vortex core and that their trajectories intersect the trajectories of particles initially outside the vortex core. The larger 250/μ diameter particles move radially outward faster than 50/μ diameter particles. This result suggests two mechanisms whereby a trailing vortex system acts as a charge separator and charge generator. The
Fig. 117: Particle Radius vs. Axial Distance
Fig. 118: Particle Radius vs. Axial Distance
first is through separation of particles to the outside of the vortex core. The result was also verified by the measured density contours (compare Figure 74 with Figures 75 through 77.) The second is through particle-particle interaction which would increase the charge level of the particles. The results of the density contours, Figures 75 and 76, somewhat substantiate this possibility. Comparison of Figure 75 with 76 indicate that the number of particles near the vortex core does not noticeably decrease with increase in distance downstream from the trailing edge as indicated by the math model. This could be due to the particle interactions or due to the incomplete rolling up of the seeded vortex. Additional density contours at stations farther downstream from the airfoil trailing edge are needed to resolve this question.

6.2 Inclusion of Electric Field Effects In The Particle Trajectory Equations

The trajectory equations derived in Section 6.1 do not include the effect of charge residing on the solid particles. The equations governing particle trajectories will now be modified to include electric field effects due to the electrostatic charges carried by the individual particles.

The forces and moments acting on a solid particle are due to the net charge, electric dipole caused by the electric field set up by the other charged particles, and the aerodynamic drag force. Gravitational
and magnetic effects have been neglected. In vector notation, the resultant force on each particle can be written as

\[ \vec{F} = q\vec{E} + \nabla(\vec{p} \cdot \vec{E}) \quad (6.27) \]

From the experimental results of the electric field measurements, the electric field is assumed to act only radially. Hence, the governing equations for the particle trajectories are

\[ \frac{du_p}{dt} - \frac{v_p^2}{r} = F(u - u_p) + \frac{qE_r}{m_p} + \frac{1}{m_p} \frac{d}{dr}(pE_r) \quad (6.28) \]

\[ \frac{dv_p}{dt} + \frac{u_pv_p}{r} = F(v - v_p) + \frac{qE_\theta}{m_p} \quad (6.29) \]

\[ \frac{dw_p}{dt} = F(w - w_p) + \frac{qE_z}{m_p} \quad (6.30) \]

To evaluate the contribution of the electric dipole on the particle trajectory, the procedure outlined in Reference (55) will be followed. The dipole moment is the volume per particle \( V_p \) times the polarization \( P \),

\[ p = V_p P = \frac{m_p}{\rho_p} \left[ \frac{3(\varepsilon_\rho - 1)}{\varepsilon_\rho + 2} \right] \varepsilon_0 E \quad (6.31) \]

where \( V_p = m_p / \rho_p \) and \( P = K\varepsilon_0 E \). The electric susceptibility, \( K \), has been modified to include the effects of other particles on the particle in question.
The force on a particle, due to the net charge, is a product of the charge times the electric field. The flow pattern of particles downstream of the airfoils is assumed to be axisymmetric. Assuming the field at a radius \( r \) is a function of the radius squared, the ratio of the force due to dipole to the force due to electrostatic repulsion is according to Reference (55).

\[
\frac{F_d}{F_e} = \frac{3(\varepsilon_r-1)}{\varepsilon_r+1} \left( \frac{M_r}{\pi r^2 \rho_p} \right) \left( \frac{\rho_p}{\rho_p} \right)
\]

where \( M_r = \int_0^R \rho_r \, r \, dr \)

and \( \rho_p \) is the density of the particulate phase in a multiphase system. However, the system considered here is that of a dilute solution for which \( \rho_p \ll \rho \), and the dipole effect is negligible.

To determine an expression for the electric field to be used in this work, recourse is made to experimental results. The electric field measurements downstream from the airfoils indicate that contours of constant electric field strength are approximately circular. The magnitude of the electric field increases approximately linearly along a radius from the vortex center as indicated in Figure 109. It can be seen that the slope of the curve of field intensity versus radius are nearly the same over much of the flow. From these results, a first approximation to the electric field is

\[
E_r = E_o r
\]

(6.33)
The electric field measurements at \( Z=12 \) and \( Z=23 \) show that the electric field-strength remains approximately constant in the axial direction \((E=0)\) and axisymmetric \((E_o=0)\).
where $E_0^1 = 1,000$ volts per meter per inch. The electric field is assumed to be axisymmetric and variation of the field in the axial direction at a specific radius is assumed to be negligible.

The governing equations of the particle trajectories are now

$$\frac{du_p}{dt} = \frac{V_p^2}{r} = F (u-u_p) + \frac{q}{m_p} E_0^1 r$$ \hspace{1cm} (6.34)

$$\frac{dv_p}{dt} + \frac{V_p u_p}{r} = F (v-v_p)$$ \hspace{1cm} (6.35)

$$\frac{dw_p}{dt} = F (w-w_p)$$ \hspace{1cm} (6.36)

To nondimensionalize these equations, the same parameters as used previously are employed. Hence, lengths are nondimensionalized using the injection radius $r_o$, the time by $r^2_0$, etc. The resulting equations in the $\theta$ and $Z$ direction are the same as before. The $r$-equation is altered by the inclusion of the term which includes the electrostatic effects. The complete set of governing equations in non-dimensionalized form are

$$\frac{d^2 r^*}{dt^{*2}} = r^* (\frac{d\theta}{dt^*})^2 + B \frac{dr^*}{dt^*} = Bu^* + B \cdot ELCN \cdot r^*$$ \hspace{1cm} (6.37)

$$\frac{d^2 \theta}{dt^{*2}} + \frac{\theta}{r^*} \frac{d \theta}{dt^*} \frac{dr^*}{dt^*} + B \frac{d\theta}{dt^*} = \frac{Bv^*}{r^*}$$ \hspace{1cm} (6.38)

$$\frac{d^2 Z^*}{dt^{*2}} + B \frac{dZ^*}{dt^*} = BW^*$$ \hspace{1cm} (6.39)
where a new non-dimensional parameter $ELCN = (q/m_p)(r_0/r)(E^1_o r_o/F)$ has been introduced. This system of differential equations has been solved numerically using a digital computer. The results are plotted in Figure 115 through 118. The values of $q/m$ obtained from the particle charge measurements and the value of $E^1_o$ obtained from the electric field measurements carried out during the course of this study give a value of $ELCN = 0.0001$. The numerical solutions indicate that an individual particle trajectory is not altered by the electric field set up by neighboring particles. The numerical solutions indicate a field strength two orders of magnitude above the measured field strength is required to retard the radial flow of particles from the vortex core.

In concluding the discussion on the mathematical solution of the particle trajectories it can be seen in Figures 117 and 118 that when $\alpha = \pm 12$ the particles move away from the vortex core at a faster rate than when $\alpha = \pm 7$. This is to be expected since the centrifugal force is greater when $\alpha = \pm 12$. Considering the particle charge levels for $\alpha = \pm 7$ and $\alpha = \pm 12$, Figures 78-91, it can be seen that the charge level of particles near the core of the vortex is lower than the charge level of particles outside the core of the vortex. Thus the increase in the charge levels of the particles away from the vortex core must be due to collisions with other particles. Since the particles are moving away from the vortex core faster when $\alpha = \pm 12$ it is to be expected that the charge level of these particles would be greater than for the $\pm 7$ case. The results given in Table 7 show this is the case.
CHAPTER VII
CONCLUSIONS

The major conclusions which can be drawn from the results of this study are:

1. The differential airfoil is capable of generating a stable vortex whose position in the wind tunnel is independent of the wind tunnel flow velocity, angle of attack and distance downstream. (pg.112)

2. A new vortex probe design (the air-bearing vortex probe) has demonstrated that it is capable of measuring rotational velocities in a trailing vortex system. The calibration results of the new air-bearing vortex probe show negligible effects due to variation in wind tunnel flow velocities. The air-bearing vortex probe has been tested and shown not to require correction factors due to friction losses. A new calibration technique, employing a telemetering device, permits calibration of the vortex probe over a much greater range of rotational velocities that here-to-fore reported in the literature. (pg.70)

3. The particle feed system designed and fabricated as part of this effort does seed particulates into the wind tunnel flow with minimal disturbance to the flow and a nearly homogeneous distribution. There is a gradient in the particle distribution due to gravity effect at the tunnel inlet. (pg.156)
4. A filter system was designed and found to be capable of containing particles as small as 50\ microns with 99% efficiency. (Pg. 35).

5. It has been demonstrated that an electric field meter is capable of making electric field measurements in the quasi-steady field set up by the flowing particles. (Pg. 152).

6. A particle impact (density) probe, as designed in the course of this study, is capable of determining the particle density distribution and an indication of the particle charge. The probe is sensitive to particle impacts and particles passing near the probe; hence, the effective probe diameter is approximately twice its actual diameter. (Pg. 91).

7. The trailing vortex system in a flow seeded with particles does establish a quasi-static electric field distribution due to the electrostatic charge which resides on the swirling seed particles. (Pg. 152).

8. The charge distribution on particles within the vorticity field increases with distance from the vortex center, in the region of measurement. (Pg. 168).

9. A mathematical model of the particle trajectories in a trailing vortex system was developed. (Pg. 204-225). The measured radial component of electric field was included in the radial momentum equation. The solution to the math model shows that the paths of particles moving downstream with the vortex intersect within one to two chord lengths. The collision between particles is a possible cause of the increased charge measured on particles outside the core of the vortex.

10. The core of the vortex appears to be turbulent. (Pg. 189).
11. The electric field distribution downstream of the airfoils is approximately linear with radial distance from vortex center and roughly axisymmetric at each downstream station in the region of measurements. (Pg.191).

12. The particle density downstream of the airfoils is approximately linear with radial distance from vortex center and axisymmetric at each downstream location in the region of measurements. (Pg.196).

13. The particle charge measurements indicate the charge level on particles outside the vortex core is greater than particles near the core. The particle charge increases with increase in the angle of attack of the airfoils. Comparison of particle charge for the $\alpha = \pm 7^\circ$ and $\alpha = \pm 12^\circ$ cases indicate a greater charge level exists on the particles when $\alpha = \pm 12^\circ$. (Pg.198). This increase in charge is nearly the same proportion as the increase in the maximum tangential velocity of the trailing vortex; i.e., as the increase in circulation. (Pg.198).
CHAPTER VIII
RECOMMENDATIONS

The results satisfy the basic goal of this study which is determining if a trailing vortex system shed from an airfoil tip can act as a charge separating device. In the course of the study, many new possibilities for research become evident. A listing of these possibilities follow:

1. Study the nature of the particle charging and separation process to determine the reasons for the normal distribution of voltage levels on the particles.

2. Make vorticity, electric field, and particle density measurements at stations far downstream from the airfoils. Observe the vorticity data to see if vortex breakdown occurs.

3. Place bodies downstream of the airfoils and measure the charge deposition due to the seeded vortex flow. These bodies should be sufficiently large so that the electric field meter can be located inside the bodies to monitor the electric field level (if the body is a dielectric).

4. Run tests with one size particulates. Then see if charge distribution varies with the radial distance from the vortex core.
5. Run tests with the airfoils covered with different materials. See what effect airfoil material has on the electric field and particle charge density.

6. Fix the inlet screen of the wind tunnel with an electrical system capable of neutralizing the particle charge as they enter the wind tunnel.

7. Develop a better instrument for measuring the electric field which would not be affected by the charged particles colliding with it.

8. Modify the positioning device so all but the cross bars are located outside the wind tunnel. This would allow for higher test velocities.

9. Run additional tests with smaller diameter sand particles.

10. Check locations and exhaust flow direction of particle feed nozzle to reduce the particle density stratification.
APPENDIX A

EQUIPMENT

This section of this paper describes the details of the equipment designed and fabricated so that the vorticity and electrostatic measurements throughout the trailing vortex system could be measured. Drawings and photographs of the equipment are referred to whenever it makes for a clearer understanding of the particular piece of equipment being discussed.

A.1 Wind Tunnel

A low-turbulence, subsonic wind tunnel was designed and constructed, Figure 119. The low turbulence level of the flow is achieved through the use of 1 to 3 fine mesh screens, located at the inlet to the wind tunnel. Also, the large contraction ratio on passing from the tunnel inlet to the test section helps to dampen out the fine turbulence due to these entrance screens. Details on the design and construction of the inlet, settling chamber, contraction region, and initial 3 feet of test section are discussed in Reference (13).

An additional ten feet of test section was added to the existing inlet section. The cross-sectional area of test section is
Fig. 119: Front of Sub-sonic Wind Tunnel

Fig. 120: Top View of New Wind Tunnel Test Section
three square feet. No allowance was provided for boundary layer buildup; therefore, the flow accelerates slightly from inlet to exit.

The test section is constructed out of 3/4 inch plywood. The test section is framed in steel angle iron for strength and to prevent distortion of the test section due to sagging. The corners inside the tunnel have been filleted with 3/8-inch wood molding. The inside of the tunnel received over ten coats of varnish, using a non-pigmented varnish in order to obtain good dielectric properties for the tunnel walls.

The new test section has two large viewing windows on each side and on the top (Figure 120). The top, completely removable, consists of two flanged sections that are held in place with thumbscrews to the sides of the wind tunnel. Each section of the top has handles to facilitate easy removal and assembly. The ability to remove the top of the test section completely was necessitated by the size of the equipment used in making the required measurements; i.e., the positioning device, inlet bell and aft diffuser. These pieces of equipment are discussed in Section 3.3.1. Three large doors on each side of the wind tunnel, Figure 119, permit installation of small equipment; i.e., airfoils, probes, models. These doors also provide entrance to the test section for making electrical connections, taping down electrical leads, and maintenance of the positioning device.

The last two feet of both side walls of the wind tunnel are hinged to permit this portion of the wind tunnel flow area to be varied
Fig. 121: Flow Control Doors - with Hand Crank In Place. Limit Switches For Automatic Control Are Shown On Angle Brace In The Center.

Fig. 122: Turning Box Showing Turning Vanes
Figure 121. In this way, the flow velocity throughout the wind tunnel test section, can be varied. These hinge sections are, hereafter, referred to as flow control doors. These doors can close completely to the center of the wind tunnel to give zero flow in the test section. When completely open, the doors are flush with the inside walls of the test section. The ends of the doors have been tapered and thin metal flanges attached. As the doors are closed across the tunnel area, air is drawn into the tunnel through the openings created by the closing of the doors. The flanges act as guide vanes for the incoming flow and reduce the turbulent mixing between this incoming stream and the flow of air coming through the wind tunnel test section.

The movement of the flow control doors can be done manually or automatically, Figure 121. A threaded shaft with left and right hand threads on each half passes through two threaded brass supports mounted in the flow control doors. The brass mounts are free to pivot inside aluminum mounting discs. As the threaded shaft turns, the doors swing together, Figure 120, (or away from each other depending on the direction of rotation of the shaft) across the end of the test section. The pivoting of the brass supports prevents binding on the shaft.

At the exit of the test section, a 3-foot long transition section which mates with the 24-inch by 18-inch rectangular test section at one end and with the 24 inch diameter entrance of the diffuser pre-
ceeding the fan at the other end. The rectangular entrance to the transition section has a four-inch diameter external cylindrical lip on the two vertical sides to assure smooth air inflow into the diffuser when the doors on the aft end of the test section are closed.

The diffuser, proceeding the fan, is 8.5 feet long and increases in cross-section from a 2-foot diameter to a 3.5-foot diameter. The seams in the diffuser were filled with body putty and polished smoothly to inhibit separation of the boundary layer from the throat of the diffuser. The axial vane van is 42 inches in diameter and has fourteen blades equally spaced on a 21-inch diameter hub. The fan is belt driven by a 20 h.p. motor.

Aft of the fan is an exit diffuser which is 4-feet long. This diffuser increases in cross sectional area from 42 inches in diameter at inlet to 54 inches in diameter at the exit.

The exit diffuser empties into a large turning box which turns the flow vertically, Figure 122. The turning box is 56 inches square and is connected to the exit of the diffuser by means of hinge couplings. Inside the turning box are four large turning vanes. These vanes are on radii of r/d equal to 0.2, 0.4, 0.6 and a fourth extending in an arc from the middle of the base of the turning box to the mid-point of the back of the box. (r/d is ratio of radius to box height). The positioning of the turning vanes in the box were determined somewhat arbitrarily since the only experimental data found for this type of turning vane was for circular cross sections.
The efficiency of the turning box was determined by comparing the pressure drop of the system with the turning box in place and with the turning box removed. The difference in pressure drop between the two systems was negligible.

Each tunnel section is mounted on adjustable supports to permit leveling when the wind tunnel is located on an unlevel floor. The doors have rubber stripping along the hinged end so that, when the door clamps are opened, the doors automatically swing open. The door clamps are easily opened by a nudge of the arm which enables a tunnel operator to use both hands to hold a piece of equipment and still gain access to the interior of the tunnel.

A.1.1 Calibration of Wind Tunnel Flow Field

The flow field in the wind tunnel test section has been calibrated to determine the magnitude of the mean velocity of the tunnel "core" flow, the shape of the velocity profiles across the test section, the flow angularities, and the magnitude of the turbulence levels at various points across the test section. The instruments used in making these measurements were two pitotstatic tubes, four static taps, located on the center of each wall of the tunnel, a total head probe, a yaw-tube, and a hot-wire anemometer. The wind tunnel inlet has been calibrated previously (13); however, it was then at a different location in the laboratory, the additional 10 feet of test section had not been installed, and the ductwork downstream
from the test section has been completely replaced. A different fan now drives the tunnel than had been used previously. Due to the changes made in the wind tunnel, a complete calibration of the flow in the test section was performed.

A.1.1.1 Velocity Profiles

The velocity profiles across the wind tunnel test section were measured at three vertical positions, 5 7/8, 11 7/8, and 17 7/8 inches above the wind tunnel floor, at a distance 35 inches downstream from the inlet to the test section. The measurement of the velocity profiles was performed using a total head probe, pitot-static tubes, and a hot-wire anemometer. The results of the total head probe measurements are plotted in Figure 123 in the form of non-dimensional pressure versus distance across the tunnel test section. Measurements were made at two dynamic pressures, 23.3 lb./ft.² and 26.8 lb./ft.², corresponding to mean velocities of 140 ft./sec. and 150 ft./sec. respectively.

The results of the pitot-static tube measurements are shown in Figure 124. The profiles shown are those which developed with various pieces of equipment installed in the wind tunnel test section. The velocity profile, obtained with the test section empty, is also shown. The tunnel "core" velocity can achieve a maximum speed 187 ft./sec. with the tunnel empty. With the inlet bell-positioning device (rack)-diffuser combination in the test section, the "core" velocity drops to
Nondimensional Pressure - From Total Head Probe
April 24, 1970

Vert. Dist. Dynamic Pressure

<table>
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Test Conditions
T = 75°F
P = 29.8 IN HG
Inlet Screen

\[
\frac{P_{AMB} - P_T}{q} = 23.3 \text{ lb/ft}^2 \quad (\text{at } 5\frac{7}{8} \text{ IN})
\]

\[
\frac{P_{AMB} - P_T}{q} = 26.8 \text{ lb/ft} \quad (\text{at } 11\frac{7}{8} \text{ IN, } 17\frac{7}{8} \text{ IN})
\]
Feb 6-10, 1970

Test Section Velocity Profiles

Diffuser Exit Velocity Profiles

Tunnel Center Line

FIGURE 124
Installation of screens in front of the fan and in the large diffuser preceding the fan reduces the core velocity in the test section to 135 ft./sec.

The flow in the test section pulsated slightly when the inlet bell-rack-diffuser combination was installed in the test section. In an attempt to determine the cause of this pulsation, pitot-static tube measurements were made across the mid-point of the wind tunnel fore/aft of the inlet ball and the aft diffuser. The velocity profiles, resulting from these measurements, are also shown in Figure 124.

The smoothness of the velocity profiles obtained aft of the small diffuser are somewhat questionable. The plotted profiles are actually average values of the flow at that point and for that particular time. The water levels in the differential monometer, attached to the pitot-static tube, oscillated over a considerable range during these measurements. This oscillation is due to the turbulent nature of the flow exiting from the small diffuser. A few pitot-static measurements were made below the mid-point of the small diffuser, and the resultant velocity profiles were considerably changed from those in Figure 124. Near the wind tunnel floor, the velocities are less in magnitude and not nearly so developed as those across the midpoint of the diffuser. The corresponding values obtained for the velocity profiles fore and aft of the diffuser were
used to compute the diffuser efficiency for the small diffuser. In each case, the diffuser efficiency was greater than 100%. To determine the diffuser efficiency accurately, it is necessary to have the velocity profiles over the entire plane of the test section fore and aft of the diffuser.

A hot-wire anemometer was used to measure the velocity profiles at the same locations as the pitotstatic tube. The shapes of the velocity profiles, as measured with the hot wire, were identical to those measured with the pitot-static tube; however, the hot-wire anemometer indicated an over-all rise in the magnitude of the velocity of about 10%. The measured velocity profile and turbulence level in the test section are shown in Figure 125. Due to the disagreement in the results from the pitotstatic tube and the hot wire, a second pitotstatic tube was used to measure the velocity profiles. The results obtained from this pitotstatic tube were in agreement with the data from the first pitotstatic tube.

In an attempt to resolve the difference in the measured values of velocity, as indicated by the pitotstatic tubes and the hot-wire anemometer, static taps were located at the center of each of the four wind tunnel walls. The value of mean velocity was then determined from the average of the four readings. The magnitude, of the velocity obtained using this value for static pressure, was still nearly 10% below the value indicated by the hot-wire anemometer. The
Hot Wire Anemometer Data
No Airfoils \( T = 71^\circ F \) \( P = 29.38 \) IN HG.
Distance from Test Section Inlet - 5 Ft
Equipment in Test Section
1. Inlet Bell
2. X-Y Positioning Device
3. Diffuser
Date 3/27/70

![Graphs showing distance across tunnel versus velocity and turbulence level.](image)
effect of the mean velocity on the results expected on the present work was not known; thus, discrepancy between the hot-wire anemometer measurements and the pitot-static tubes was not resolved. A possible explanation for the difference in the two measurements is discussed below.

In a wind tunnel (or any flow system) in which pitot-static tubes are used to make measurements on the suction side of the fan, reliable static pressure data is difficult to obtain. The maximum total pressure is the ambient pressure existing outside the tunnel. When the pitot-static tube is inserted into the flow field, the total pressure changes only a few hundredths of an inch of water.

Static pressure taps must be properly made (16, 14, 19, 46) requiring a good finish and geometry to give reliable results. One cause for the discrepancy between the hot-wire measurements and the pitot-static tubes is believed to be due to errors associated with the static taps.

The velocity profiles indicate a 2 to 3-inch boundary layer on each wall and a smooth "core" flow extending over 12 to 15 inches of the test section. The thickness of the boundary layer agrees well with the predicted thickness according to turbulent boundary layer theory.*

The boundary layer is turbulent and assumed to begin formation at the entrance to the contraction region. Assuming a length of 10 feet, boundary layer theory predicts a boundary layer thickness of approximately 2.0 inches. This is determined from the following expression for turbulent boundary thickness:

\[
\frac{\delta}{x} = 0.37 \left( \frac{U_\infty x}{\nu} \right)^{-\frac{1}{5}}
\]

A.1.1.2 Flow Angularity

The flow angularity in the wind tunnel test section was measured using a yaw tube. The particular type of yaw tube used is a cylindrical tube with two holes positioned 78.5 apart. The yaw tube is connected to a differential manometer. The probe axis is perpendicular to the flow. The probe is rotated about its axis until the water level in both arms of the differential manometer are the same.

The angularity at each location in the flow field is measured relative to the centerline flow. The yaw tube is initially positioned at the center of the tunnel. The yaw tube is rotated until the differential manometer indicates equal pressure in both arms of the manometer. This point is the reference zero. A pointed indicator, attached to the yaw tube, is set to correspond with this zero-degree line. A mark representing the zero reference is also made on the out-
side of the tunnel wall. The yaw tube is moved back and forth across the wind tunnel test section, rotating the probe about its axis until the differential manometer indicates equal pressure in both arms. The angle between the indicator, attached to the yaw tube and the zero degree mark, attached to the wind tunnel wall, is the angularity of the flow field at this point.

The determination of the angle between the indicator of the yaw tube and the reference mark on the wind tunnel wall is, at best, questionable. To permit a more positive measurement, the indicator on the yaw tube was modified. Two 1 x 3 x 0.25 inch pieces of aluminum were attached to the yaw tube and spaced 1 inch apart. The yaw tube and a pointed piece of 1/8-inch drill rod were passed through two holes in the aluminum plates. The holes are spaced about 2 1/2 inches apart. The probe was held to the plates with set screws. The drill rod slides freely in the two holes provided for it. The centerline reading was measured, and the location where the point of the drill rod touches the wind tunnel was marked. As the yaw tube is moved back and forth across the wind tunnel test section, the point of the drill rod is kept flush with the wind tunnel wall. The angle between the initial location of the drill rod and each new location is the angularity of the flow.

The results of the flow angularity tests showed negligible angularity across the wind tunnel test section when referenced to the center line flow.
A.1.1.3 Turbulence Level

The turbulence level was determined from hot-wire anemometer data. The hot wire was positioned at the same vertical and axial locations (i.e., 5 7/8, 11 7/8, 17 7/8 inches vertical and 35 inches axially) in the test section as the pitostatic tube. From Reference (13), equation (F.6) the turbulence level is (as per cent)

\[ I = \frac{1}{U_\infty} \sqrt{\frac{u'^2}{\lambda}} \times 100 \]  

(A.1)

where isotropic turbulence is assumed. The axial velocity and turbulence levels as measured with the hotwire anemometer are plotted in Figure 125. A comparison of Figures 124 and 125 show that the velocity profiles obtained with the pitotstatic tubes indicate a similar boundary layer thickness as measured with the hot-wire anemometer.

A.1.1.4 Comparison of Hot Wire and Pitot-tube Data

To compare the magnitude of flow velocity as measured by the pitot-static tubes and the hot-wire anemometer, the pressure measurements from the pitotstatic tubes must be converted to velocity. Using Bernoulli's equation, a relationship between the static pressure drop and the mean velocity in the wind tunnel can be derived. A graph of this relationship has been plotted in Figure 126 of Reference (13) for various values of free-stream velocity. A plot of the differential-pressure \( P_T - P_s \) and the corresponding velocity profile
<table>
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<th>Correction Factor For Velocity</th>
<th>Ambient Temp. (°F)</th>
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<td>55</td>
</tr>
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</table>

Curve Plotted For T=70°
T=70° P=29.921 in Hg.

Fig. 126: Velocity Entering Test Section (Ft./Sec.)
is shown in Figure 127. A comparison between the velocity profiles, in Figures 125 and 127 show the similarity in the shape of the profile and the difference in their magnitudes.

The main concern about the flow in the wind tunnel test section is that it be relatively smooth (i.e., laminar) with little angularity, and have a flat profile extending over most of the region where measurements are to be made. The results of the wind tunnel calibration indicates these requirements are satisfied by the present low-turbulence, subsonic wind tunnel.

A.1.2 Airfoils

Two sets of differential airfoils were used to generate the trailing vortex in the wind tunnel. A differential airfoil (26) is actually two airfoils with the same shape, thickness, and chord length. The span of each airfoil is half the test section width. The airfoils are mounted tip to tip, one airfoil being mounted at an angle of attack equal and opposite to that of the other. The advantage of using a differential airfoil is that a stable single vortex is produced, whose position in the wind tunnel remains almost completely independent of velocity, angle of attack and distance downstream.

One set of airfoils has flat tips and the other rounded tips, Figures 128 and 129. The airfoils were supported in the test section by a 1/2 inch diameter steel rod which spans the airfoils at their
Comparison of Pitot-Static and Hot-Wire Data

No. Airfoils $T = 72^\circ F$ $P = 29.20$ IN HG

Distance from Test Section Inlet - 5 Ft.

Equipment in Test Section
1. Inlet Bell
2. X-Y Positioning Device
3. Diffuser

Date 2/7/70

$\Delta P_s - P_T \sim$ IN of H$_2$O

Velocity $\sim$ FPS

FIGURE 127
Fig. 128: Differential Airfoil - Rounded Tips 0012 Shape

Fig. 129: Differential Airfoil - Angle of Attack Indicator
quarter-chord position and extends 1 inch through both tunnel walls. The steel rod slides into an aluminum tube fixed to the airfoils. The angle of attack can be varied by rotating the airfoils about the steel support rod. The ends of the aluminum tube, nearest the wind tunnel walls, have been notched to receive the inserts extending from the angle of attack indicators.

Two angle of attack indicators, Figure 130, are attached to the position of the support rod which projects through the wind tunnel walls. Each indicator consists of a steel cylindrical sleeve to which is attached a steel pointer and steel handle. At one end of the cylindrical sleeve are two inserts which fit into notches in the aluminum tube of the airfoils. The other end of the sleeve has a cylindrical boss to which the pointer and handle are attached. The angle of attack indicators are slid on the support rod until the cylindrical boss is pressed against the wind tunnel. This ensures that the inserts are properly located in the notches of the support rod. Protractors are mounted on each tunnel wall beneath the pointers, Figures 130 and 131. The angle of attack of the airfoils can be varied while the wind tunnel is operating by movement of the indicator handle. The variation in the angle of attack is obtained by noting the initial and final location of the pointer with respect to the angular graduations on the protractor.

The airfoils are made of bass wood which is used for the trailing edge and birch wood which is used for the leading edge. The pieces
Fig. 130: Angle of Attack Indicators Mounted On The Wind Tunnel

Fig. 131: Angle of Attack Indicators Showing 0012 Differential Airfoil in Test Section
are glued together, and the surfaces sanded smoothly to conform to the G012 airfoil shape. The airfoils are painted with a non-pigmented varnish to improve the di-electric properties of the wood.

The airfoils are positioned at the midpoint between the top and bottom of the wind tunnel test section and 35 inches aft of the entrance to the test section inlet.

A.2 Particle Feed System

To inject particles into the wind tunnel flow, it was necessary to design and construct a particle feed system. The feed system has to be capable of feeding the particles into the wind tunnel flow field without disturbing the flow, yielding a homogeneous mixture of particles and air. Provision for monitoring the feed rate of the particles also had to be included in the design of the feed system, since no other means of sampling the seeded flow, as it travels through the wind tunnel, was available.

Several techniques for seeding the wind tunnel flow with particles were considered; among them were gravity drop inside the tunnel inlet and also outside the inlet screen, use of an impeller, and peripheral jets. The gravity-drop technique was rejected because, for a mixture of particles, the heavier particles under the influence of gravity would tend to fall lower in the tunnel than the lighter particles. Also for the size range of particles used, if dropped from the top of the tunnel, the calculated trajectories of the
particles indicated few drop below the wind tunnel center line as they travel through the test section. Use of an impeller was rejected because of the disturbance that the impeller would cause in the flow field and because of the uncertainty in the mixing of the particles and the tunnel flow. Peripheral jets were also rejected due to uncertainty in the mixing process and the amount of plumbing and control valves required to put such a system in operation. The system used to inject the particles into the tunnel flow consists of a spring suspended hopper, a venturi to draw the particles into the system, and a nozzle which directs the mixture of air and particles onto the inlet screen of the wind tunnel, Figures 132, 133.

The hopper, Figure 132, is an inverted pyramid 18 inches high, 25 1/2 inches square at the top, and converging to a 1-inch square at the bottom. It is made from sheet metal with welded seams and can hold 50 lbs. of particles. The hopper is suspended at its four corners by rods; each one is attached to a spring. The bottom of each spring rests on a metal disc attached to the metal framework of the hopper assembly. The hopper is covered with 18-mesh screen to filter out larger particles when the particles are dumped into the hopper. The particles leave the hopper through a 1-inch square tube that is 2 inches long, then through a 1-inch square to round transitional piece, 1 1/2 inches long, and then through a 3/8 inch diameter tube, 4 inches long. The end of the one-inch tube moves freely inside a 1 1/4 inch diameter sleeve leading to the throat of the venturi.
Fig. 132: Hopper And Venturi

Fig. 133: Feed System Nozzle
The mass of particles leaving the hopper is regulated by a sliding mechanism located in the one-inch square tube, Figure 134. This mechanism consists of two thin plates, one sliding over the top of the other. One plate is fixed to the inside of the one-inch tube and the other is free to move through a slot in the wall of the tube. The fixed plate spans slightly more than half the width of the tube and has a v-shaped notch in its end. The moveable plate also has a v-shaped notch in it so that, as the top plate is withdrawn from the tube, a diamond-shaped opening appears in the center of the one-inch square tube. This mechanism is shown in Figure 136.

The maximum flow rate depends on the particles used to seed the flow. The rate at which the particles leave the hopper is indicated by a pointer; one end is fastened to the hopper, and the other free to sweep across a graduated plate attached to the metal framework of the hopper assembly. The pointer is held by a pivot located near the hopper so a slight variation in the vertical position of the hopper is greatly amplified at the end of the pointer which sweeps across the graduated plate. The plate is graduated in increments of one pound.

The particle-flow rate is the total weight of particles at the start of a test, divided by the time required for the hopper to empty.

The particles are drawn from the hopper through a tube connected to the throat of a venturi, Figure 134. The inlet, throat, and exit diameters of the venturi are 1.25, 0.444, and 1.25 inches respectively.
Fig. 134: Hopper Flow Control and Flow Rate Indicator

Fig. 135: Hopper Assembly and Air Supply Control Valves
Fig. 136: Particle Flow Valve
A vacuum gage is also connected at the throat of the venturi. The air flow control values, Figure 135, of the feed system are adjusted until the vacuum gage reading is maximum. A detailed drawing of the venturi is shown in Figure 137.

The mixture of particles and air from the venturi pass through a 1 1/2 inch rubber hose to a Y, and through two one-inch diameter hoses into the mixing chamber back of the nozzle. Unseeded air is also fed to the mixing chamber through another 1 1/2 inch rubber hose to a Y, and through two one-inch diameter pipes into the chamber. A third air supply line, that is a 3/4 inch rubber hose, supplies air to a sting passing down the axis of the nozzle, Figure 133.

The nozzle and mixing chamber are one unit, 5 9/16 inches long, Figure 138. The nozzle was machined from a 3-inch diameter piece of aluminum bar. The curvature of the diffusing section, as drawn in Figure 138, is only approximate, due to difficulties in machining a parabolic curve. The sting and cone assembly, which is inserted along the nozzle axis, is shown in Figure 139. The details of the nozzle design are given in Appendix A.3.

It should be mentioned that, prior to running tests with any of the three mentioned particulates, the feed system flow rate had to be calibrated. This was necessary in order to determine the setting of the particle flow valve corresponding to a particle mass flow of 1.67 lb./min. The settings for the PVC pellets were obtained with the
Both Ends Threaded For 1 1/4" Pipe Butted To Bottom Of Well

To Vacuum Gage

Fig. 137: Venturi For Particle Feed System Throat Diameter=0.444 in.
Fig. 138: Feed Nozzle ~ Full Scale
Fig. 139: Feed Nozzle Sting
feed system operating. The flow rate was checked during several test runs with PVC pellets and found to be 1.67 lb./min. To determine the setting of the particle flow valve for the sand, the feed system venturi was removed from the feed system. The particle flow valve was closed and the feed hopper filled with particles. Below the spout extending beneath the particle flow valve was positioned a container placed on a scale. The particle flow valve was then adjusted until the desired particle flow rate was attained (1.67 lb./min.).

During the actual test runs, there were occasions when the flow rate of particles from the feed nozzle would vary noticeably. This was due to periodic clogging and clearing in the throat of the venturi. This problem was avoided by carefully setting the airflow rate through the venturi and nozzle system. During two different runs, the mass flow rate of particles was 25 lb. and 17 lb. during the intervals of 15 min. and 10 min. respectively.

The flow rate of sand from the feed hopper appeared from visual observations to be greater, at times, than 1.67 lb/min. This cannot be stated as fact since, during the test runs with the sand samples, only one operator was present to record the electric field measurements, density distribution, and charge data. The feed system is located near the wind tunnel inlet which made recording of the mass flow rate during recording of the other experimental data impossible.
APPENDIX A.3

DESIGN OF PARTICLE-FEED NOZZLE

A.3.1 Background

The analysis of the particle-feed nozzle was performed using the theory and results of experimental data presented in Reference (3). In Reference (3), an approximate analysis of the mean velocity distribution within the diffusing jet plume of both two and three dimensional jets is presented along with experimental data covering a range of each independent variable, which justifies the analysis and yields the unknown constant for each case.

The assumptions used in the analysis of Reference (3) are:
1. The pressure is hydrostatically distributed throughout the flow.
2. The diffusion process is dynamically similar under all conditions.
3. The longitudinal component of velocity within the diffusion region varies according to the normal probability function at each cross section.

If the Reynolds Number for the fluid efflux from a submerged boundary outlet is not too low, the mean velocity at any point in the plume, Figure 140, should depend only on the coordinates x, y, and z on the efflux velocity $v_0$, and on a characteristic length $L_0$, of the outlet. Writing the variables in a dimensionless relationship,

$$\frac{V}{V_0} = f \left( \frac{x}{L_0}, \frac{y}{L_0}, \frac{z}{L_0} \right)$$  

(A.3.1)
Fig. 140: Schematic Representation of Jet Diffusion
The volume flux $Q$ past successive sections normal to the flow may be written as the integral of the differential flux $v_x dA$ over the area. Due to entrainment, $Q$ will vary with longitudinal distance $x$ from the outlet, thus
\[ \frac{Q}{Q_o} = \int_0^\infty \frac{v_x dA}{V_o A_o} = g\left(\frac{x}{L_o}\right) \quad (A.3.2) \]

Similarly, the ratio of momentum flux at any section to $M_o$ at the outlet is
\[ \frac{M}{M_o} = \int_0^\infty \frac{(v_x^2) dA}{V_o^2 A_o} = h\left(\frac{x}{L_o}\right) \quad (A.3.3) \]

and ratio of energy flux
\[ \frac{E}{E_o} = \int_0^\infty \frac{(v_x v_y) dA}{V_o^2 A_o} = j\left(\frac{x}{L_o}\right) \quad (A.3.4) \]

The velocities $V$, $V_o$, and $V_x$ are defined in the illustration of Figure 40.
The only force producing deceleration of the jet and the acceleration of the surrounding fluid is the tangential shear within the mixing region. Since this process is wholly internal, it follows that the momentum flux must be a constant for all sections normal to the flow.
\[ \frac{M}{M_o} = \int_0^\infty \frac{(v_x^2) dA}{V_o^2 A_o} = 1 \quad (A.3.5) \]

The analysis used in (3) indicates that the characteristics of the mean flow would be dynamically similar.
Therefore, the same velocity function must characterize every section within the diffusion region and experimental data follow the general trend of the Gaussian normal probability function.

\[ \frac{V}{V_{\text{max}}} = \left[ \exp\left(-\frac{r^2}{2\sigma^2}\right) \right] \]  
\hspace{1cm} (A.3.6)

Using this expression for the velocity distribution permits the characteristics of the entire flow pattern to be expressed in terms of two parameters; the vorticity at the centerline \( V_{\text{max}} \) and the standard or root-mean-square deviation \( \sigma \). Therefore, equation A.3.1 reduces to

\[ \frac{V_{\text{max}}}{V_0} = k \left( \frac{x}{L_0}, \frac{\sigma}{x} \right) \]  
\hspace{1cm} (A.3.7)

but the constancy of the momentum flux, together with the similarity of the velocity profiles at successive sections, suggest one form of the solution as shown in Reference (3) is

\[ \frac{\sigma}{x} = C \]  
\hspace{1cm} (A.3.8)

That is, the jet will spread at a linear rate defined by the constant \( C \).

Using equations A.3.5, A.3.6, and A.3.8, all characteristics of the mean flow pattern for any specific boundary condition can be determined analytically with the exception of one coefficient which is determined experimentally. The characteristics of flow in the zone of flow establishment and zone of established flow are first determined for a two-dimensional jet, and the results are modified to describe
the characteristics of jet flow from a circular orifice.

A.3.2 Zone of Flow Establishment

Consideration will be given first to flow from a two-dimensional slot. The distribution of the velocity \( V_x \), across the flow at any point with the zone of flow establishment, can be represented two symmetrical halves of the probability curve connected with a straight line through the constant-velocity core. Using the condition \( \sigma/X = C_1 \), the momentum-flux integral of equation A.3.5 gives

\[
\frac{X_\infty}{B_0} = \frac{1}{\sqrt{\pi}} \frac{C_1}{C}
\]  

(A.3.9)

where \( X_\infty \) is the distance from the slot to the end of the zone of establishment. The inner boundary between the core flow and the diffusion region can be expressed as

\[
\frac{B}{B_0} = \left( 1 - \frac{X}{X_\infty} \right)
\]

(A.3.10)

The velocity distribution for the diffusion region can now be expressed

\[
\frac{V_x}{V_0} = \exp \left[ -\left( \frac{\sqrt{\pi} C_1 X}{2} - \frac{B^2}{2} \right) \right]
\]

(A.3.11)

The volume flux ratio using equation A.3.11 for the velocity distribution in the diffusion region

\[
\frac{Q}{Q_0} = 1 + \sqrt{\pi} (\sqrt{2} - 1) C_1 \frac{X}{B_0}
\]

(A.3.12)
The rate of change in volume flux with longitudinal distance \( \frac{dQ}{dx} \) must equal twice the velocity of entrainment at a considerable distance \( y \) from the jet, then it follows

\[
\lim_{y \to \infty} \frac{v_y}{v_0} = -\frac{1}{2} \sqrt{\pi} \left( \sqrt{2} - 1 \right) C_l
\]  

(A.3.13)

Flow from a circular orifice is assumed to differ from that of a two-dimensional orifice only in the substitution of the orifice diameter \( D_0 \) for the slot width \( B_0 \) and the substitution of the radial distance \( r \) for the lateral distance \( y \) in the basic equations. With the assumption that \( \sigma / x = C_x \), the momentum relationship evaluated at \( x = x_0 \) yields

\[
\frac{X_o}{D_0} = \frac{1}{\varepsilon C_x}
\]  

(A.3.14)

The general solution of the momentum relationship yields a relationship which differs from the two-dimensional case in that the border of the diffusion region for three-dimensional flow is not a linear function of \( x \), but instead is represented by

\[
\frac{D}{D_0} = \sqrt{1 + \left( \pi - 4 \right) C_x^2 \left( \frac{x}{D_0} \right)^2} - \sqrt{\pi} C_x \frac{x}{D_0}
\]  

(A.3.15)

The difference between this curvilinear function and the approximation

\[
\frac{D}{D_0} = 1 - \frac{x}{X_o}
\]  

(A.3.16)
is assumed to be no greater than the error due to approximating
the actual velocity profile by the probability curve. Thus, the
velocity distribution within the region of diffusion is written as
\[
\frac{\nu_x}{\nu_o} = e^{\exp\left[\frac{-(r+C_2x-D_0/2)^2}{2(C_2x)^2}\right]} \tag{A.3.17}
\]
Using this velocity profile, the variation in the volume flux
ratio with distance from the orifice is then
\[
\frac{Q}{Q_o} = 1 + 2\left(\sqrt{2\pi} - 2\right)C_2 \frac{x}{D_o} + 4\left(3 - \sqrt{2\pi}\right)\left(\frac{C_2x}{D_o}\right)^2 \tag{A.3.18}
\]
From consideration of continuity, it can be seen that the radial
velocity \(v_x\) beyond the diffusion region will vary inversely with the
radial distance from the flow centerline and the product \(rv_x\) approaches
a finite limit such that
\[
\lim_{r \to \infty} \frac{\nu_x}{\nu_o} = \frac{-1}{4}\left(\sqrt{2\pi} - 2\right)C_2 - (3 - \sqrt{2\pi})C_2^2 \frac{x}{D_o} \tag{A.3.19}
\]

A.3.3 Zone of Established Flow

Beyond the zone of flow establishment, the ratio \(\sigma/\kappa\) will be
indicative of the rate of outward spread of the eddy region. For the
two-dimensional case, it is assumed that \(\sigma/\kappa = C_1\), the evaluation of the
flux relationship yields

\[
\frac{V_m}{V_o} = \sqrt{\frac{1}{\sqrt{\pi}} C_i} \frac{B_o}{x}
\]

\( (A.3.20) \)

where \( B_o/\sqrt{\pi} C_i x = x_o \) as determined for the zone of flow establishment.

The distribution of velocity in the zone of established flow is then

\[
\frac{V_x}{V_o} = \sqrt{\frac{1}{\sqrt{\pi}} C_i} \frac{B_o}{x} \left\{ e^{xP} \left[ -\frac{y^2}{2(C_i x)^2} \right] \right\}
\]

\( (A.3.21) \)

The equation for volume flux in the established zone is

\[
\frac{Q}{Q_o} = \sqrt{\frac{2}{\sqrt{\pi}} C_i} \frac{x}{B_o}
\]

\( (A.3.22) \)

and differentiation with respect to \( x \) yields the rate of entrainment, and the lateral velocity is a considerable distance from the jet

\[
\text{limit}_{y \to -\infty} \frac{V_x}{V} = -\sqrt{\frac{\sqrt{\pi}}{8} C_i} \frac{B_o}{x}
\]

\( (A.3.23) \)

Replacing \( y \) by \( r \) and \( B_o \) by \( D_o \), and integrating over corresponding areas, the expressions for the three dimensional case can be determined for the case \( \sigma/x = C_2 \). The momentum equation yields

\[
\frac{V_m}{V_o} = \frac{D_o}{2x C_2}
\]

\( (A.3.24) \)

where the distance \( D_o/2C_2 = x_o \) corresponds to the distance at the limit of the zone of flow establishment. The velocity distribution is then
\[
\frac{V^2}{V_o} = \frac{D_o}{2 \times C_z} \left[ e^{\exp\left\{ -\left( \frac{r^2}{2 \times C_z \times x^2} \right) \right\}} \right] \quad (A.3.25)
\]

the volume flux is

\[
\frac{Q}{Q_o} = 4 C_z \frac{x}{D_o} \quad (A.3.26)
\]

and

\[
\lim_{r \to \infty} \frac{V}{V_o D_o} = \frac{-C}{2} \quad (A.3.27)
\]

The results of the center-line velocity measurements in Reference (3), yielded a value of $C_2 = 0.081$ for flow from a three-dimensional jet.

A.3.4 Nozzle Dimensions

In the design of the nozzle, to be used with the particle-feed system, the following conditions had to be met:

1. The volume flow into the wind tunnel inlet should be 25,200 ft$^3$/min.
2. The inlet velocity should be 17 ft./sec., and
3. The plume should be at least 5.5 feet in diameter, five feet from the nozzle exit in order to cover 90% of the tunnel inlet.

To determine the volume flow rate into the tunnel inlet, the total amount of flow including entrainment in the jet plume must be determined. The desired tunnel flow is 420 ft$^3$/sec. in the test
section. The nozzle chamber pressure is 80 p.s.i. This provides a maximum exit velocity of 1,570 fps. From equation A.3.26, the required exit diameter for the nozzle is found to be 2.5 inches. To provide for some margin for error, the exit diameter of the nozzle was made 3 inches. The spread of a straight jet from a nozzle with an exit diameter of 3 inches such that the minimum axial velocity at the outside of the plume is 17 fps was found to be 2.5 ft. (at a distance 5 feet from the nozzle). Since a 5.5 foot spread was required, the nozzle had to have a diverging exit with a divergence angle of 19°.

An exit velocity of 1570 ft./sec. through 3 inch diameter exit provides a 77 ft.³/sec. volume flow through the nozzle. The throat is 1.7/16 inches in diameter and to provide the divergence angle of 19°, the diffuser section of the nozzle is 2 1/16 inches long.

The basic design of the nozzle completed, such that it would deliver the proper volume rate of air and particles to the wind tunnel; it was now necessary to alter the shape of the exhaust plume. The shape of the exhaust plume from the nozzle is long and narrow with the maximum velocity along the centerline of the plume. The velocity on the nozzle flow centerline at the wind tunnel inlet is 480 fps. In order for the nozzle flow not to have an effect on the wind tunnel flow is necessary to reduce the centerline velocity and widen the plume. To do this, a 7/16 inch diameter hollow metal sting was placed down the center of the nozzle, extending slightly past the nozzle exit plane. Attached to this sting is a cone 1.375 inches high with a base diameter
of 1.5 inches. The boss on the base of the cone has 8 jets, located circumferentially through which air, passing down the hollow sting, is directed normal to the exhaust plume from the nozzle. By properly positioning the cone in relation to the nozzle exit, the plume velocity profiles can be altered so as not to influence the wind tunnel inlet flow.

A.4 X-Y Positioner

The x-y positioner, Figure 141, is a device which is designed to accurately position the vortex and electrostatic probes within the tunnel flow field. This device locates the probes in a plane normal to the axis of the wind tunnel.

The entire positioning device is enclosed within a rectangular aluminum frame. This frame's outside dimensions are 1 1/2 feet by 3 inches outside and has rounded corners in order to provide a close fit with the tunnel's corner fillet, Figure 142. The device can be moved up or down the test section to obtain data at various locations aft of the airfoils. At each corner of the positioning device there is mounted an aluminum block which acts as support for two lead screws. These blocks are fitted with set screws and ball bearings upon which the lead screws ride and provide a solid base for smooth operation of the positioner.

The lead screws are 1/2 inch stainless steel rod and function as the driving mechanism for two cross rods. The lead screws have 13 threads per inch and allow the probes to move within 4 inches of each wall. These screws are capped on the end and ride on ball bearings,
Fig. 141: X-Y Positioner

Fig. 142: X-Y Positioner in Wind Tunnel Test Section
mounted within the corner blocks. The cross rods pass through a rectangular block made of aluminum which is the base upon which the probes are mounted, Figure 143. The rods, passing through this block, one slightly behind the other and perpendicular to it, are precision fit and prevent any vibration or play of the hub upon the cross rods allowing for positive probe placement. The aluminum block is square with rounded corners and a tapered, conical nose, Figure 143. It is 3 inches long overall, and has a 1-inch deep hole drilled into the nose center capable of receiving a 3/8 inch probe sting. A set screw assures a solid and sturdy mount. To the back of the block is attached a hollow elliptical shaped aft-body made of aluminum. The aft-body screws onto the back of the aluminum probe support block. This fixture was added to provide a storage area for the electrical connectors. A streamline shape was used to reduce wake turbulence from the probe.

The motors, used to drive the lead screws, are one amp, 26.5 volt servomotors. These motors operate at 840 rpm, but a 14 to 1 gear reduction reduces the output rpm to 60. One motor drives the horizontal lead screws, and the second motor drives the vertical lead screws. Each lead screw is equipped with a 12-tooth sprocket as is the shaft of the motor. Each power train consists of a 1/4-inch roller chain connecting the motor, two lead screws and a cam activated counter system which will be discussed later. The controls and dc power supply for the motors is located outside the tunnel on the control panel and is connected by an eight-conductor cable to a connector fixed to the positioner.
Fig. 143: X-Y Positioner (Showing Probe Support Block In Center).
Each counting system consists of a one-to-one right angle drive. The output shaft has a tear-drop cam mounted upon it. The shaft turns at the same rpm (60) as the lead screw. At each revolution, the cam comes in contact with a micro switch which sends an electrical pulse to an electric counter. Each electric counter is capable of addition and subtraction. Thus, the counter registers one count per revolution of the lead screws. Since every revolution moves the probe one thread along the cross rods, each count corresponds to a movement of 1/13, 13 threads per inch, or 0.077 inch. The counters are also located outside the tunnel near the motor controls on the control panel. The wiring for these counters is contained within the same cable as the motor wiring. There are separate counters for the horizontal and vertical directions.

A.4.1 Inlet Bell-Aft Diffuser

Due to the large pressure drop, associated with the positioning device, it was decided to decrease the aerodynamic loses associated with the device. To do this, it was necessary to shield from the flow stream the frame, motors, chains, and lead screws which were causing excessive turbulence and the resulting high pressure loses.

The system constructed to do this consists of an inlet bell and an aft diffuser. The two pieces fit for and aft of the x-y positioner forming a converging-diverging nozzle; the positioning device is located at the throat, Figure 144. As indicated in the discussion of the velocity profiles, obtained at the centerline of the exit of
These additions extended the run of the inlet bell to the back cross bar of the positioning device.

The inlet bell was painted with a non-pigmented varnish to improve its dielectric properties. The outside was sanded, where required, to assure that the inlet bell could be moved freely up and down the length of the wind tunnel test section.

The aft-diffuser is rectangular fore and aft. Its flow area increases from 1.7 sq. ft. at its throat to 3.0 sq. ft. at exit. It is 37 inches long with a mean angle of 4.0 degrees. The diffuser is constructed of 1/4 inch plywood coated with non-pigmented varnish to improve its dielectric properties. The throat is made from sheet metal formed to assure clearance over the motor mounts and drive chains of the positioning device. The corners of the diffuser have been rounded to conform with the inside of the wind tunnel. The diffuser can be moved up or down the entire length of the test section.

A.5 Vortex Probe Calibration Device

To calibrate the vorticity probes, a device has been designed and constructed capable of calibrating both vorticity probes throughout an angular speed range varying from 0 to 30,000 rps. The calibration device, Figure 147, magnetic pickup for a digital counter, a cylindrical canister, telemetry system (Section 3.5), air bearing, support bearings, and the vortex probe as discussed in Section 3.2. During preliminary tests, the system achieved a rotational speed of 13980 rpm.
Fig. 146: Inlet Bell and Positioning Device Installed In The Wind Tunnel Test Section
the aft diffuser, Figure 124, the flow is still highly turbulent. The inlet bell and aft-diffuser did provide for 1.0 inch of static pressure which corresponds to an increase in the test section velocity of 10 fps.

Several months of testing were carried out attempting to increase the test section velocity to 150 fps. The flow velocity in the test section core was measured with a hot wire anemometer and found to be 169 fps. The difference in the velocity readings, obtained from the static pressure taps (along the wind tunnel section floor), and the hot wire anemometer are probably due to the large turbulent boundary layer entering the wind tunnel test section.

The inlet bell, Figure 145, is made of wood. The outside dimensions of the bell are 2.0 feet by 1.5 feet by 6.0 inches. The four outside corners have been rounded to provide a close fit with the fillets of the wind tunnel, Figure 146. The inside of the bell has a parabolic contour with a major axis of 6.0 inches and minor axis of 2.4 inches on the top and one side, and 2.6 inches on the bottom and opposite side. The variation in the thickness is necessary to avoid interference between the inlet bell and chain drive of the positioning device.

To keep the slot (provided for the passage of the cross bars of the positioning device) between the inlet bell and aft diffuser to a minimum, two 0.25-inch thick by 1.0-inch wide pieces of wood were attached to the back edges of the top and bottom of the inlet bell.
Fig. 144: Aft-Diffuser, X-Y Positioner, and Inlet Bell Prior to Installation In The Tunnel

Fig. 145: Inlet Bell Positioned In Test-Section
Fig. 147: Calibration Device
The base plate, Figure 147-A is steel, 0.6 inch thick, 6 inches wide and 26.5 inches long. The motor mounts, support bearing mounts, air bearing mount, and magnetic pickup are bolted to the base plate. After being assembled on the base plate, the entire calibration system is moveable for easy installation in the wind tunnel test section.

The variable speed universal motor, Figure 147-B, is a 110 volt 0.4 amps (0.5 H.P.), d.c. motor. It is capable of 35,000 rpm at which point the electric pickup brushes start to fail. The output shaft of the motor is 0.375 inch in diameter and 2.0 inches long and delivers 19-in. oz. of torque. The speed of the motor is regulated by a variac.

The rotational velocity of the calibration device is monitored by a magnetic-head pickup which is mounted next to the connecting sleeve, Figure 147-D, running between the motor and the canister. The magnetic pickup senses each passage of a set screw located on the shaft. Each impulse, sensed by the pickup, is sent to a Beckman EPUT digital counter and displayed once each counting cycle, which is normally once each second.

The output shaft of the motor fits into a connecting sleeve 0.65 inch in diameter. A stepped shaft, sized to fit into the other end of the connecting sleeve, passes through the bore of the support bearing, fits into the back hub of the canister, and is held in place with a set screw. The set screw also activates the digital counter monitoring the rpm of the device.
The aluminum canister, Figure 148, is 6.25 inches long and 2.2 inches in diameter. The canister has a well bored into each end; one is to hold the FM transmitter and the other is to hold the battery. The well for the radio is 1.74 inches in diameter and 2.60 inches deep. This well is deep enough to insure clearance between the terminals on the top of the radio and the hub into which the canister threads. The well for the battery is 1.80 inches in diameter and 3.10 inches deep. At the base of this well is a second well, 1.60 inches in diameter and 0.25 inches deep. The part of the canister between the two wells has a 1.0 inch diameter bore. The well, provided for the battery, has two 0.05-inch grooves, spaced 0.5 inches apart, running axially down the length of the deeper well. These slots provide clearance between the battery and canister wall for the transmitter antenna lead and battery lead. The second well provides space for the battery leads which gather when the battery is inserted into the battery well. The extra length of lead is necessary because they must be soldered to the battery terminals when the battery is outside the canister.

Both ends of the canister have been threaded, and the canister threads into a hub at one end; and (depending on the type of vortex probe in use) is threaded either into a hub or into the journal of the air bearing at the other. The back hub, Figure 147-E, is designed so that, when screwed tightly onto the battery end of the canister, it presses slightly against the battery and prevents lateral movement of
Fig. 148: Aluminum Canister
the battery when the canister is rotated. When the four-vane non-rotating vortex meter is being calibrated, the canister threads into a similar hub at the other end, Figure 149. The shaft of the four-vane probe passes through a 0.375-inch hole on the centerline of this hub.

The air-bearing, Figure 150, is used in the calibration device when the air-bearing vortex probe is being calibrated. Its function is similar to that of a pneumatic-slip-ring.

Due to the high rotational speeds encountered during calibration of the vortex probes, the use of conventional pneumatic-slip-rings was ruled out. The failure rate of pneumatic-slip-rings was expected to be high, and it was questionable if an entire calibration test could be completed during the life expectancy of the pneumatic slip-rings.

The air bearing consists of a brass outer race and a inner aluminum journal. The brass outer race is held stationary by the air-bearing support. A 0.250-inch hole in the brass air-bearing race mates with a similar threaded hole in the aluminum support. The air-supply port threads into the hole, Figure 150-151, in the aluminum support. The inside of the brass outer race has circumferencial grooves milled in it. The largest, 0.375 inches wide, is located at the midpoint of the brass outer race and intersects the 0.250-inch air inlet port and flows around the inner aluminum journal through the large 0.375-inch groove. Six 0.10 inch wide by 0.10 inch deep grooves evenly spaced, three to each side of the larger groove, impede the passage of air as it flows out of the central groove.
Four Vane Probe Calibration Device

Fig. 149: Four Vane Probe Calibration Device
Fig. 150: Air Bearing

<table>
<thead>
<tr>
<th>ITEM</th>
<th>NAME</th>
<th>MAT'L</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Air Inlet Port</td>
<td>Brass</td>
</tr>
<tr>
<td>2</td>
<td>Bearing Support</td>
<td>ML</td>
</tr>
<tr>
<td>3</td>
<td>Pneumatic Bearing</td>
<td>Brass</td>
</tr>
<tr>
<td>4</td>
<td>Journal</td>
<td>ML</td>
</tr>
<tr>
<td>5</td>
<td>Sleeve</td>
<td>H1</td>
</tr>
</tbody>
</table>
Fig. 15.1: Air Bearing Probe Calibration Device
axially along the outside of the aluminum journal. The inside diameter of the brass inner race is 2.454 inches, which provides 0.002-inch clearance between itself and the aluminum journal. To improve the operation of the air bearing, two aluminum sleeves were placed over each end of the aluminum journal. Both sleeves have four circular grooves, 0.06 inch wide by 0.10 inch deep and spaced 0.06 inches apart radially. The sleeves were held in place on the inner aluminum journal by set screws. Pieces of 0.002-inch shimstock were inserted between the sleeve and the facing of the brass outer race to insure uniform clearance between the sleeve and outer race.

The support bearings and their arrangement on the base plate for each vortex probe are shown in Figures 149 and 151. Both probes are supported on precision roller bearings. The calibration canister rides in a large roller bearing. Its purpose is to restrain the canister in the event of failure of any of the support bearings when the calibration is rotating at high rotational speeds. The support bearings, numbers 1 and 2, slip onto each probe from the ends and constrain the lateral movement of the system.

The vortex probes have been discussed, and details regarding their design and fabrication were discussed in Section 3.2.

Photographs of the vortex probe calibration device and the unassembled air bearing are shown in Figures 152 and 153. Figure 153 shows the grooves in the brass air bearing and an aluminum sleeve which reduces the amount of air leakage from the calibration device.
Fig. 152: Vortex Probe Calibration Device

Fig. 153: Air Bearing From Vortex Probe Calibration Device
A.6 Telemetry System

To monitor the amount of vorticity sensed by the sensors of each vortex probe during calibration of the probes, it is necessary to conduct the signal from the rotating calibration device located inside the wind tunnel to a stationary indicator outside the wind tunnel. The usual technique used to do this has been to employ slip-rings which are operable at moderate rotational speeds, 0-5,000 rpm. The common problems with slip rings are electrical (slip-ring) noise and wear. Slip-ring noise is due to the vibration of the slip-ring brushes against the slip-ring races. Wear is caused by the constant abrasion of the brushes against the slip-ring races. Both problems increase as the rotational speed increases, though not in any predictable way. To circumvent these difficulties, a new system has been employed to replace the slip-ring assembly. The electric signal from the sensor of the vortex probe is sent through leads from the sensor to a telemetering system which transmits the signal to a receiver outside the wind tunnel. The telemetry system consists of an F.M. radio transmitter, a 12-volt rechargeable battery and an F.M. radio receiver.

A.6.1 F.M. Transmitter

The F.M. radio transmitter, Figure 154, was purchased from the Accurate Instruments Corporation. It has an all transistorized F.M. sub-carrier oscillator and F.M. radio carrier oscillator. The sub-carrier oscillator, an F.M. phase shift type, provides excitation to
Fig. 154: Telemetry Transmitter and Battery

Fig. 155: Telemetry System - Transmitter Receiver
Digital Counter and Oscilloscope
the strain gage bridge. The impedance of the bridge controls the frequency of the sub-carrier oscillator. The output of the sub-carrier modulates the frequency of the radio carrier. Thus, the impedance of a bridge-type sensor is broadcast in form of an audio frequency. Variations in pitch and frequency of the subcarrier oscillator are linearly proportional to variations in bridge impedance.

The electronic components, making up the transmitter, are encapsulated in plastic formed into a cylinder. Terminals, extending through the top of the plastic cylinder, provide the electrical connections for the leads from the strain gage bridge, power supply, and for the external antenna connections.

There are two means for coarse adjustments of signal frequency accessible at the top of the transmitter. One is a large tuning slug which positions the broadcast signal within the 88–108MC range of the receiver. The second is a 20-turn potentiometer used for center band-tuning. Fine tuning is done with the tuning knob of the receiver. The use of each of these adjustments will be discussed in the context of obtaining the transmitted signal from the transmitter with the receiver.

A.6.2 Power Supply

The power supply, Figure 155, used when calibrating the probes and during data acquisition, was a 12-volt nickel cadmium rechargeable battery (Burgess CD-29). Purchased from the Burgess Battery Division
the Clevite Corporation, this battery is capable of 450 milliamperic hours. The drain on the battery is 15 ma (10 ma in the sub-carrier oscillator and 5 ma in the radio carrier). The power requirements for the transmitter range from 12 volts to 9.6 volts; hence, the battery is capable of providing 10 hours of continuous service between recharging.

During initial data acquisition, a standard plug in variable d.c. power supply was used. This power supply created noise in the transmitted signal from the sensor; and much of the time, the transmitted signal was accompanied by the broadcasted signal from the university F.M. station. Two rechargeable batteries were available at all times; hence, the plug-in power supply was not used.

A.6.3 F.M. Receiver

The F.M. receiver, Figure 155, is an F.M. radio whose output is linearly proportional to the original signal generated by the sensor. Other connectors permit the use of head phones and/or an oscilloscope for monitoring the transmitted signal from the sensor.

The signal from the radio transmitter is received by a receiving antenna attached to the F.M. receiver. The F.M. receiver demodulates the radio carrier, yielding the audio frequency of the sub-carrier oscillator. This frequency represents the impedance of the sensor and is converted to an equivalent d.c. voltage.

The use of head phones, for monitoring the output, is primarily during the initial capture of the transmitted signal. When the tuner
is receiving the transmitted signal, one might hear a high-pitched sound or a relatively quiet spot. Once this spot has been located on the tuner dial, the output is then fed into an oscilloscope for further adjustment.

The transmitted signal appears as a chopped sine wave when displayed on an oscilloscope.

Adjustment of the potentiometer, located on the transmitter, and the tuning dial of the receiver is made until the amplitude of the signal, displayed on the scope, is maximum (20V P-P). With the signal displayed on the oscilloscope, the sensor is stressed and the variation is the frequency observed to insure that the sensor is functioning properly. When the signal displayed on the oscilloscope is satisfactory, the output from the F.M. receiver is then fed into an EPUT counter which displays the instantaneous magnitude of the signal frequency for recording purposes.

A:6.4 Initial Signal Reception

To capture the transmitted signal once the sensor and battery leads have been connected to the appropriate terminals on the transmitter, it may be necessary to adjust the tuning slug and potentiometer of the transmitter. Headphones are plugged into the receiver; and while listening to the receiver, the 88-108MC band is traversed by means of the tuning knob on the receiver. It is quite probable what will be heard is commercial broadcasts and interchannel noise. The 88-108C band is traversed until either a high-pitched sound or an
absolute quiet is received. When neither the high-pitched sound or a quiet spot can be found, the receiving antenna is moved closer to the transmitter antenna. If still one is unsuccessful in receiving either the high-pitched sound or the quiet spot, adjust the tuning slug slightly and traverse the 88-108MC band again. This procedure is repeated until the high-pitched sound or quiet spot is located. The receiving antenna is now removed to its original position. If the signal should disappear, slight returning with the tuning knob on the receiver should bring the desired signal back. If the signal from the transmitter occurs at the same frequency as a commercial broadcast, the tuning slug should be readjusted until the transmitted signal occurs at a frequency not occupied by a commercial broadcast. The output of the receiver is now plugged into an oscilloscope, and the signal from the transmitter displayed. The signal is adjusted using the tuning knob of the receiver until the amplitude of the displayed signal is maximum (20mV). The AFC of the receiver is switched on by means of a switch located on the front of the receiver. The output of the receiver is now plugged into an EPUT counter. The frequency of the transmitted signal is displayed at the end of each counting interval. The no-load, (zero stress), frequency should be 10,000 Hz. If the frequency of the displayed signal is other than 10,000 Hz, the transmitter potentiometer is adjusted until this value of the transmitted frequency is achieved. The telemetry system is now tuned to transmit and receive data from the sensor.
A.7 Vortex Probe Calibration Procedure

This section describes the assembly of the calibration device, the hookup and operation of the electronic equipment, and other details associated with the operation of the calibration device. The sensor is first checked to insure that it has electrical continuity and proper resistance levels in each arm of the wheatstone bridge. The sensor is inserted into a slit in the large center boss of the sensor mount. A tapered set pin holds the sensing element to the sensor mount. This sensor assembly is now placed into the calibration device using a special cylindrical sleeve. The sleeve passes over the sensor and presses onto a cylindrical boss at the base of the sensor mount. This permits handling of the sensor assembly without danger of damaging the sensing element. The sensor assembly is inserted into a well in the aluminum journal of the air bearing. The lead wires from the sensor are passed through two holes located diametrically opposite each other at the base of the well. Two set pins, extending into the well from its base, mate with two holes drilled into the base of the sensor mount. The sensor assembly is pressed against the two set pins and rotated slowly until it drops onto the two set pins. This assures that the sensor assembly does not rotate and shear off the sensor leads when the probe body is screwed into place.

The probe body with the shaft and sensing vanes in place is now installed. To be positive that there is no grit or dust on the shaft and airbearings, a cleansing with Acetone prior to inserting the shaft into the body is recommended. The probe body is pushed through the
bore of the front support bearing to within approximately one inch of the well containing the sensor assembly. The probe shaft is slowly moved relative to the probe body until the sensing element slides into a slit in the end of the shaft. A tapered set pin holds the shaft and sensing element together. The probe body is slipped into the well to permit the threads of the probe body to engage those of the well. The probe body is screwed into the well for the remaining distance. To insure that the probe body is screwed into the well properly, an indicator mark has been scribed into the probe body. If the scribed mark does not become flush with the face of the aluminum hub when the probe is screwed into place, this indicates that the brass mounting disc is not properly seated on the set pins in the well. The probe body is removed and the sensor mount repositioned on the pins. The probe body is once again screwed into the well.

The leads from the sensor pass through two holes along the centerbine of the aluminum journal and extend into the well bored to receive the aluminum canister. The leads are soldered to the terminals of the F.M. transmitter. During soldering of the leads, the radio is supported so it rests partially within the canister well. In this way, the leads from the sensor to the transmitter can be kept short eliminating electronic difficulties due to excessive capacitance in the sensing system. Short leads also eliminate signal noise caused when the leads from the sensor become pressed against the terminals of the transmitter. Two leads, each about a foot long, are soldered onto the two power supply terminals of the transmitter.
(marking on the transmitter eliminate any possibility of confusion) and a third lead, somewhat longer in length, is soldered onto the antenna terminal.

The aluminum canister is slid forward in the bore of the large roller bearing. The power leads and antenna lead are drawn through the canister and the transmitter placed into the canister. Clearance for these leads are provided by two 0.1 inch-square slots running axially along the outer surface of the transmitter. The bore of the canister is several thousandths larger than the outside diameter of the transmitter. This permits the canister to be rotated relative to the transmitter. A right-hand threaded 3/8 inch diameter rod is inserted into the canister and screwed into the base of the transmitter. The transmitter has a threaded hole on its axis for this purpose. The rod is screwed into the transmitter until it's sufficiently tight to hold the transmitter stationary as the canister is rotated. The canister is screwed into the well in the aluminum journal while the transmitter is held motionless. The rod is withdrawn from the transmitter by pulling the transmitter firmly against the inner step of the canister (using the rod) and slowly unthreading the rod.

The antenna wire is drawn through a hole in the wall of the canister and wrapped several times about a plastic disc which has been pressed onto the canister. The hole in the canister wall is drilled oversized, refilled with epoxy; thus, only a small opening in the center of the epoxy is left for the wire. The plastic disc is
pressed over the hole in the canister wall and has a hole drilled in
it which mates with the hole in the canister. The disc is grooved
to receive several turns of antenna wire.

The power leads are cut to proper lengths, soldered to the
battery terminal and the battery is placed into the canister. Either
the positive or negative lead can be soldered to its corresponding
battery terminal first (i.e., positive lead to positive terminal),
and the battery pressed into the canister. The remaining lead is
cut so it just reaches the other terminal of the battery. The longer
lead passes between the battery and the canister wall where a notch
is provided.

The back hub of the calibration device is now threaded onto the
canister. The variable speed motor and the magnetic pickup are
bolted to the base plate on the calibration system. The bearing
assemblies supporting the probe, canister, variable speed motor, and
air bearing must be carefully bolted down to the base plate to
prevent binding in the bearings. The motor mount should be bolted
down first and then proceeding along the calibration device, the back
bearing mount, the large roller bearing mount, and air bearing mount,
and the probe bearing mount are bolted down respectively. The cali-
bration assembly is rotated by hand to see if any of the bearings
bind while the system is rotating. The large air bearing is
thoroughly checked to assure that it's running free and that the air
passage between the inner aluminum journal and the outer bronze sleeve
are free of dust and grit. The air supply is then connected to the air
inlet port of the air bearing.

Occasionally, it may be necessary to wipe the outer surface of the aluminum journal and the inner ridges of the bronze sleeve with a fine-grit emery cloth; this procedure was required to smooth both surfaces after they were damaged due to galling. Frequent cleansing with acetone also keeps the air bearing free of dust and grit. The final step in assembling the calibration device is to "size" the antenna. The F.M. receiver is turned on and turned to the frequency at which the F.M. transmitter transmits without an antenna. For the particular transmitter used, this frequency was about 106 Mega cycles. The length of the antenna on the calibration canister is then cut, several inches at a time; and the tuner adjusted slightly about 106 Mega cycles to see if the signal from the transmitter is being received. The output from the receiver is displayed visually on an oscilloscope. The proper signal when it appears is a 10 Hertz sine wave with the amplitude slightly chopped. The signal may be slightly distorted and further tuning of the receiver above or below 106 Mega cycles may be required. Once the signal has been received and the final tuning completed, the output from the receiver is fed to a digital counter. The digital counter displays the frequency of the transmitted F.M. signal per counting time interval (usually 10 seconds). When the sensor is stressed, the frequency of the signal changes in proportion to the stress and is displayed on the digital counter.
The calibration device is now installed in the wind tunnel. The base plate of the calibration device is supported at a height such that the vortex probe is located at the center line of the tunnel. The magnetic pickup is checked to assure its working properly. The pickup point is setscrew on the shaft leading from the variable speed motor to the canister. By rotating the calibration canister by hand, clearance between the magnetic pickup and setscrew can be checked. The coaxial lead from the magnetic pickup is connected to a digital counter. Each passage of the set screw past the magnetic pickup causes one count to be displayed on the counter. The digital counter displays the R.P.M. of the calibration device per unit of counting time (usually 1 second). The leads from the motor are plugged into a 0-140 volt variac. Power is supplied to the motor from the variac, and the calibration device begins to rotate.

The calibration device was rotated over a range of rotational speeds from 0 to 12,000 R.P.M. This was done at tunnel flow velocities of zero and 140 ft./sec. The rotational speed was increased in increments of 20 to 30 rps and as each new value of rps was attained, the frequency reading was permitted to stabilize before being recorded. The time required for the transmitted signal to stabilize was less than 10 seconds. The fluctuation in the signal was due to the probe sensing the rotational acceleration of the calibration as it was varied from one rps level to the next.

Several calibration runs were made due to mechanical and electrical difficulties with the calibration device. Each set of data was
plotted on graph paper giving curves of frequency versus rps. The zero frequency of the transmitter varied from run to run due to difference in tuning, drift in the radio, discharging of the batteries, and variation in antenna location. To reduce the data to a single curve, all recorded frequencies were referred to the zero frequency recorded prior to rotation of the probe. The resultant delta-frequency versus rps curves were in good agreement. The trend of the calibration curve follows a parabolic law. This verified a simple force analysis of the sensing vanes which indicates the torque produced on the vanes will vary as the rotational speed squared. The curve of delta-frequency versus rps is the calibration curve for the vortex probes. When used to measure vorticity in the flow, the probes are positioned at various locations in the stream; and the transmitted frequency at each location is recorded. A value of frequency obtained at a location in a non-rotational part of the flow is subtracted from all recorded frequency values. These values of frequency are then converted to rps using the calibration curve.

Two major difficulties were experienced while calibration of the vortex probe was carried out. The most annoying was electronic noise which distorted the transmitted signal so severely as to render the recorded values of frequency worthless. The second difficulty was the binding in the air bearing, caused by misalignment of the bearings, dust and grit between the aluminum journal and the bronze bearing, and improper operation of the calibration device.
Signal distortion, due to electronic noise, was encountered at the outset of calibration. It was, at first, believed to be due to faulty solder connections on the sensor and to the radio. Occasionally, faulty connections were the cause of the noise in the transmitted signal, but even when extreme care was exercised in making all soldered connections, the noise in the signal persisted. A wheatstone bridge was constructed using 120 ohm resistors in place of the sensor assembly. The resistors were soldered to the transmitter terminals to eliminate any effect the sensor leads had on the transmitted signal. During rotation of this system, the signal remained nearly noise free, indicating that a major source of noise was probably due to the capacitance effect of the sensor leads and the strain gage sensor assembly. As the calibration device is rotated, static charge builds up on the system. Due to the improved lubrication of the support ball bearings during rotation, the static charge does not leak off to the base plate instantaneously; but probably, it builds up and leaks off at random, depending on the contact between the ball bearings and the bearing race.

At one point during calibration of the vortex probe, it was thought that the noise in the signal was generated by the transmitter antenna due to contact with the walls of the aluminum canister. To eliminate this source of noise, a plastic canister was used. The transmitter no longer required an antenna since the signal passes unhindered through the plastic canister. When the calibration device (with the
plastic canister installed) was rotated, the noise level in the received signal had increased. The increased noise is believed to be due to electrostatic charge buildup on the plastic canister.

The aluminum canister was reinstalled in the calibration device and an electrical pickup brush installed and grounded to the base plate of the calibration device. The brush was positioned so it pressed against the back hub of the calibration device. The static charge which had built up on the canister, was bled off through the brush to the base plate of the calibration system. A substantial decrease in the noise level was obtained with the brush rubbing against the calibration canister. During one calibration run, the noise level was negligible up to 200 rps.

Mechanical difficulties with the large air bearing also hindered calibration of the vortex probe; however, these difficulties were eventually eliminated. The major mechanical problem was the galling of the large air bearing which caused intermittent siezing of the journal. The galling of the air bearing was caused by dust and grit that had been blown into the clearance between the aluminum journal and the bronze bearing. The source of the dust and grit was a short piece of copper tubing used to connect the air supply to the large air bearing. During the initial assembly of the calibration device, the copper tube was not properly cleaned; and when air was supplied to the air bearing, the dust and grit in the tube entered the bearing. The resulting galling of the aluminum journal and bronze bearing was so severe, smooth rotation of the calibration system could not be
achieved. Attempts were made at lubricating the journal and bearing, but lubrication never completely alleviated the binding in the bearing. The bronze bearing was finally replaced, and the aluminum journal reworked to eliminate the occurrence of binding in the air bearing.

A second cause of binding in the air bearing is improper alignment of the calibration canister and vortex probe in their respective support bearings. The aluminum journal is designed to rotate concentrically within the bronze bearing. If the bearing supports of the probe and canister are not bolted to the base plate properly, the journal becomes misaligned relative to the bronze bearing and results in binding of the air bearing when the system starts to rotate. The proper alignment is a matter of patience and experience.

Figures 152 and 153 show the calibration device assembled to receive the air-bearing vortex probe and the brass air bearing, aluminum journal, and aluminum guard ring.
APPENDIX B

ANALYSIS OF THE FLOW DISTURBANCE IN THE VICINITY OF THE VORTEX PROBE DUE TO FLOW OVER THE INLET BELL

The positioning device used to position the various probes in the wind tunnel test section created a severe pressure drop when first installed in the tunnel. The large pressure drop associated with the positioning device is due to the blunt shapes which make up the positioning device (e.g., bearing blocks, frame, lead screws). The flow over and around these blunt shapes results in large drag losses and separates the flow which reduces the efficiency of the fan.

To reduce the pressure drop associated with the positioning device, an inlet bell and aft diffuser were constructed which, when placed fore and aft of the positioning device, reduces the pressure drop and flow separation to acceptable levels. The inlet bell is of primary concern here as it extends six inches in front of the positioning device and into the flow field; 2.0 inches on one side and bottom and 2.6 inches on the opposite side and top. The shape of the bell is elliptical with a semi-major axis of 6.0 inches and semi-minor axis of 2.0 and 2.6 inches respectively. Since the probe extends only 10 inches in front of the positioning device, the streamlines of the flow over
the inlet bell were calculated to give the amount of flow angularity in the vicinity of the probe head.

The technique used to obtain the streamline plot is the standard relaxation technique. The flow field is divided into a number of grid points, the boundary values of the stream function are specified and the interior grid points are relaxed until the difference between the newly calculated value of the stream function, \( \psi_i^n \), and the old value of the stream function, \( \psi_i^{n-1} \), is less than some prescribed value.

For the sake of simplicity, the elliptical configuration was represented as straight-line sections. Plots of the streamlines of the flow over both the 2.0 inch section and the 2.6 inch section are given in Figures 156 and 157. The streamline plots indicate the flow angularity 7.0 inches from the midstream to be at most 55 minutes and 5.0 inches from midstream to be at most 35 minutes. This amount of angularity is considered negligible since the possibility of mounting the vanes on the probe shaft, so they make an angle with the free stream less than 35 minutes, is questionable; and secondly, the sensing device is wired so as to give a null reading when experiencing bending.
Fig. 156: Streamlines About Inlet Bell
Fig. 157: Streamlines About Inlet Bell

Inches From Tunnel Wall

Inches Upstream From Positioning Device
APPENDIX C

DETERMINATION OF STRESS LEVEL
IN VORTEX PROBE SENSING ELEMENT

The sensing element of the air bearing probe is a thin (0.002 inch), narrow piece of stainless steel shim stock one-inch long. To calibrate the probe, it is assembled into the calibration system which is capable of rotating the probe about its own axis over an angular speed range from 0 to 30,000 R.P.M. The maximum stress level in the sensing element has been determined to insure that the maximum allowable stress, (which is approximately 8,000 psi for steel), is not exceeded. Maintaining the stress level below this figure insures that the sensing element does not suffer permanent deformation. A simple verification of this design point is the ability of the probe to return to its zero reading after each traverse of the vortex center, where the torque is maximum.

The torque delivered by the shaft to the sensing element is the sum of the torques produced on the four vanes when the probe is placed in a rotating fluid. The torque on each vane is the product of the aerodynamic pressure acting at the center of pressure of the vane and the moment arm from the probe axis to the center of pressure of the vane.
The aerodynamic pressure on the probe vane results in a drag force acting on the vane which can be expressed as
\[
D = C_D \rho \frac{V^2}{2} (\text{VANE AREA})
\]

The local velocity near the probe vane is due to the angular rotation of the probe, therefore,
\[
D = C_D \rho \left( \frac{1}{2} r^2 \Omega^2 \right) (\text{VANE AREA})
\]

The drag coefficient for a flat plate normal to the flow with a width twice its height is 1.15

An elemental torque acting on a vane of length 1 is:
\[
d\tau = \frac{1}{2} \rho \Omega^2 \lambda r^3 dr
\]

Integrating from the axis of rotation to the tip of the vane \( r \), the torque on each vane is
\[
\tau = \frac{1}{8} \rho \Omega^2 \lambda r^4
\]

For a vane of 0.2 inch radius, 0.15 inch in length in air rotating at 30,000 R.P.M., the torque per vane is 2.68 \( (10^4) \) in-lb. Hence, the total aerodynamic torque transmitted to the sensing element is 1.072\( (10^3) \)in-lb. Torque of the same magnitude is assumed to be produced due to drag.

The maximum stress in the sensing element is Reference (62).

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"Fluid Mechanics" (Binder, pg.183)
\[ \tau_{\text{max}} = \frac{3 \beta}{\alpha^2 b} \]  

where \( \alpha \) is the thickness and \( b \) is the width of the sensing element, and \( T \) is the total torque on the element. For a sensing element, 0.002 inches thick and 0.25 inches wide, the maximum shear stress on the order of \( 10^3 \text{lb/in}^2 \). Therefore, even under the most severe of operating conditions for the vortex probe, the stress level in the sensing element is nearly an order of magnitude below the allowable stress level.
APPENDIX D

ELECTROSTATIC SENSING DEVICES

Prior to the development of the electric field mill which is discussed in Chapter 3, several other probes were fabricated and placed in the seeded flow to monitor the electric field. A brief description of these probes and some of the results obtained through their use are discussed in this section.

D.1 Langmuir Probe -- Model 610B Keithley Electrometer

A langmuir probe was inserted into the wind tunnel flow field to measure the electric field distribution set up by the swirling particles. The probe is the same as that used in the leaf electroscope tests; i.e., the center conductor of a co-axial cable.

In order to treat the seeded flow field as a plasma, it is necessary that the Debye Length be much smaller than characteristic flow dimension which for these tests, is the wind tunnel's width. The Debye Length, \( L_D \), can be expressed mathematically as:

\[
L_D = \sqrt{\frac{\varepsilon_o K T}{q^2 n}} \tag{D.1}
\]

where
- \( L_D \) = the Debye Length
- \( q \) = particle charge
- \( \varepsilon_o \) = the permittivity
- \( K \) = Boltzmann's constant
- \( n \) = particle density
- \( T \) = absolute temperature
The particle density is determined from the mass flow rate in the wind tunnel. The charge per particle was obtained from (10) published results where the particle diameter and flow velocity were similar to the present test conditions. The Debye Length was found to be less than 0.1 cm; hence, the Langmuir probe readings should be unaffected by the walls of the wind tunnel.

The first tests performed with the Langmuir probe were a measurement of the voltage and current at various locations in the flow. The output of the probe was connected to a model 610B Keithley electrometer. The probe was placed 1 inch off the wind tunnel centerline, and the airfoils were removed. A voltage of 15 volts was measured in the seeded flow. In an effort to increase the output of a probe, a 2-inch long, 1/4 inch diameter, thin walled copper tube was soldered to the center-lead of the probe. This probe gave a reading of 30 volts without airfoils in the wind tunnel and 50-55 volts at the same position with the airfoils positioned in the wind tunnel at 7° angle of attack. The probe was then positioned on the wind tunnel centerline, 2 ft. downstream from the trailing edge of the airfoil. The voltage, created by the swirling flow, was measured at three flow velocities: 70, 95, and 135 fps. The voltage, measured at all three flow velocities, were 15, 15 and 12.5 volts respectively. The probe was then positioned 4 inches off the tunnel centerline and the voltage recorded again at flow velocities of 70, 95, and 117 and 135 fps. The measured voltages were 17, 26, 100+ and 100+ respectively.
The readings 100+, recorded at velocities of 117 and 135 fps, indicate the voltage level exceeded the range of the electrometer. Tests with this probe were repeated at flow velocities of 70 and 117 fps with the probe positioned 2 ft. aft of the trailing edge of the airfoil, on the tunnel centerline and four inches off the tunnel centerline. The measured voltages all exceeded the range of the electrometer, that is, they were greater than 100 volts. Similar tests were run 4 inches aft of the airfoil trailing edge. The centerline voltage was measured to be -100 volts initially, but during a later test was found to be +92 volts. During additional tests with the model 610B electrometer, it exhibited considerable instability and was replaced.

All the previously mentioned tests were run with the probe supported by a non-conducting rod spanning the wind tunnel test section. This method of support was used initially to minimize any effect that the metal positioning device might have on the electrical characteristics of the flow.

D.1 Victoreen Proximity Voltmeter

A Proximity Voltmeter was obtained from the Victoreen Instrument Division with the capability of measuring up to 1,000 volts, Figure 58. A high-sensitivity probe is used with the voltmeter which is 1.1 inches in diameter and 3.25 inches long. The front of the probe has a 0.120-inch diameter aperture which required shielding to prevent dust particles from entering the probe through the aperture,
Model 5051 Proximity Voltmeter

Figure (158)

Figure (59) Model 5051-35 and Model 5051-25 Probes
The Victoreen probe was mounted in the x-y positioner 3 ft. aft of the trailing edge of the airfoils. The tunnel flow was 135 fps. The probe was moved vertically through the trailing vortex and voltage levels recorded, at the center of the vortex, the measured voltage was 150 volts. The voltage, 1 inch from the vortex center-line, varied from 200 volts (below center) to 310 volts (above the center). The voltage, 2 inches above the center of the vortex, was 500 volts. Repeated measurements through the vortex center gave voltage readings of 60 volts and -30 volts. The voltage recorded with no dust in the airstream was 60 volts. Voltage readings of over 1,000 volts were recorded in the exhaust plume from the nozzle.

The test, in which the particles were dropped onto a section of airfoil and then to a piece of aluminum foil, was repeated. The Victoreen probe recorded voltages of 45-100 volts, depending on the rate at which the particles are poured onto the airfoil. The leaf electroscope was connected to the aluminum foil during these tests; however, it did not deflect during these tests.

D.2 Langmuir Probe -- Model 602 Kiethley Electrometer

A model 602 Kiethley electrometer was obtained which is capable of making off-ground measurements. This allowed the Langmuir probe to be used in series with a variable voltage supply. The voltage of the variable power supply was varied from 1,000 volts to -1,000...
Figure 160: Spatial Resolution Of Victoreen Probes
volts, and current readings were taken. The tunnel flow velocity, airfoil angle of attack, and probe location was varied. The results of the tests using the Model 602 Keithley electrometer and a bias voltage were not conclusive due to the limited off-ground voltage range of the electrometer and the large fluctuations of the instantaneous current, at a set bias voltage, about the same mean value.

D.3 B. K. Sweeney Co., Electrostatic Voltmeter

Another commercially available probe, considered for making electrostatic measurements, was a probe obtained on loan from the B.K. Sweeney Manufacturing Company of Denver, Colorado. The probe consists of a hemispherical cylinder with a radio jack screwed into the tip. The probe head contains the electronics which permits current-free voltage measurements. For use in weak potential fields, the probe sensitivity is increased through the use of a radioactive source attached to the tip of the probe. The radioactive source provides an ionic coupling between the probe and the potential field. It was suggested by the manufacturer that a small piece of tritiated foil be used as the radioactive source. During the interim period, when application for the radioactive source was being processed, phosphorous 32 was used as the radioactive source. Several measurements were made of the potential field between large parallel plates connected to a variable voltage supply. The phosphorous 32 was contained within a hypodermic needle tip. A brass adapter was made which screwed onto the radio jack tip of the probe. The hypodermic
needle, containing traces of phosphorous 32, was then pressed down over the brass adapter.

The parallel plate capacitor consisted of two 3-foot square by 1/8-inch thick aluminum plates with a separation distance of one foot maintained by four wooden blocks. Various combinations of dry cell batteries were connected to the plates permitting a voltage range from 0 to 208 volts.

Phosphorous 32 has half-life of 2 weeks and emits a 1.7 Mev beta particle. Particles of this energy can travel approximately 200 to 300 inches in air. Due to the short half-life of phosphorous 32, the strength of the source decays rapidly; hence, each source was usable for only a few days. Four phosphorous 32 sources were used for these initial tests. The results obtained with the first source in place at the tip of the Sweeney probe indicated the instrument was sufficiently sensitive to monitor potential levels below 50 volts. The measurements of the potential field between parallel plates indicated a nearly linear variation of the potential field with distance above the grounded lower plate.

After discussions with the Radiation Safety Department, it was decided to abandon the B.K. Sweeney probe. The bombardment of the tritiated foil with the plastic pellets and eventually sand could result in the release of tritium (H₃) into the laboratory. This is a radioactive health hazard.
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