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THE ACQUISITION AND FREQUENCY ANALYSIS
OF DIGITAL DATA FROM A SINGLE SCREW EXTRUDER

DISSENTATION

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

By
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It is becoming increasingly difficult for any individual to "single handedly" recognize, define, and solve complex technological problems. Interaction with other interested, knowledgeable experimentalists and specialists is a must. It has been a great privilege for me to be able to interact and work with many of these people. I wish to thank them now but, more importantly, I hope that this interaction has added to their growth as it has to mine.

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INTRODUCTION

According to Tadmor and Klein (49A), the earliest industrial extruder was built by Joseph Brahman in 1795 for the continuous manufacture of lead pipe. However, not until 1925 and the extrusion of poly (vinyl chloride) did the commencement of modern extruder technology begin. Since that time, development in the extrusion field has been largely concerned with improvements in the physical characteristics and geometric design of the plasticating screw. Recently, however, the development of twin-screw extruders has shown that significant advantages may be realized by utilizing radically different approaches in the processing of polymers. Nevertheless, the advantages of lower initial and maintenance costs, reliability and--not least of all--familiarity, which single screw extruders offer, insure their use for many years to come and, therefore, continued study and development are warranted.

During the past fifty-five years, the systematic investigation of the extrusion process has shown that no single mathematical model can be used to adequately describe flow through the entire extruder. That is, very different physical processes are controlling over different zones of the extruder. These zones have been defined as

1. The feed zone
2. The solids conveying zone
3. The melting zone
4. The metering zone.

The screws used in single stage extruders are designed to optimize these physical processes and the geometry of the screw generally cor-
responds to the controlling process in any particular zone. (Note: For the remainder of this dissertation, zone will be used when referring to the extruder and section when referring to the screw.) The classical screw design has three sections:

1. The deep channel constant depth section-- (feed-solids conveying)
2. The compression or tapered section--(melting)
3. The shallow channel constant depth section-- (metering).

(Shown in Figure 1)

Depending on variables such as type of screw, type of polymer, and processing conditions, the actual location and/or size of the melting zone of the extrusion process will vary and, in general, will not coincide exactly with the compression section of the screw. As a result, the size of the solids conveying zone of the process will not completely coincide with the deep channel constant depth section of the screw nor will the metering zone coincide with the shallow channel constant depth section. In fact, it has been shown that the metering zone may not exist at all under certain conditions, and, further, that the location and size of the melting zone are not constant during the process but that they shift within the extruder in either a periodic or non-periodic manner.

Using differential analysis procedures such as microsectioning of screw "push-outs" (49C) the mechanisms involved in the melting and the metering zones of the extruder have been more or less understood and defined leading to the development of melt flow theories and improved plasticating screws.

However, the causes of instabilities in the extrusion process
Constant Depth
Deep Channel Section

Tapered Section
Constant Depth Shallow Channel Section

Feed Zone

Solids Conveying Zone of Extruder
Melting Zone of Extruder
Delay in Melting Zone of Extruder
Metering Zone of Extruder

Figure 1 - Extruder Zones and Screw Sections
have not been adequately determined and with the trend toward higher production rates and higher quality, the effects of these instabilities become increasingly important.

To be more explicit, the theories describing the extrusion process were developed largely as a result of experimental work and techniques developed in the 1960's when high production rates were not of such great concern. These theories are based on the assumption of localized steady state conditions and cannot account for periodic or non-periodic fluctuations in the process. In addition, the solids conveying zone was considered relatively unimportant and few studies were concerned with it during this decade.

In recent years, both the effect of instabilities in the process and the significance of the solids conveying zone have received much attention. Nevertheless, the origin and movement of instabilities within the extruder are still in question and more experimental data are needed from which the relationship between melt flow instabilities and the solids conveying process can be determined.

This study is concerned with collecting data from a 2½ inch extruder. The instabilities detected during "steady state" operation of the extruder will be displayed and quantitatively analyzed through a frequency analysis procedure. As a result of this analysis, a relationship between the conveying zone and melt flow instabilities will be proposed.

In order to collect these data, the extruder was isolated from external disturbances. That is, measuring systems were developed which could accurately monitor important process variables including.
input feed rate, output flow rate, pressures, temperature and screw speed without influencing those variables. Also, a data collection routine was developed based on a real-time fast data acquisition computer which was capable of collecting data from the variables simultaneously at rates up to 640 Hertz.

The digital data acquisition system was selected because it offers significant advantages over the more usual method of using strip chart recorders to collect data. First, digital systems are capable of collecting data at extremely fast rates. This speed enables the experimenter to examine in detail a particular event provided the response time of the measuring element is sufficiently fast. Second, some of the data require manipulation before they can be readily used. For example, flow rate data are not collected as flow rates but rather as weights of either the feed or the output hoppers. In order to determine a flow rate, the data must be differentiated. (As digital data the calculations can be easily and quickly performed --on line if necessary.) Third, instead of using electronic filters which discard much of the data, all data points can be recorded and stored for later use and manipulation, thus eliminating the need to predetermine the filtering needs of the data. Fourth, the use of digital acquisition systems allows the experimenter the freedom to record tremendous amounts of data with built-in organizational and retrieval capabilities. Finally, with modern interactive graphics systems readily available, the digital data system offers an infinite variety of display capabilities so that the collected data may be presented in a more meaningful way. That is, the data may be plotted,
manipulated and then replotted until all useful information from the
data has been extracted and displayed. For example, the data may
be analyzed and/or filtered using techniques such as the fast Fourier
transform to determine frequency content of the data and cross correla-
tion routines to determine the relative effects of the variables stud-
ied. Because of the improvements in recent years in the speed of
calculation of these routines and others, the data may be accurately
and quickly analyzed and displayed—on line if necessary.

This dissertation, therefore, is concerned with the collection
and display of digital data from a single screw 2\frac{1}{2} inch extruder.
Instabilities occurring in this "steady state" data are examined and
through frequency analysis of these data the origin, periodicity,
and significance of these fluctuations are determined.
LITERATURE REVIEW

In general, studies of the extrusion process are limited to the examination of one particular zone or mechanism involved in the process. Therefore, it is easiest to review the literature concerning extrusion by zone. These zones which have been listed before are

1. The feed zone
2. The solids conveying zone
3. The melting zone
4. The metering zone

Also, a section on stability and screw design based on the mechanisms involved in the extrusion process will be presented.

The Feed System

The feed zone of an extruder will be defined in this study as the hopper section and includes only that portion of the flow which is affected by gravitational forces. Since the gravitational force in this section is of the same order of magnitude as cohesive, frictional, and pressure forces and, further, since the system is far from continuous, the exact nature of the flow can be and often is extremely complex. Few papers have actually dealt with the hopper zone as defined here although many studies have considered gravitational flow of solids.

One study which did consider the problems involved in the hopper zone was that done by Fugel (17). He attempted to isolate a 2½ inch extruder from feed fluctuations by effectively eliminating the variations in head pressure caused by changes in the feed height. He
concluded that using feed baffles to eliminate hopper flow fluctuations reduced process instabilities significantly. The improvement in flow, he found, was a function of the intrinsic flow characteristics of the polymer-polymer geometry system (i.e., powder, pellets or flake). That is, the improvement in polystyrene flake feeding, which is normally a poor feeding material, was greater than that of polystyrene pellets which flow easily. There is no doubt that the physical properties which govern these flow characteristics are extremely complex. The coefficient of friction alone, according to Klein (21), requires an equation with 18 terms. Because of the complexity of the terms involved, Kruder (27) states that the results obtained from his study of the feeding characteristics of single screw extruders can be considered valid only for the particular samples tested and do not necessarily reflect the characteristics of any broad family of polymers since differences in pellet geometry, additives, moisture level, temperature, etc. can exert a major influence in polymer feeding.

In an effort to avoid the highly empirical and recently controversial (7, 21) problems associated with the hopper zone, it was effectively eliminated from the present study. That is, an isolated hopper system was developed (described later) which eliminated hopper flow fluctuations. Therefore, although feed fluctuations can still exist they are confined to the solids conveying zone.

The Solids Conveying Zone

For the purposes of this study, the solids conveying zone in the extrusion process will be considered to include those portions
of the flow which are acted upon directly by the rotation of the screw excluding that part of the flow system where melting has occurred.

A diagram of the affected flow region is shown in Figure 2 (dotted line). Analysis of this section requires that it be broken into the following three subregions:

1. the circulation region
2. the constant pressure solids conveying region
3. the variable pressure solids conveying region.

The Circulation Region - Although no references have been found which deal with the circulation section, the existence of it has been demonstrated during this study. Basically, when the compressive forces developed by the screw exceed the force developed as a result of pressure head, circulation occurs in the feed opening.

Constant Pressure Solids Conveying - The constant pressure region is defined as that section of the solids conveying zone where solid pellets are conveyed within the feed opening by the screw toward the closed barrel. Darnell and Mol (13) were the first researchers to adequately describe the flow in this region analytically. This classic work has provided a basis for many theoretical and experimental investigations of the solids conveying zone and it will be briefly discussed here.

In their development, Darnell and Mol assumed that the flow of solid along a helical screw acts as a solid elastic plug and contacts all sides of the screw and barrel surface. Other assumptions were

1. Internal isotropic pressure exists within the plug and may be a function of helical distance along the screw.
2. The coefficient of friction between the plastic and metal surface is independent of pressure.
Figure 2 - Solids Conveying Zone
3. The screw is single flighted and the width of the flight is negligible.

4. Gravity forces are negligible.

The forces then acting on a differential section of the uncoiled channel are shown in Figure 3A. An equation can be determined for the flow rate by considering the velocity vectors in Figure 3B. This equation is given below.

\[ \frac{Q}{N} = \frac{\pi^2 D h (D-h) \tan \theta \tan \phi}{\tan \theta + \tan \phi} \]  

where
\[ \theta \] = the angle of movement of the outer surface of the solid plug
\[ \phi \] = the helix angle of the screw
\[ h \] = the channel depth
\[ D \] = the diameter of the screw and barrel
\[ N \] = rotational speed of the screw
\[ Q \] = volumetric delivery rate of the solids.

In order to evaluate the above equation the value of \( \theta \) must be determined. It can be found by considering the static equilibrium case. That is, at the point when the plug is on the verge of moving the resultant of all forces acting on the plug is zero these forces are then resolved into component parts--those acting parallel to the screw axis and those acting perpendicular to it. While the parallel forces can be added algebraically, the perpendicular forces act tangentially because of the curvature of the screw and must be balanced as torques. Integration of the resulting balance equations over a finite length of the screw leads to the following equation:
Figure 3A - Forces Acting on a Differential Element

Figure 3B - Velocity Vectors
\[ \cos \theta = k \sin \theta + c (k \sin \phi_s + c \cos \phi_s) \]
\[ + \frac{2h}{t} (k c \tan \phi_s + e^2) \]
\[ + \frac{h e}{Ldh} \sin \phi_A (e \cos \phi_A + k \sin \phi_A) \]
\[ \times \ln \frac{p_2}{p_1} \] (2)

(See Ref. 13 for explanation of terms.)

Combining the last three terms gives

\[ \cos \theta = k \sin \theta + M \] (3)

Insight into the physical implications of the model can be gotten by examining specific cases of it. For no forward movement, the angle of movement \( \theta \) is 0 and \( M \) must be equal to 1. \( M \) itself consists of three parts where the last term represents the effect of back pressure and the middle term represents the effect of the screw flights. When pressure is constant and there is no contact with the trailing flight, equation (2) reduces to

\[ \cos \theta = k \sin \theta + c[k \sin \phi_s + \cos \phi_s] \] (4)

Assuming the coefficient of friction for the screw is negligible, equation (1) reduces to

\[ \frac{Q}{N} = \frac{\pi^2}{4} D h (D-h) \sin \phi \cos \phi \] (5)

and can be compared to a general ideal flow equation given as

\[ \frac{Q}{N} = \frac{1}{4} \pi^2 (D-h)^2 h \sin \phi \cos \phi \] (6)

The comparison shows that the volumetric delivery rate for the solids
is about twice that for melt flow again with negligible screw friction, no back pressure, and no effect of the trailing flight. If any of these effects becomes significant the flow rate can be drastically reduced. In the feed entrance, which occupies approximately two turns of the screw, equation (2) holds. That is, Kruder (27) has shown that $\theta$ may vary from 72 degrees (maximum for square pitch) at zero back pressure to approximately 10 degrees at high back pressure for several systems. These results indicate that in the absence of back pressure solids should be conveyed as close to the maximum angle as possible.

Varying Pressure Solids Conveying - Although the model was developed to account for variable isotropic pressure, the accuracy of the flow rates predicted is poor (21). Other more complex models were developed to improve accuracy.

Most of the studies concerned with improving accuracy attempted to either add terms to the basic equation developed by Darnell and Mo1 or increase the complexity of the existing terms.

In 1969 a paper was published by Schneider (44) in which the assumption of isotropic pressure at any point along the screw channel was changed. The mean along channel pressure or compressive stress was taken as a reference and constants of proportionality were specified as $k_1$, $k_a$, and $k_2$ corresponding to pressures at the screw root, the flight edges, and the barrel surface respectively. Using the same approach as Darnell and Mo1, he calculated the angle $\theta$ to be
\[
\cos \theta = k \sin \theta + \frac{\mu_f k_a}{\mu_b k_2} \frac{2 h e}{s t} (k \tan \phi_A + e) \tag{7}
\]

\[
+ \frac{\mu_s k_1}{\mu_b k_2} c \cos \phi_1 (k \tan \phi_1 + c)
\]

\[
+ \frac{\mu_a \sin \phi_a}{\mu_b L k_2} (k \tan \phi_a + e) \ln \frac{P_2}{P_1}
\]

(See ref. 44 for explanation of terms.)

This development more accurately determines the effect of back pressure on the flow rate. Lovegrove and Williams (29) attempted to improve the model by taking into account the gravitational and centrifugal forces involved in the process and also they attempted to account for higher pressure on one side of the channel resulting from the compressive action of the screw. They found that an exact solution to the problem was not possible because of the complexity of the equations involved. A numerical solution was possible, however, and showed that as a result of the variation of the direction of the gravitational force with respect to the rotating plug, a cyclical variation in pressure is predicted. The theory also predicts that negative pressures which are impossible in a loose solid, exist. Nevertheless, the authors point out that by assuming that the negative pressures predicted are actually zero, a cyclic variation still exists and further that this variation depends on angular position at the beginning of the channel. Their analysis depends heavily on the assumptions that the screw channel is always full and that either the output or the pressure build-up is constant. Since both of these assumptions are functions of downstream conditions their validity is questionable.
\[
\cos \theta = k \sin \theta + \frac{\mu_s k_s}{\mu_b k_2} \frac{2he}{st} (k \tan \phi_A + e) \tag{7}
\]
\[
+ \frac{\mu_s k_1}{\mu_b k_2} c \cos \phi_1 (k \tan \phi_1 + c)
\]
\[
+ \frac{hw \cos \phi_a \sin \phi_a}{\mu_b L k_2} (k \tan \phi_a + e) \ln \frac{p_2}{p_1}
\]

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In a second paper by Lovegrove and Williams (30) the problem of centrifugal forces is dealt with. In short, they found that for screw speeds under 600 rpm, centrifugal forces are negligible.

Broyer and Tadmor (5) derived an improved solids conveying theory which modified that presented by Darnell and Mol. The new theory allows for variable channel depth, variations of bulk density as a function of pressure, and for non-isotropic pressure distribution in the plug. Since this modified model must be solved numerically, general conclusions are difficult to derive. However, some specific cases were examined for the following system:

2.5 diameter extruder
Square pitched screw--flight with width = .25"
Channel depth = .375"
Coefficient of friction = .35 barrel = .25 screw

Density varies according to

$$\frac{\rho_x - \rho}{\rho_x - \rho_0} = e^{cP} \tag{8}$$

$\rho_x$ - maximum density; $\rho_0$ - initial density; $P$ - pressure; $c$ - constant

Results showed that the effects on pressure and therefore on density are:

1. As taper increases the length of solids conveying zone to reach 1000 psi is decreased and that at high taper excessive pressure greatly reduces output.

2. The assumption of non-isotropic pressure results in the prediction of much lower pressures in the down channel direction and consequently a much lower forward drag force.

The same authors, in a second paper (48), considered the effect
of non-isothermal conditions on the model. The main conclusion to be drawn from this work is that the maximum pressure developed in the solids conveying zone is in large part limited by the temperature rise of the solid plug surface. That is a lower temperature rise will result in lower melting and a longer solids conveying section and, consequently, a higher pressure rise.

A somewhat confusing model was presented by Wolemar Tedder (50), He disregarded the force balance method used by these other authors and based his development on the principle of virtual displacements. That is, "If for each infinitesimal virtual displacement of a system compatible with its constraints the work produced by the active forces is zero, then the system must be in equilibrium." The application of this principle involves:

1. Replacing the displacement and work with velocity and energy
2. Considering work rather than force
3. Assuming virtual displacement (velocity) is a possible displacement (velocity). Therefore the principle is applicable to both static and dynamic systems.
4. Neglecting inertial forces.

Although his development is interesting, when applied his theory is useful only for systems where the coefficient of friction of the screw is higher than that of the barrel--a condition rarely encountered and certainly undesirable.

A second radically different approach to the problem was described by Chung (9). From his experiments he concluded that viscous drag resulting from a melt film on the wall controlled the solids conveying zone. That is, he assumed that the area controlled by solid-to-solid or coulomb friction mechanism was very small and could be
neglected. Although his derivation follows the general outline as that used by Darnell and Mol, the resulting equations are quite different as are the flow rates predicted. Unfortunately, he does not provide any experimental evidence that conclusively proves his theory and many authors have not accepted his assumption that coulomb friction is unimportant.

In fact, Klein (21) who is a leading authority in the field of extrusion, recently wrote that "Whereas at low production rates melting had always been the limiting factor in extruder performance, at high production rates, solids conveying rates becomes the single most important factor governing an extruder." He continues to explain that although some authors disregard the model proposed by Darnell and Mol, he has found that the error lies in the use of a simplified coefficient of friction rather than in the validity of the theory. In another article (22) he demonstrates how the use of an eighteen term coefficient of friction equation combined with a computer program solved a particular production problem.

Kruder (26,27) recognized that the solids conveying section of the extruder was the least understood aspect of the extrusion process. Because of the controversy over the mechanisms involved and the diverging nature of the theoretical models being produced he developed an experimental set up (see Figure 4) to determine empirically the true nature of the solids conveying zone without the effect of melting at the wall of the extruder. With his system, Kruder was able to show that under zero back pressure conditions, the Darnell and Mol equation works very well for the polymer systems which were studied.
Figure 4 - Kruder's Experimental Apparatus
He also showed, however, that once even minor output pressures developed the agreement between experiment and theory was very poor. That is, he suggests, the theory becomes impractical because the coefficient of friction against the screw and barrel surfaces can be pressure dependent and therefore variable. Some other interesting phenomena which he observed were

1. Height of feed in the hopper made absolutely no difference in the output flow rate.

2. The existence of "output floors" was demonstrated. That is, output decays exponentially with back pressure and reaches a near constant level at elevated pressures—between 10 and 15 psi at two turns into the barrel.

3. Stability of the pressure decreased rapidly with pressure (back pressure).

4. Temperature appeared to have little effect on pressure or output.

In a similar study, Mizoguehi (37) also showed the existence of an "output floor." However, he found that although there was little effect of temperature on pressure or output at moderate temperatures (80°C), a tendency for the solids conveying rate to increase with temperature at higher temperatures was observed.

Although the solids conveying zone covers only a small section of the extruder it remains a major obstacle to the complete understanding and modeling of an extruder.
The Melting Zone

The melting zone or transition zone is defined as that portion of the extruder in which solid polymer and melt co-exist. This zone is not limited to the transition section of the screw which is defined as that section which is tapered—usually linearly—from the deep flights of the solids conveying zone to the shallow flights of the metering zone. A subsection of the melting zone sometimes classified as a separate zone itself is the delay in melting zone. This is somewhat of a misnomer since it is defined (10) as that section of the extruder where "a melt film begins to form on the barrel surface but not in sufficient quantity to create the melting zone." That is, since most of the melting in an extruder occurs through viscous shearing which requires that the thickness of the melt film be greater than the flight clearance, the delay zone is characterized as that section where melting occurs largely through conduction--where the thickness of film is less than the flight clearance. This zone is probably best described mathematically by Chung's (10) theory and is usually termed a non-productive zone. The viscous melting zone, on the other hand, is very important and was first qualitatively investigated by Maddock (32, 33, 34) and by Street (47) using screw push out and visual inspection techniques. These techniques were extended so that a quantitative analysis of the melting mechanism was obtained which ultimately led to the development of a theoretical model presented by Tadmor and Klein (49B). Basically, the model considers

1. Newtonian fluids and non-Newtonian power law fluids

2. Curvature of the channel
3. Flight Clearance

4. Variable viscosity as a function of a linear or non-linear temperature profile

4. Solid bed shape

It predicts the trend in the solid bed width and the proper shape of the profile in the different geometrical sections. Briefly stated, the general melting phenomena in extruders is understood. That is, the theory that the solid bed is forced to the front of the flight while a melt pool is collected on the pushing flight (see Figure 5) is widely accepted for systems with low clearance ($\varphi^C$). However, at high clearance, Chung (10) proposes an atypical melting mechanism in which the solid plug rather than the pushing flight scrapes polymer from the barrel (see Figure 6). He suggests that if extruders were designed with large flight clearances, greater energy efficiency could be realized. However, very few other authors have accepted this theory of higher efficiency although the mechanism may occur.

Although there is wide acceptance of the low clearance model, it is also understood that in these systems the model can not predict the often very periodic occurrence of the instability known as solid bed break up. That is, the periodic or non-periodic break in the solid bed helix which has been described by many authors and visually demonstrated by Anastas, Lynn and Brodkey (2). This phenomenon will be discussed in more detail later on.

The Metering Zone

The metering zone of an extruder controls or meters the flow rate of polymer and is the last section before the die. According
Figure 5 - Flight Profile Low Clearance

Figure 6 - Flight Profile-High Clearance
to Tadmor (4gD) a satisfactory theoretical model for this zone should include equations which specify flow rate, pressure temperature and velocity distributions across the channel and down the channel. Most theoretical models developed for this zone have been based on continuum mechanics and these are extensively covered in the above reference. However, there have been some studies done which have not been based on continuum mechanics. The most notable of these was reported by Marshall et al. (35) who used a regression analysis to fit a system of empirical equations to experimental data obtained from a highly instrumented extruder. This approach relies on a large amount of experimental data being available and it is unwise to extrapolate outside the range of conditions used. Also, it does not add any fundamental understanding to the mechanisms involved in the extrusion process.

Because the mechanisms involved in this zone are well understood including the phenomena of melt fracture, there is no need to resort to empirical equations.

Surging and Screw Design

As was stated earlier, the trend in recent years as a result of increased cost of raw materials and energy has been toward higher production rates. However, output uniformity is one of the main factors limiting production from single screw extruders according to Fenner et al. (14). In a recent paper, he states that surging in the extruder is the main cause of non-uniformity in an extruder. The cause of this surging has been considered by many authors.
Chan et al. (6) carried out an analysis on transient viscoelastic melt flow and Kirby (20) determined the response of melt flow in the metering section of an extruder to small disturbances in the polymer melt supply. However, these approaches could not determine the cause of the surging but rather only the result. Lovegrove and Williams (31) showed that pressure fluctuations are inherent in the solids feeding mechanism and that they must occur at the frequency of the screw. Using the model described earlier, they determined that, depending on processing conditions, these fluctuations may or may not be significant relative to the overall pressure generating capacity of the extruder.

Many studies have demonstrated that a relationship between surging and melt flow instabilities exists. Solid bed break up is the most common cause of this instability. That is, for a stable system, the solid bed should be described by a continuous helix in the downstream direction with its width and depth progressively diminishing to negligible proportions. Bed break-up occurs when the helix breaks. Pressure surging accompanies the break-up which usually occurs at a frequency five to ten times lower than that of the screw rotation. Klein (25) suggests that one of the causes of this bed break-up is directly associated with wedging in the transition zone due to an excessive taper. That is, the solid bed seeks to grow wider than the channel width and becomes lodged between the leading and the trailing flights until pressure behind the wedge forces it to break. This is one form of bed break-up. Although Klein says that the solid bed velocity is established at a very early point in the solids conveying zone and
tends not to accelerate further, this wedging phenomena must be interpreted as an acceleration-deceleration occurrence in the solid bed.

It is interesting to note that two recent publications by Rahim (40) and Fenner et al. (15) consider solid bed acceleration to be occurring continuously over the whole melting zone. Consequently, Rahim suggests that transition length should be decreased and necessarily taper increased for better stability as a result of reduced acceleration. Therefore, they describe the occurrence of bed break-up as a result of the stretching and some structural weakness of the bed. Then, although it is accepted that bed break-up is a major cause of melting instabilities and surging, the exact cause of the break-up is still in question.

Finally, low frequency surging may be the result of very slow fluctuations on the order of minutes or even hours caused by control changes or environmental changes. Fontaine (16) noticed fluctuations on the order of 30 minutes during his study and found that these could be attributed to lower line fluctuations during experimentation.

The competent screw designer must be able to assimilate all this material and much more. According to Chung (8) screw design at present requires a thorough knowledge of all the various mechanisms that can and do occur inside an extruder and more importantly, a broad empirical knowledge of the many different screw designs. By combining this knowledge with the simulation capabilities of a high speed computer program, optimization of conventional designs and development of new more efficient ones is possible.

Two of the more widely used unconventional screws are double
flighted screws and multiple stage screws.

The double flighted screw can be designed to separate the flow into two components—the melt and the solid. For example, the Waldron-Hartig Mc-3 screw (melt control third generation) is so designed. However, most double flighted screws are designed just to redistribute the solids and melt for improved melting. Similarly, multiple stage screws according to Kruder (27) are designed to redistribute the laminar melt structure of the shallow first metering channel as the polymer is forced into the decompression section of the second stage. Besides better melting and more uniform melt temperatures, these screws offer the added advantage of being able to be used for applications for which they were not originally designed.

In spite of these improvements, however, the problem of surging still remains a major stumbling block at high production rates. Before truly optimal screws can be designed, the mechanisms causing surging must be more fully understood and mathematically modeled.
Much of the equipment used in this study has been previously described. Where appropriate, the references which describe a particular piece of equipment will be listed in addition to or in place of a description in this section.

The Extruder

A 2\frac{1}{2} inch NRM single screw extruder was used in this study. The extruder which was manufactured by NRM Corporation of Akron, Ohio has an L/D ratio of 24/1. A photograph of the extruder with peripheral equipment is shown in Figure 7.

The barrel of the extruder consists of a heat-treated, one-piece steel cylinder lined with Xaloy. It has a working pressure of 10,000 psi and is connected to the feed section of the extruder through a flange. The barrel is heated by four separate heater sections each consisting of the two 2-kW finned aluminum resistance heaters. Four manually operated cooling fans are positioned under the barrel. The four zones are controlled by barrel time proportioning controllers and on-off relay switches. Each zone controller incorporates a limit switch which shuts off the power if the temperature exceeds 316°C. The extruder can be run with one of many different screw designs. A 40-horsepower D.C. motor drives the screw through a 4-belt connection with a helical gear drive transmission. The power for this motor
Figure 7 - Extruder and Peripheral Equipment
is supplied by a Reliance Electric Company, rectified-power, silicon control rectifier (SCR), variable speed drive unit. This unit is powered by available 208 VAC through a Reliance three-phase, 51 KVA, 460/208 volt transformer. Manual control knob to control screw speed, an rpm meter, and an ammeter are located on the main support frame of the extruder.

The screw is fed through a 4-3/4 x 2\(\frac{1}{2}\) hopper opening, and the inlet port is water cooled to facilitate feeding. Cooling water must be manually regulated. At the front end of the barrel is a standard breaker plate and a four part screen pack. Downstream of the breaker is a fifteen turn valve assembly which is used to adjust the back pressure. Polymer flowing out of the valve is directed through an adapter which changes flow from circular at the entrance to rectangular at the exit. Four tubular 230 volt 250 watt chromalox heaters implanted in the adapter supply heat to it through an adjustable variac. This heat was not controlled during the study. However, pressure and/or temperature of the melt was recorded during the study. Finally, from the adapter, polymer melt flows through a die and to take-up equipment. The die used in this study was developed by Hertenstein (19) and is generally known as a pelletizing die. Heat to this die is supplied through two Harrel controllers to eight more chromalox heaters. Implanted above and below the flowing polymer as two banks of four, the polymer actually flows through thirteen 1/10 inch holes in the die.

Take-up Equipment

The plastic chopper used in this work is described by Hertenstein
As the polymer strands flowed from the extruder, they were pulled through a 7-foot water cooling bath and solidified. A variable speed 0 to 1750 rpm motor controlled the take-up speed of the strands which were drawn through two rolls driven by this motor and finally fed to the chopper. Although the chopper has its own drive rolls, by pulling the plastic through with an independent set of rolls, a failure in the chopper would not necessitate a run abortion.

The Screw

Three different screws were used in this study. They include

1. A conventional three zone screw
2. A two-stage screw
3. A two-stage plasta screw (double flighted).

All screws had a length to diameter ratio of 24/1 and were all built by the NRM Corporation.

The Conventional Screw - The conventional screw used in this study was a square pitched screw with approximately equal length for each of the three zones (see Figure 8 for exact dimensions). The design capacity of the screw is 2.2 pounds of feed per hour per revolution per minute. The compression ratio of the screw is 3 to 1. The screw was machined from alloy steel, heat treated and chrome plated.

The two-stage screw - The two-stage screw used in this work was designed specifically for polystyrene. Again, the screw was machined from alloy steel, heat treated, and chrome plated. The capacity of the screw was rated as 2.5 pounds of feed per hour per revolution per minute. Compression ratios for the two stages were 2.7 to 1 and 2 to 1 respectively.
Figure 8 - Feed Screw Dimensions
Two-stage double-flighted screw - Finally, a two-stage double-flighted feed screw was used. This screw was specifically designed for low density polyethylene. The double flight had equal clearance and the compression ratios were 3.5 to 1 in the first stage and 2.5 to 1 in the second stage. The rated capacity was 1.8 pounds of feed per hour per revolution per minute.

Computer

The computer used in this study was a real-time fast data acquisition system based on two Digital Equipment Corporation PDP-15 computers intimately linked in a dual processor configuration. The details of the software involved in the linkage are described by Bartram (3). Briefly, the dual processor is an extension of the input-output processor used with most computers. The difference is that the second computer is now programmable as opposed to a processor with hard wired operating sequences. The computers communicate through shared memory and the real-time data interface is the major unit under control of the second processor. A 64-channel multiplexed analog-to-digital converter, Raytheon computer model MADC15-04-64, digitalizes input signals in the range -10.0 to +9,9994 VDC. The converted value is a fifteen bit twos compliment word. The conversion of all 64 channels is accomplished in .642 milliseconds. Because only twenty Hertz data were desired, the time lag between successive channels is considered negligible in this study. The operating system used was an RSX-III based system enabling all programs to be written in Fortran. However, because of time considerations involved in the transfer of data, one
routine was written in assembler language. Also, random noise in the system obscured the low order four bits of the data word. In order to improve the accuracy of the signal, block averaging of 640 Hertz data in sets of 32 was used to ultimately produce 20 Hertz data for the fast data studies. Similarly, for the slow data studies, 64 Hertz data were used to produce 2 Hertz averaged data.

All averaged data were recorded first on a fixed head disk and then transferred to dectapes for storage and later analysis.

For quick monitoring of both the raw data and the analyzed data, a Digital Equipment Corporation graphics 15 unit was used. This unit is equipped with six push buttons and a light pen for interactive manipulations. The effective grid area of the unit is 1024 x 1024 and an offset work area may be added to that grid area. This unit is more completely described by Steacy (46).

Once it was determined what data should be kept as a permanent file, a digital plotter was used to record this data. The Hewett-Packard plotter model number 7225A was capable of resolving an integer data signal to one part in ten thousand. The plotter is a highly accurate and extremely sensitive recording device. For more details consult the 7225A plotter manual.

A schematic diagram is shown in Figure 9.

The Feed Hopper

The feed hopper in this study was independently suspended from the ceiling. The system is shown in Figures 10 and 11. The hopper itself was constructed from 20 gauge sheet aluminum and structurally
Figure 9 - Schematic of Data Acquisition Computer System
Figure 10 - Schematic of the Feed Hopper System
Figure 11 - Feed Hopper System
supported with 3/4" angle aluminum. As was stated earlier, one objective of the study was to eliminate feed fluctuations caused by feed height variation. Fugel showed that by diverting the flow of pellets through two successive 45 degree angles head pressure fluctuations were effectively eliminated. A second important result of this configuration is that all of the weight above the 45 degree angles is then effectively supported by hopper and further, by weighing the hopper continuously, an accurate measure of the flow rate can easily be obtained by differentiating the weight vs. time curve.

In order to accurately weigh the feed hopper a load cell was built through which the hopper was supported. The cell (see Figures 12 and 13) was designed for rugged use and high accuracy. Basically, the hopper was suspended on a 5/8" piece of drill rod which was beveled in the center. This rod was fit snugly on a piece of 3/4" 16 gauge spring steel which was supported horizontally by adjustable bolts. As load increased, the spring steel was forced to flex and the total deflection under full load was 3/8". Bonded to the spring steel on either side were BLH strain gauges model No. A-1-S13. Any deflection in the spring steel placed one strain gauge in tension and one gauge in compression. These two strain gauges were then connected to two fixed resistors to form a full bridge circuit. The circuit was powered by a separate power supply designed and built at the Chemical Engineering Department of the Ohio State University. The signal obtained from the load cell was amplified by an operational amplifier and filtered with a first order filter which had a time constant of .025 seconds.
Figure 12 - Schematic Drawing of Output Load Cell
Figure 13 - Feed Load Cell
The Output Hopper

In order to determine the mass flow rate of material out of the system, two strands of the polymer flowing from the die were allowed to flow into an output hopper which was also suspended through a load cell. The system is shown in Figures 14 and 15. The design of the load cell was similar to that of the input hopper load cell with the exception that a smaller spring steel support beam was used. That is, only two-thirteenths of the flow out was collected. Therefore, the force needed to deflect the strain gauge circuit had to be reduced and a $\frac{1}{4}$" 22 gauge piece of spring steel was used. By simply adjusting the distance between support arms, the total deflection and therefore the gain could be adjusted through a wide range. Again, a separate power supply and amplifier were designed and built. The electrical diagram is listed in Appendix E.

Screw Speed Measurement

As described earlier, the extruder is equipped with an rpm tachometer-generator. The signal from this generator is read by means of an analog panel meter. The response time of the meter, however, was determined to be too slow and an independent means of rpm determination was developed. (see Figure 16.)

The system consists of a pulse generator and detector and a frequency to voltage conversion circuit. The pulse generator consists of a clear plexiglass disk mounted on the exposed end of the flywheel. Incorporated into the disk are 360 evenly spaced black lines. A digital plotter described earlier was used to make the disk. Rotation of
Figure 14 - Schematic of Output Hopper
Figure 15 - Output Hopper and Load Cell
Figure 18 - Screw Speed Pulse Generation System
the screw and disk caused an interrupt in the circuitry of a GE optoelectronics photosensor for each line or pulse on the disk. That is, output voltage from the optical transistor jumped from 3 volts ± .5 to 12 volts ± .5 each time light from a led emitter was blocked by a passing disk pulse. This pulse signal was then reconverted into a continuous voltage through an analog devices frequency to voltage conveter model No. 451J. Briefly, the frequency to voltage converter senses any change in voltage through 6.0 ± .5 volt band and converts the rise and fall of the signal through this band into a square wave pulse regardless of the original wave form. The sensed pulses are continuously integrated to produce a corresponding output voltage signal. The ± 10 volt signal thus produced was then read directly through the adc. This voltage varied linearly with input signals corresponding to 25 rpm to 125 rpm.

An amplifier for the system was constructed at the Chemical Engineering Department of the Ohio State University.

Wiring diagrams are listed in Appendix E.

Pressure Measurement

Melt pressures were determined at six points in the extruder and front end. Dynisco pressure transducers were used in this study. These transducers are mercury filled strain gauge based sensors and were all either 420 models or 420A models. For more information see the Dynisco Transducer Catalog, Dynisco Corporation, Norwalk, Mass.

The actual ranges used were
1. 0-1000 psi (58670)
2. 0-3000 psi (117846)
3. 0-3000 psi (116735)
4. 0-3000 psi (111995)
5. 0-5000 psi (110303)
6. 0-10000 psi (51993)

(Serial number in parenthesis.)

Power supplies and amplifiers for the transducers were designed and constructed at the Chemical Engineering Department of the Ohio State University. Specifications approximately match those of the power supply units supplied by Dynisco. Wiring diagrams of the units are shown in Appendix E.

Temperature Measurement

It has been shown that the standard flush mounted thermocouple does not measure the temperature of the melt but rather a temperature which is influenced by viscous heating, mass of the barrel, and mass and heat capacity of the thermocouple among others. That is, because polymer is processed in a very viscous medium significant temperature gradients are built up in the flowing material (ca, 1 to 10 °K/mm). This means that the stagnant polymer material at the wall may give a poor indication of the mean temperature flowing through the system. A detailed mathematical model was developed by Laurence (28) based on the effect of varying thermal conductivity in the barrel wall material. In essence, they used a pair of thermocouple sensors—one with a highly conducting and one with a poorly conducting face placed in the wall. They concluded that because of the extreme difficulty in experimentally varying their model predicted values are only as good as temperature sensors that project into the flow stream.
One study that used projecting thermocouples to measure bulk temperature was that done by Marshall et al. (35). In this previously described study, they placed thermocouples along the screw using slip rings to monitor the voltages. Temperature corrections were fitted by non-linear multiple regression functions. Results showed that corrections ranged from 0 to 50% of the difference between the screw temperature and the extended probe temperature. In other words, the temperatures measured in this fashion were subject to a high degree of error. In addition, the extended probe interfered with the normal flow patterns of the polymer to some degree. Clearly a better non-interacting method to accurately measure the bulk melt temperature was desirable.

Within the last decade optical fiber systems have become increasingly important especially in the communications field. Although the acceptance of infrared temperature sensors in the extrusion industry has been slow, the advantages which they offer to anyone seriously interested in determining the true mechanisms involved in the process cannot be overlooked. These advantages include

1. No interaction between measuring element and system
2. Insensitivity to the wall conditions
3. Response time on the order of milliseconds
4. Rugged yet compatible with digital systems

Several papers have been concerned with the development and application of these systems (38, 42, 43, 51)

The Infrared Temperature Probe

An infrared fiber optic probe system was used in this study. The system, model number 1201, was manufactured by Vanzetti Infrared
and Computer Systems, Inc. The system includes a fiber optic probe fitted with standard male 1"-20 threads so that the bottom of the probe fits flush mounted with the inside barrel wall. A mounting bracket was made so that the probe could be securely held by the detector which fits on top of the probe (see Figure 17). Power supply, amplifier and ac to dc converter, etc. are housed in a separate unit. This unit is defined as a passive detective system of the infrared radiation as a function of temperature. The fiber optic probe was optically polished at both ends and was enclosed in a stainless steel sheath for protection and noise inhibition. The performance specifications of this system were

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature response, °C</td>
<td>200 to 1200</td>
</tr>
<tr>
<td>Accuracy %</td>
<td>± 2% of reading</td>
</tr>
<tr>
<td>Field of view, degrees</td>
<td>60</td>
</tr>
<tr>
<td>System response time</td>
<td>100 milliseconds</td>
</tr>
</tbody>
</table>

Briefly, the system collects infrared radiation from heated objects and transmits that radiation through a tuning fork chopper which modulates the energy at a rate of 400 Hertz. This modulated pulse then impinges on a lead sulphide detector which produces a signal proportional to the incoming power. The ac signal coming from the detector is then amplified through two amplifiers—one adjustable—and converted to a dc signal. This signal is then recorded. The flow diagram is shown in Figure 18.

**Calibration Equipment**

The equipment and associated electronics used for flow rate measurements—both in and out, screw speed detection, pressure measurement and temperature measurement required calibration. The sensors were
Figure 17 - Fiber Optic Probe and Detector
Figure 18 - Fiber Optic System
calibrated both statically and dynamically.

**Static Calibration** - In order to calibrate the feed load cell, a separate water tight hopper was built. The hopper was initially filled with 30 pounds of water and allowed to empty into a beaker supported on a digital balance in incremental amounts. Readings from the load cell were recorded digitally and input values from the scale were typed into the computer. The balance was accurate to ± 1 gm. A digital scale Fisher Scientific Equipment Corporation model No. EWO-4010 was used to calibrate the feed and output load cells statically.

**Dynamic Calibration** - Dynamic calibration could be accomplished only by calibrating one load cell against the other. This procedure is described in a separate section.

Screw speed calibration was accomplished by modifying a Phillips 212 electronic turntable with a rated rpm fluctuation of less than .1 rpm. A spindle was built to support the pulse disk which was rotated at either 33 or 45 rpm. In addition, the electronic circuitry of the system was calculated by supplying a pulse to the frequency to voltage converter with a Tektronics FG 501 pulse generator. The system was dynamically calibrated by removing some of the pulses from the disk at several points to determine the response time of the system.

The pressure transducers used in this study were also calibrated statically and dynamically. The apparatus involved is shown in Figure 19. For static calibration of the transducers the system consists of a steel block fitted with two transducer sockets and two cylindrical
Figure 19 - Pressure Calibration Equipment
chromalox heater bars. The pressure transferring medium used was mineral oil.

This apparatus includes a steel block for mounting the transducers, two Heise pressure gauges, a nitrogen cylinder and an American Instrument Company hydraulic pumping system capable of producing 12,000 psig. For static calibration, the system was pressurized to 1000 psi using nitrogen pressure and then pumped to 2400 psi using the hydraulic pump.

For dynamic calibration the system was brought to the desired operating pressure and pulsed using the hydraulic pump. That is, the frequency of the pump was 1 Hertz. By adjusting the volume of nitrogen in the reservoir and setting a variable relief valve at the desired operating pressure, a 1 Hertz pressure pulse of any amplitude ranging from 1 psi to 200 psi could be obtained.

(Polymers used in this study were high density polyethylene (.956) supplied by Amoco and impact modified polystyrene by Dow Chemical.)
EXPERIMENTAL

Before a workable experimental schedule was formulated and implemented, an extensive preliminary investigation of the operating characteristics of

1. The extruder
2. The digital collection system
3. The measuring transducers and associated electronics

was carried out. All characteristics were examined, defined and documented where possible.

The Extruder

Operation of an extruder is extremely complex. The number of variables involved in the extrusion process requires that the experimenter first obtain hands on experience before designing an experimental schedule. The number of practical problems involved in the process can easily obscure the researcher's ability to effectively isolate and study a particular aspect of the extrusion system. For this reason, many exploratory runs were made to familiarize the author with the equipment and run conditions necessary to obtain "steady state" conditions generally defined in terms of output uniformity and die pressure fluctuation. These runs involved basically determining the temperature profile along the axis of the extruder which produced an acceptable output product while the following conditions were varied:
1. Screw speed (20-100 rpm range)
2. Screw type (three screws described in the equipment section)
3. Polymer type (crystalline polyethylene and amorphous impact modified polystyrene described in the equipment section).

Although no digital data were recorded during these runs, the system variables were monitored to determine if steady state had been attained in each test. Having shown that steady state conditions could be obtained over the range of experiments proposed, attention was shifted to the characterization of the digital collection system.

The Digital Collection System

The development and operation of a digital data collection system often presents the researcher with many perplexing problems which must be first recognized and then isolated and solved. These problems are often related to the limitations of the digital system. Basically, the system is

1. Finite
2. Subject to noise interference
3. Restricted by real-time constraints.

The finite data word limits accuracy. As previously mentioned, the analog to digital conversion system used in this study was a 15-bit ±10 volt converter. This means that a signal may be resolved into $2^{15}$ units with the limit of resolution therefore set theoretically at .6 millivolts. In order to determine the actual resolution of the converter, it was isolated from any downstream disturbances by disconnecting those downstream lines and properly grounding the system. Data were recorded with the system in this configuration at the
collection frequency to be used in the proposed experiments. The data thus collected showed that four bits or eight counts of the converted signal were lost to random or white noise. It was shown, however, that the signal could be brought to within a resolution of one bit or .6 millivolts with confidence levels of 90% by block averaging 32 data points per collected sample. Therefore, in order to collect 20 Hz data the collection rate was actually set at 640 Hz with an averaging scheme written into the collection program.

The finite data word of the computer itself also severely limits the accuracy and scope of the data analyses which may be carried out. That is, the single precision data word of the PDP-15 has a precision of six significant figures with double precision having nine significant figures. Recursive calculations are then subject to round off error and the scope of the analysis is somewhat limited. This problem will be discussed more fully in another section.

The third important limiting factor of the digital collection system is the real-time constraint. For example, the dual processor PDP-15 is capable of collecting approximately 64,000 data points per second. However, because of core storage limitations, all of the data collected cannot be retained within the computer but have to be transferred to some peripheral device. Both fixed head disks and dectape transfers are used. The rated transfer rate for these peripherals is approximately 62.5 kilohertz maximum for the disks and 5 kilohertz for the tapes. Depending on many variables, these rates may be severely reduced. In order to determine the actual transfer rate a series of tests were conducted. It was found that the
maximum transfer rate for single word integer data values was one kilohertz. Therefore, the data collection programs were written to accommodate this limitation.

Measuring Transducers and Associated Electronics

Finally, attention was focused on the signal measuring transducers. In order to determine the signal processing characteristics of the pressure, temperature (fiber optic), flow rate and screw speed transducers, they were all calibrated statically and dynamically with the exception of the fiber optic system which calibration was the concern of a separate thesis project (45). Results of this work are discussed later.

Calibration of the pressure transducers involved the equipment shown in Figure 19. A static calibration was obtained by heating the pressure block and transducer to the approximate temperature at which the transducer would function in the extruder. Five or ten point calibrations were then taken by increasing the pressure of the block using nitrogen pressure over mineral oil--mineral oil filled the heated block and this oil in turn was pressurized using nitrogen. The technique was chosen rather than using just nitrogen throughout the system because as the pressure was increased or decreased using only nitrogen gas the time needed to reach equilibrium was excessive. Because of the strong dependence of pressure on temperature, the additional gas added to the block would have to be allowed to thermally equilibrate in the case of a pressure increase and similarly with a pressure decrease. Since volume of the mineral oil is only slightly
dependent on the pressure range in this study, a much shorter equilibration period was required. On the other hand, a system completely filled with mineral oil could not be used because the closed system could not be smoothly or continuously adjusted using a hydraulic pumping system. Using this system, then, the pressure transducers were statically calibrated four times during the experimentation. Dynamic calibration of the system was accomplished by pulsing the system with the hydraulic pump at a frequency of 1 Hertz and amplitudes of 1, 10, and 100 psi pulses. Data were collected from the transducers and plotted to determine the response characteristics of the system.

Calibration of the flow rate transducers was accomplished by allowing water to flow from the transducer to a beaker placed on a digital mettler balance. Periodically the flow was stopped, the transducer allowed to equilibrate and a weight recorded. A second order equation was then fitted to the data. The system was calibrated twice during the experimentation. Dynamic calibration of the systems was obtained by allowing water to flow from the input flow system to the output flow system through tubing. A 1 Hertz pulse was introduced into the flow by squeezing the tubing and stopping flow. The magnitude of the pulse was approximately 5 grams.

Finally, calibration of the screw speed detector was accomplished by first running the extruder without a feed screw and calibrating the system against the tachometer-generator system incorporated into the extruder itself. Results from this method of calibration are subject to the greatest error since screw speed from the tachometer-generator must be read from a volt meter. A second method of calibration
was to place the pulse disk described earlier on a Phillips 212 electronic turntable and run the system at 33 and 45 rpm. Although only two points could be obtained in this way, it should be emphasized that the drifting or pulsing characteristics of the system were of greater concern than the absolute value of the screw speed. Accordingly, the system was allowed to operate at both of these speeds while fast data were collected. Results showed that the detector had negligible drift and that pulsing due to the inconsistency of the disk itself was limited to less than ±1 rpm. Finally, a pulse generator was used to input a very uniform signal to the system over a range of frequencies corresponding to the rpm range of the detector system. Results indicate that the electronics of the circuit are accurate to better than .01 rpm. Dynamic calibration of the system involved the preparation of a disk with known pulse fluctuations. The system was operated with this disk and data recorded. The time constant of the system was determined to be less than .05 sec.

Having examined and documented the characteristics of the extruder, the real time data acquisition system, and the measuring transducers, a realistic experimental program centered around those extruder variables earlier mentioned was formulated. This program included the measurement of six pressures at the locations shown in Figures 20 and 21. Figure 20 shows the positions used for the single stage feed screw and Figure 21 shows the positions used for both two stage screws; flow rate in and flow rate out of the system were measured in the same manner for all runs— all of the flow into the extruder was measured and only two of the thirteen output strands were measured.
Figure 20 - Single Screw Extruder, Single Stage Screw
Figure 21 - Single Screw Extruder, Two Stage Screw
The positions measured were the fifth and ninth holes of the die symmetrically spaced about the center (seventh) hole. It was determined that although the magnitude of any fluctuations in the output may vary across the die, that the frequency of the fluctuations did not and therefore could be accurately determined at all or any of the die head positions.

Screw speed was recorded for all runs also in the same manner. Finally, a non-interacting fiber optic temperature probe was used to determine, qualitatively, its feasibility as an indicator of the temperature and, in particular, as an indicator of bulk temperature fluctuations in the polymer. In order to determine how the probe reacted in the extrusion environment, one test run was done. In this run the probe was placed at the head of the extruder and also at the same axial position in the extruder a combined pressure-temperature transducer was placed 180 degrees opposed to the fiber. Fast data were collected and the results and analysis of these data are displayed and discussed in the analysis section.

Two sets of data were collected during each run--slow data which were taken at a rate of 2 Hertz and fast data which were taken at a 20 Hertz rate. Again, in each case block averaging of 64 Hertz and 640 Hertz data was used respectively.

The actual procedure involved in the collection of data have followed stepwise:

1. All systems were calibrated preceding the experiment.
2. The feed screw was removed and cleaned.
3. After replacing the screw all transducers were positioned on the extruder and the system heated to operating temperature.
4. The transducers were then monitored to insure proper operation
under known static conditions.
5. After heating for 2 hours the temperature of the system was
adjusted to run conditions.
6. Production was started and screw speed was increased to a
predetermined value.
7. The system was allowed to equilibrate under run conditions
for approximately one-half hour while all variables were
visually monitored via a display screen.
8. After one-half hour and/or "steady state" had been achieved
data collection was begun taking 17.06 minutes of slow data
immediately followed by 2.93 minutes of fast data. (Note:
The output hopper generally had to be emptied between the
fast and slow runs.)
9. Steps 6, 7, and 8 were repeated for each data run of the
day (usually four).
10. One of the data collection runs was repeated.
11. After each run and the repeat run data were transferred from
the disk to dectape, labeled and stored for analysis.
12. The equipment was shut down and allowed to cool.

A statistical approach was not used in this study because the
complexity of the process has been shown to restrict the applicability
of these studies within narrow limits and, further, this type of
approach offers no insight concerning the mechanisms involved in the
process. However, the experiments were performed in an arbitrary
order to minimize consistent errors. In addition, seven runs were
repeated to determine the reproducibility of the results.
DATA

Two types of data are presented in this section,

1. Calibration data
2. Experimental data.

In addition, the programs which were developed for the collection and storage of these data are briefly reviewed.

Calibration Data

Static calibration data were recorded for all transducers used in this study. In addition, dynamic calibration data were recorded for the pressure transducers, the flow rate transducers, and the screw speed transducer.

A sample of the static calibration data is shown in Table 1. This Table is the result of least squares fitting of the data from the static calibration of the input flow rate transducer, Table 1 shows a first order fit and a second order fit. The standard deviation for first order is 0.01948 and for second is 0.01159. It was determined, therefore, that the transducer follows a second order curve. Similarly, the output flow transducer was found to follow a second order curve. However, all other transducers used in the study with the exception of the fiber optic probe were first order. Calibration constants for all transducers are listed in Table 2.

Dynamic calibration data are presented in graphical form with accompanying statistical data. Dynamic calibrations are difficult
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<tr>
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<td>Fiber Optic</td>
<td>Probe</td>
</tr>
</tbody>
</table>

\[ X = M_1 (\text{voltage})^2 + M (\text{voltage}) + b \]

$X$ is Pressure, Temperature, or Screw Speed.

$R$ is the correlation coefficient of the least squares fit of the data.

---

\(^a\)
to determine because often the experimentalist is using state of the art instruments whose response characteristics are optimum. It is, therefore, difficult to find a "standard" against which the devices may be meaningfully calibrated. In this study, this difficulty was overcome in part by calibrating the devices against one another. That is, the input transducer was calibrated against the output and the responses compared statistically in terms of variance, standard deviation and probability density. Pressures were also compared by calibrating two at a time. Screw speed, however, could not be compared in this way since there was only one device available.

The results of this cross calibration technique for the flow rate transducers is shown in Figure 22. The effect of allowing water to flow from the input transducer system to the output transducer system while superimposing a 1 Hertz pulse on the flow at a point between them can be used to determine the response characteristics of both transducers and further the relative magnitudes of these responses to a single disturbance can be determined. While the input transducer signal matched the impressed pulse very well, the output response was less satisfactory.

The six pressure transducers were calibrated in pairs and the results are shown in Figures 23, 24 and 25. The plots show exceptional similarity in the response characteristics of any two pressure transducers. Although there is disagreement in base values the standard deviations are within 2% in all three cases. The histograms of the pairs are nearly identical and cross correlations confirmed
Figure 22 - Comparison of Input and Output Flow Rate Transducers' Response to a 1 Hz Pulse
Figure 23 - Comparison of Pressure Transducers' Response to a 1 Hz Pulse---Line #49 and Line #51
Figure 24 - Comparison of Pressure Transducer's Response to a 1 Hz Pulse
Line #48 and Line #53
Figure 25 - Comparison of Pressure Transducers' Response to a 1 Hz Pulse
Line #52 and Line 50
the equivalence of the paired responses.

In order to determine the response characteristics of the screw speed transducer it was calibrated three ways. First, the system was mounted on an accurate turntable and run. Results are shown in Figure 26 (Bot). Second, a pulse generator was used to input a uniform evenly-spaced pulse to the electronics of the system. Results are shown in Figure 26 (Mid). The standard deviation of the turntable system is .1 while that of the system using a pulse generator is .0058. Assuming the turntable is very stable, it is concluded that irregularities in the pulse disk are more significant than electronic noise. In order to determine the response time of the rpm detection system, a step decrease in pulsing was applied to the system by removing 24 pulses as a block from the disk. At 45 rpm this block is equivalent to a .05 second pulse which means that for .05 seconds with every turn of the disk no pulses were input to the detection system. The response is shown in Figure 26 (Top). The output from the system showed a very uniform drop in screw speed to 60% of the initial value.

Calibration Programs

1. Stacal - Stacal is the driver routine for three subroutines--Matrix, Point and Plot8. The program is capable of calibrating two transducers at once and will accept up to one hundred data points. Data are collected and displayed until the operator signals through a remote sensor that a data point is to be collected. Each point collected is the average value of 50 points collected in less than .1 second. Once all points have been collected, a least squares fit is applied to the data to determine coefficients for the transducer.
Figure 26 - Dynamic Response Characteristics of Screw Speed Transducer
First, second, third and fourth order polynomials can be fit and plotted. (Subroutines--Point, Matrix, Plot 8.)

2. Dyncal - The program Dyncal is used to dynamically calibrate one or two transducers. The program is basically a modification of the data collection routine and collects and stores data in the same fashion. (Not listed--See Data Program.)

3. Cali - Although thermocouple data were not recorded during the experimentation, thermocouples were used to monitor process conditions before and after each run and therefore had to be calibrated. The routine Cali is capable of calibrating up to 25 thermocouples simultaneously. A first order least squares fit is then used to determine coefficients for each thermocouple. (Routine Print3)

Programs are listed in Appendix B.

Experimental Data

The data in this study were collected as two separate files. For each run approximately 17 minutes and 4 seconds of data were collected at a rate of 2 points per second per variable--these data will be referred to as slow data from this point on. Also, approximately 2 minutes and 56 seconds of data were collected at a rate of 20 points per second per variable--these data will be referred to as fast data. All data runs include the readings from six pressure transducers, a fiber optic probe, two flow rate load cells and a screw speed detection system. The arrangement and display of these data for all runs are shown in Figures 27 through 38. See Appendix C for greater detail and statistics. In each figure, experimental rates are displayed
Figure 27 - Polyethylene, Fast Data. Single Stage Screw, 30, 60, 90 rpm (Bottom to Top)
Figure 28 - Polyethylene, Slow Data, Single Stage Screw, 30, 60, 90 rpm (Bottom to Top)
Figure 29 - Polystyrene, Fast Data, Single Stage Screw, 30, 60, 90 rpm (Bottom to Top)
Figure 30 - Polystyrene, Slow Data, Single Stage Screw, 30, 60, 90 rpm (Bottom to Top)
Figure 31 - Polyethylene, Fast Data, Two Stage Screw
30, 60, 90 rpm (Bottom to top)
Figure 32 - Polyethylene, Slow Data, Two Stage Screw, 30, 60, 90 rpm (Bottom to Top)
Figure 33 - Polystyrene, Fast Data, Two Stage Screw, 30, 60, 90 rpm (Bottom to Top)
Figure 34 - Polystyrene, Slow Data, Two Stage Screw, 30, 60, 90 rpm (Bottom to Top)
Figure 35 - Polyethylene, Fast Data, Two Stage Plasta Screw, 30, 60, 90 rpm (Bottom to Top)
Figure 36 - Polyethylene, Slow Data, Two Stage Plasta Screw, 30, 60, 90 rpm (Bottom to Top)
Figure 37 - Polystyrene, Fast Data, Two Stage Plasta Screw, 30, 60, 90 mm (Bottom to top)
Figure 38 - Polystyrene, Slow Data, Two Stage Plasta Screw, 30, 60, 90 rpm (Bottom to Top)
including either the fast or the slow data for three different screw speeds with one of the three feed screws and either polystyrene or polyethylene. For example, Figure 29 displays the data from runs F1, F3, and F5 (Fast data) at 30, 60 and 90 rpm (bottom to top) respectively. For polystyrene using the single stage feed screw described earlier, the thirty-six runs have then been compressed into twelve figures. The locations of the measuring elements in each particular run are shown in Figures 20 and 21. For all single stage feed screw runs the positions were the same. In Figure 20, the numbers refer to the following:

1. screw speed
2. input flow rate
3. pressure at the beginning of the transition zone
4. pressure at the middle of the transition zone
5. temperature at the end of the transition zone (fiber)
6. pressure in the middle of the metering zone
7. pressure in the middle of the metering zone
8. pressure downstream of the valve
9. die head pressure
10. flow rate out.

For all runs using the two stage feed screws, the following order of measured variables was used: (Figure 21)

1. screw speed
2. Flow rate in
3. Pressure in the middle of the first transition zone
4. pressure in the middle of the first metering section
5. temperature at the end of the first metering zone (fiber)
6. pressure at the end of the second feed zone
7. pressure in the middle of the second transition zone
8. pressure at end of screw
9. die head pressure
10. flow rate out of the system.

These positions correspond to positions in the plots starting from the bottom in each 10 variable set.

The data from each variable are first normalized and the normal-
ized value is then multiplied by 980. Thus, the resolution of the plot is one part in 980. Since the actual data can be resolved to one part in 16382, the resolving power of the display system severely limits total resolution. Nevertheless, if better resolution is desired the full expanse of the plotter may be used for a particular record, increasing the resolution to one part in 10000.

Since the fast data were actually collected at 640 Hertz averaging and recording sets of 32 evenly spaced points, the data are extremely accurate and required no filtering except for the flow rate data which was actually collected as a voltage and required differentiation.

The procedure to convert this voltage to a flow rate involved first, fitting the data to a second order curve. That is, through calibration it was determined that the load cells for both input and output flow rate were second order. Therefore, a second order curve was fitted to each data set and subtracted from it. The data then were filtered through a Fourier transform (the technique is described in the analysis section). Finally, the linear trend of the curve was added back to it after filtering and derivatives (flow rates) were obtained by fitting the curve in a stepwise manner with first order curves. It is the slope of these lines which determine the flow rates and which were plotted.

For each variable plotted, the maximum, minimum, average difference, variance and standard deviation were calculated and recorded. In addition, an eleven point histogram or probability density plot was determined.

Slow data tended to be obscured by aliasing since these data were
recorded at a frequency close to the Nyquist folding frequency. In order to extract the true trends of the data, filtering was required for all variables. Although several filtering techniques were tried, including window averaging and polynomial fits of the data, the best technique involved filtering through the Fourier transform; a low pass filter allowed all frequencies lower than .5 Hertz to pass and eliminated all higher frequencies. Input and output variables were treated similarly to those for fast data.

Data Collection Programs

1. **Data**

   The routine data is a driver program for three other subroutines--Data 1, Data 2, Aver. This program collects and stores on disk either 20 Hertz data or 2 Hertz data from 10 channels which are specified by the operator at run time. The data are stored as one file.

2. **Dtrans**

   The routine Dtrans is called after completing a run. The program separates and labels the variables as 10 individual files. It also transfers the data to dectape.

3. **Print**

   A routine was written to print out every eighth value of each variable data set. This was done so that a quick visual check of the data run could be performed after each run.

4. **Monitor**

   A monitor routine was used in this study to visually examine the processing conditions within the extruder before a run was started.
This program also printed out the conditions, including eight thermocouple readings, six pressures, two flow rates, and the screw speed. Initial conditions are listed in Appendix D. Programs are listed in Appendix B.
Analysis of the extrusion process has been the concern of numerous studies in the past fifty-five years. Analysis techniques have included equilibrium force balance analyses and dynamic modeling techniques. Unfortunately, a basic assumption in these developments requires that localized steady state conditions exist. Anastas, Lynn and Brodkey (2) were able to visually demonstrate melt flow transients which occurred with step changes in screw speed using a 1-inch extruder and a polymer-plasticizer solution. In this study, data are presented which show that melt flow instabilities continuously and often periodically occur in a commercial size extruder under "steady state" conditions.

The extrusion process then is very much a dynamic process and, further, the basic nature of the process is periodic or almost periodic. By dealing with the system as a periodic system and, further, by transforming the data collected from the time domain to the frequency domain, a unique perspective of the instabilities involved in the process is possible. In order to appreciate the usefulness of this technique it is important to understand the theory of the transform involved--in this case the Fourier transform.

The Fourier transform has found applications in every engineering discipline. The Fourier algorithm transforms data from the time domain to the frequency domain and although straightforward in principle, the calculational procedures involved in the transformation increase
in complexity as the desired speed of the transform is increased.

The fastest calculational procedure available today is appropriately called the fast Fourier transform (FFT) and is basically a shorthand version of the Fourier transform which reduces the number of multiplication steps involved. The procedure requires a high speed computer with core storage compatible with the number of data points to be transformed.

Because the computer used in the analysis of these data had limited word length and core storage, the extent of the calculations was limited. That is, since single precision had to be used due to time and storage considerations, the use of recursive calculations had to be minimized to prevent cumulative error from influencing the result. Also because of core storage restrictions, the maximum number of data points to be transformed was limited to 2048, which in turn limited the number of harmonics or frequencies returned by the transform to 1024. Finally, since the computer does not contain hardware for floating point arithmetic, execution time limited the overall extent of the analysis.

The particular version of the fast Fourier transform used in this study was a version developed by Cooley (11,12) and made available to the Ohio State University through an IBM shared library program.

The discrete repetitive form of the Fourier transform on which this FFT is based is given by:

\[ x_k = \sum_{i=0}^{N-1} x_i(t) e^{-j2\pi ik/N} \quad (9) \]

\[ k = 0, 1, \ldots, N-1 \]
where \( N \) - number of data points
\[ x_k \] - complex Fourier coefficient
\[ x_i \] - time domain data

In order to analyze a particular record for its frequency content, the analyst must be able to determine the power spectral density of the record and/or its autocorrelation although this function gives the same information only in a different form. In addition, a collection of records may be analyzed for the existence of common frequencies by cross correlation analysis or cross spectrum analysis. The power spectral density (PSD) can be obtained through the fast Fourier transform and is given by

\[
G_x(f_k) = \frac{2h}{N} \left| x_k \right|^2
\]

where \( h \) - time interval
\( N \) - number of values
\( x_k \) - complex Fourier coefficient
\( k \) - integer value \( f_k \) - discrete frequency

The cross spectral density and cross correlation can also be obtained through the fast Fourier transform of two or more records. The cross correlation is given by

\[
G_{xy}(f_k) = \frac{2h}{N} \left| x_k^* y_k \right| = G_{xy}(f_k) - j Q_{xy}(f_k)
\]

where \( x_k^* \) - complex conjugate of the Fourier coefficient

From the cross spectrum analysis two functions are obtained. The magnitude of the correlation is given by

\[
\left| G_{xy}(f_k) \right| = \sqrt{G_{xy}^2(f_k) + Q_{xy}^2(f_k)}
\]
\[ \theta_{xy}(f_k) = \tan^{-1} \left( \frac{Q_{xy}(f_k)}{C_{xy}(f_k)} \right) \]  

\( C_{xy}(f_k) \) and \( Q_{xy}(f_k) \) are known as the coincident and quadrature functions respectively. In addition, the coherence function may be calculated via the FFT and is given by

\[ \gamma_k^2 = \left| \frac{G_{xy}(f_k)}{G_x(f_k)G_y(f_k)} \right|^2 \]  

The coherence function is a real valued function which theoretically varies from 0.0 to 1.0. When the function at a particular frequency is equal to zero the two records are considered incoherent or uncorrelated at that frequency. When the function is equal to one for all frequencies, then the two functions are said to be completely correlated.

Finally, with an efficient fast Fourier transform program available, a data set can be accurately filtered by transforming it to the frequency domain, subtracting out any undesired frequencies using low pass, high pass, band reject, band pass filters or combinations of these, and inverting the filtered harmonics back to the time domain. A filtering routine was incorporated into the display program--Draw (listed in Appendix B).

A separate program--Corr, listed in Appendix B--was developed which is capable of calculating

1. autocorrelation functions
2. power spectral density functions
3. cross correlation functions
4. cross spectrum functions
5. coherence functions.

In addition, the program was designed to

1. Cosine taper the data to eliminate nonexistent low frequency components introduced during the transformation.
2. Smooth the power spectral densities using Hann smoothing.
3. Segment average the power spectral densities to reduce statistical error (4 segment averaging was used in all plots).

In order to calculate these quantities, the raw data had to be preprocessed. That is, in this study the data were stored as integer values to facilitate speed of acquisition and reduce storage space. For display and analysis, the data were converted to floating point format and calibrated with the coefficients discussed earlier. Also, because of the averaging scheme which was used during data collection, the number of wild points in the data was minimal and no editing was required. However, it was determined that due to "cross talk" between the screw speed channel and the output flow rate channel, a linear trend was superimposed on the screw speed readings. This trend amounted to a 1% linear deflection in the data. Accordingly a line was fitted to the data and subtracted from it.

Finally, mean and mean square values were calculated for every data record and in addition a probability density or histogram was calculated for each record.

The data were analyzed in three sets, each of which includes the fast and slow runs for both polymers at 30, 60, and 90 rpm using one of the three screws described earlier. Further, the data are discussed
in terms of

1. input fluctuations
2. temperature fluctuations (determined by the infrared fiber optic probe)
3. screw speed fluctuations
4. pressure fluctuations

The effect of these fluctuations on the extrusion process will be visually demonstrated where possible.

Finally, since the purpose of this study was to show the applicability of the frequency analysis technique, only the first set will be analyzed in detail with a more general analysis presented for sets 2 and 3.

Set Number 1--General Purpose Screw. Number 1 consists of the data shown in Figures 27, 28, 29, and 30 (Runs 10, 9, 11, 5, 3, 1 slow and fast).

The general purpose feed screw used in this study was a square pitched screw designed for use with many plastics. The throughput for polyethylene at 90 rpm was lower than that of polystyrene--2.79 lbs/min or 167.4 lbs/hr for the polyethylene and 3.0 lbs/min or 180.1 lbs/hr for the polystyrene. Fluctuations in head pressure were well within those levels generally considered acceptable (1 to 3% of average head pressure). For the polyethylene (run F10) fluctuations averaged .22% and for the polystyrene (run F5) fluctuations averaged 0.5%. (See Table 3 for results from all runs.)

Input Fluctuations

At position 2--input flow rate--a visual analysis of the fast data presented in Figures 27 and 29 (see also Appendix C) indicates
# TABLE 3

AVERAGE HEAD PRESSURE AND PERCENT FLUCTUATION

<table>
<thead>
<tr>
<th>Screw Type</th>
<th>Polymer</th>
<th>Run Number</th>
<th>rpm</th>
<th>Die Head Press</th>
<th>% Fluctuation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>PE</td>
<td>10 F</td>
<td>90</td>
<td>951.87</td>
<td>0.222</td>
</tr>
<tr>
<td>1</td>
<td>PE</td>
<td>9 F</td>
<td>60</td>
<td>865.99</td>
<td>0.233</td>
</tr>
<tr>
<td>1</td>
<td>PE</td>
<td>11 F</td>
<td>30</td>
<td>652.11</td>
<td>0.083</td>
</tr>
<tr>
<td>1</td>
<td>PS</td>
<td>5 F</td>
<td>90</td>
<td>369.12</td>
<td>0.508</td>
</tr>
<tr>
<td>1</td>
<td>PS</td>
<td>3 F</td>
<td>60</td>
<td>310.89</td>
<td>0.305</td>
</tr>
<tr>
<td>1</td>
<td>PS</td>
<td>1 F</td>
<td>30</td>
<td>235.50</td>
<td>0.086</td>
</tr>
<tr>
<td>2</td>
<td>PE</td>
<td>27 F</td>
<td>90</td>
<td>1089.9</td>
<td>0.227</td>
</tr>
<tr>
<td>2</td>
<td>PE</td>
<td>26 F</td>
<td>60</td>
<td>875.02</td>
<td>0.373</td>
</tr>
<tr>
<td>2</td>
<td>PE</td>
<td>25 F</td>
<td>30</td>
<td>641.59</td>
<td>0.143</td>
</tr>
<tr>
<td>2</td>
<td>PS</td>
<td>32 F</td>
<td>90</td>
<td>451.64</td>
<td>0.430</td>
</tr>
<tr>
<td>2</td>
<td>PS</td>
<td>30 F</td>
<td>60</td>
<td>388.13</td>
<td>0.877</td>
</tr>
<tr>
<td>2</td>
<td>PS</td>
<td>29 F</td>
<td>30</td>
<td>317.69</td>
<td>0.332</td>
</tr>
<tr>
<td>3</td>
<td>PE</td>
<td>16 F</td>
<td>90</td>
<td>957.74</td>
<td>0.402</td>
</tr>
<tr>
<td>3</td>
<td>PE</td>
<td>13 F</td>
<td>60</td>
<td>864.22</td>
<td>0.077</td>
</tr>
<tr>
<td>3</td>
<td>PE</td>
<td>15 F</td>
<td>30</td>
<td>643.95</td>
<td>0.062</td>
</tr>
<tr>
<td>3</td>
<td>PS</td>
<td>23 F</td>
<td>90</td>
<td>298.25</td>
<td>4.023</td>
</tr>
<tr>
<td>3</td>
<td>PS</td>
<td>21 F</td>
<td>60</td>
<td>249.29</td>
<td>4.720</td>
</tr>
<tr>
<td>3</td>
<td>PS</td>
<td>24 F</td>
<td>30</td>
<td>185.94</td>
<td>2.225</td>
</tr>
</tbody>
</table>

a 1 - Single stage screw
2 - Two stage screw
3 - Two stage Plasta Screw

b Standard deviation divided by average pressure
that the flow rate into the system fluctuates and that apparently these fluctuations become more severe as screw speed is reduced for the polyethylene run. However, for the polystyrene run the reverse is true—the fluctuations which occur increase in amplitude as the screw speed increases. Power spectral density plots for both polymer runs show that no particular frequency is dominant with the exception of a slight pulse which occurs at the frequency of the screw. Cross correlation of the input flow data with pressure data from Position 3—located at the end of the solids conveying section—also shows little coherence in most cases. Apparently these fluctuations are random and occur as a result of pressure fluctuations upstream of the first pressure transducer which are possibly damped out by the time they reach this pressure transducer. However, the pulses which consistently occur at the frequency of the screw are significant.

Lovegrove (29) has suggested that periodic fluctuations in the input flow rate at the frequency of the screw should occur as a result of uneven conveying; although not visibly obvious in most runs, fluctuations at this frequency were detected through frequency analysis.

Screw Speed

Screw speed measurements consistently showed a pulsing with each revolution regardless of the actual screw speed or operating conditions. (See Figures 27 and 29, position #1.) In addition, the amperage drawn by the drive motor was observed to fluctuate at the screw speed frequency in each run. It must be concluded, then, that the screw is
forced to scrape the barrel wall with each revolution or that uneven feeding causes this pulsing. The maximum fluctuation of this pulse is approximately 1%. Because the frequency of the pulse is that of the screw, any fluctuations caused by it in the extruder are masked by the pulse caused by the passage of the flight.

Visually, except for the pulsing with each revolution, the screw speed plots for the fast data are quite consistent. Only very minor (< 1%) apparently random fluctuations occur. However, in the 90 rpm polyethylene run (F10) a ½ screw speed fluctuation (alternate pulses vary) can be observed in the screw speed plot. (See Position 1, run F10, Figure 27.)

At 30 rpm, power spectral density plots derived from screw speed data are shown in Figures 39A, 40A, 41A, 42A. Figures 39A and 40A are for the polyethylene slow and fast runs respectively and Figures 41A and 42A are for the polystyrene slow and fast runs respectively.

The major frequency in Figure 39A occurs at .52 Hz which corresponds to the screw speed pulse previously described. Minor peaks occur at .45 Hz (location A), and .29 Hz (location B), and a strong peak at .96 Hz (location C). The peaks at .45 and .96 Hertz are the result of Nyquist frequency folding--commonly known as aliasing. From Figure 40A which is the power spectral density derived from the fast data run for polyethylene at 30 rpm, two strong peaks occur at .52 Hz (location A) and 1.04 Hz (location B). Since the cutoff frequency for the slow data run is 1.0 Hz, the higher frequency (1.04 Hz) is folded back according to

$$f_{\text{aliased}} = 2n f_{\text{cutoff}} \pm f_{\text{observed}}$$

(15)

where n - integer value

f - frequency
Figure 39C - Screw Speed PSD, 90 rpm, Polyethylene, Slow

Figure 39B - Screw Speed PSD, 60 rpm, Polyethylene, Slow

Figure 39A - Screw Speed PSD, 30 rpm, Polyethylene, Slow
Figure 40C - Screw Speed PSD, 90 rpm, Polyethylene, Fast

Figure 40B - Screw Speed PSD, 60 rpm, Polyethylene, Fast

Figure 40A - Screw Speed PSD, 30 rpm, Polyethylene, Fast
Figure 41C - Screw Speed PSD, 90 rpm, Polystyrene, Slow

Figure 41B - Screw Speed PSD, 60 rpm, Polystyrene, Slow

Figure 41A - Screw Speed, PSD, 30 rpm, Polystyrene, Slow
Figure 42C - Screw Speed PSD, 90 rpm, Polystyrene, Fast

Figure 42B - Screw Speed PSD, 60 rpm, Polystyrene, Fast

Figure 42A - Screw Speed PSD, 30 rpm, Polystyrene, Fast
Equation (15) means that any particular frequency which appears in a power spectral density plot may not necessarily be present in the actual data but that a higher frequency which is present in the system being examined is sampled digitally such that a lower frequency appears to be present when the individual data points are connected with interpolated lines. (Figure 43 shows the result of aliasing for a hypothetical case. The broken line indicates linear interpolation between the sampled points.)

The uncertainties associated with aliasing were avoided in this study by properly filtering these data through analog filters during the experimentation as described earlier, and by collecting both fast and slow data. Any frequency peak which appears in the slow data power spectral density plots which have a cutoff frequency of 1.0 Hz should also be present at the same frequency in the fast data power spectral density plots which have a cutoff frequency of 10.0 Hz. If it is not, then the frequency is probably an aliased frequency.

At 30 rpm, then, the pulses at .45 and .96 are aliased frequencies of 1.55 (location A) and 1.04 Hz (location B) respectively. (i.e., .45 = 2 (1) (1) -1.55) and .96 = 2 (1) (1) -1.04.) The very minor pulse at .29 Hz occurs at approximately one-half the screw speed frequency. The occurrence of this one-half screw speed frequency will be shown to be quite significant. It was detected not only in this study but also by Bartram (3) who used the same experimental apparatus as was used in this study. Also, Rahim (40), in a completely separate study, appears to have detected the same instabilities.

For the polystyrene run, similar aliased frequencies exist at
Figure 43 - Digital Aliasing
.96 (location A) and .45 Hz (location B) and again a very slight peak occurs at .25 Hz (location C in Figure 41A)---slightly less than one-half the rpm frequency.

At 60 rpm, dual peaks occur at .47 (location D) and .55 Hz (location E) in Figure 39B---the polyethylene run. However, no comparable pulses are present in Figure 41B---the polystyrene run. The peaks at .97 (location F) and .98 Hz. in these figures are folded back from 1.03 and 1.02 Hz peaks. The dual peaks again occur at slightly less than the one-half screw speed frequency.

At 90 rpm, the strong fairly broad double peak .79 and .765 Hz (location G) in the polyethylene PSD plot---Figure 39C---has no comparable frequency in the polystyrene plot---Figure 41C. The two other major peaks in each of these plots are aliased frequencies.

Therefore, the only major frequency peaks in these plots occur at the screw speed frequency and at one-half this frequency. Further, although the one-half screw speed frequency is detected in all the polyethylene plots, it is only detected in the 30 rpm plot for the polystyrene runs.

Fiber fluctuations

Rahim also investigated the use of the fiber optic probe for temperature measurement. He suggests that the instabilities recorded by a fiber optic probe are caused by fluctuations in the melt solid structure of the polymer helix alone. He states that as a result of the measurable temperature differences between the polymer melt and solid, down channel fluctuations in the system can be detected.
Results from the fiber optic probe indicate that the probe is also sensitive to pressure, or rather, that the probe will follow pressure variations closely. In order to demonstrate clearly this relationship the data from a separate run (run SH2) were manipulated by subtracting out from the PSD plots those frequencies associated with the pulse created by the passage of the screw land (raised portion of the screw flight). In run SH2 the fiber optic probe pressure transducer and thermocouple were located at the head of the extruder. (Same axial position.) The pressure transducer and thermocouple were placed in the bottom of the extruder barrel, and the fiber optic probe in the top of the barrel 180° opposed. The bandwidth of the pressure transducer is rated at 100 Hz, whereas that of the fiber optic probe is 10 Hz. As screw speed is increased to 90 rpm, the effect of the screw land passing under the fiber optic probe is therefore reduced since the time that the land is in the field of view of the probe is less than the response time of the probe. Specifically, the width of the land is .25 inches and that of the flight is 2.5 inches. At 90 rpm, the entire flight passes the fiber optic probe in .66 seconds and therefore the land passes the probe in .066 seconds which is less than the response time of the infrared system. Consequently, the effect of the pressure pulse due to the land is greatly reduced. However, the faster responding pressure transducer is unaffected by the increase in screw speed. Therefore, in order to visually demonstrate the comparison between pressure and fiber optic probe data at low frequencies, high frequencies associated with the pulse caused by the passing of
the land were subtracted from the data. This was done by transforming
the data, determining the power spectral density of the transform and
subtracting out those frequencies associated with the screw speed pulse
of the system. Figure 44 shows the power spectral density of head
pressure from this run. The major frequencies associated with the
screw speed pulse of the data are

<table>
<thead>
<tr>
<th>Location</th>
<th>Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>A, B, C, D</td>
<td>1.5</td>
</tr>
<tr>
<td>E, F</td>
<td>3.01</td>
</tr>
<tr>
<td></td>
<td>4.5</td>
</tr>
<tr>
<td></td>
<td>6.0</td>
</tr>
<tr>
<td></td>
<td>7.5</td>
</tr>
<tr>
<td></td>
<td>9.0</td>
</tr>
</tbody>
</table>

(Higher harmonics are introduced because of the non-sinusoidal nature
of the pulse. Also, a 0.0977 Hz range was actually removed to account
for frequency smearing.)

These frequencies have been removed from all four data sets--
thermocouple, fiber optic probe, head pressure and screw speed, top
to bottom). The unfiltered data are shown in Figures 45A and 45B.
The filtered data are shown in Figures 46A and 46B. Inspection of
the filtered data indicates that there does exist a close correlation
between the head pressure response and the fiber optic response at
the same axial position (rotated 180 degrees). The thermocouple re-
response and the screw speed response on the other hand are not cor-
related with either the pressure response or the fiber optic probe
response. Table 4 lists the coherence values between the measuring
elements at the major frequencies. In summary, the power spectral
density plots for the head pressure and fiber responses indicate that
moderately strong frequency peaks occur at .39 (location G), .8
(location H), and 1.19 Hz (location I), plus integer multiples of these
frequencies due to higher harmonics. However, these lower frequen-
cies do not occur in either the screw speed PSD or the thermocouple PSD.
1/4 screw speed frequency (.39 Hz)
Screw speed frequency (1.5 Hz)
1/2 screw speed frequency (.8 Hz)
3/4 screw speed frequency (1.19 Hz)

Figure 44 - PSD, Head Pressure, Polystyrene, Single Stage Screw, Run SH 2
Figure 45A - Unfiltered Data, 90 rpm, Single Stage Screw, Polystyrene, Run SH4, 0-51 sec.
Figure A55 - Unfiltered Data, 90 rpm, Single Stage Screw, Polystyrene, Run S'12, 51-102 sec.
Figure 46A - Filtered Data, 90 rpm, Single Stage Screw, Polystyrene, Run SH2, 0-51 sec.
Figure 46B - Filtered Data, 90 rpm, Single Stage Screw, Polystyrene, Run SH2, 51-102 sec
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The values in Table 4 confirm the existence of high correlation between pressure response and fiber optic response at low frequencies. Correlations between the other transducer responses were poor.

Since many specifications for the fiber optic probe were not available from the manufacturer, a rigorous theory concerning its relationship to pressure cannot be developed. It is now known—among other things—the exact frequency range which the probe detects. Therefore, what is affecting the response of the probe cannot be precisely determined. Nevertheless, a mechanism can be suggested.

It is assumed that any increase in pressure will result in a decrease in flow rate and a corresponding increase in circulation at a particular position in the extruder. This increased circulation results in increased shear and viscous heating. From Tadmor and Broyer (48) the time constants associated with momentum transfer are on the order of $10^{-4}$ to $10^{-7}$ sec for viscous polymer systems. Therefore, the fiber optic probe which has a response time of 100 milliseconds should certainly be affected by these changes. In addition, although the response of the thermocouple is also sensitive to the increased shear, its response time to viscous heat generation effects is much slower than that of the probe due to the low conductivity of the film of polymer at the wall through which this heat must be conducted.

Unfortunately, the response of the probe at upstream positions in the extruder is not only affected by variable shear but also by distinct variations in temperature due to the existence of solid at these positions. That is, the cooler solid pellets cause the response of the probe to drop.
Further, because of the crystalline nature of polyethylene, the temperature of the melt and the temperature of the solid pellets are closer than those temperatures for the amorphous polystyrene. Therefore, a less distinct pulse is observed for the polyethylene than for the polystyrene. For example, the temperature fluctuations recorded by the fiber optic probe for the 30 rpm polystyrene run was 18 degrees C and for the 30 rpm polyethylene run (F11) was 1.9 degrees C.

Therefore, for the remainder of this discussion, it will be assumed that at position 5 in the extruder the combined effects of variable viscous shear and variable fluid-solid temperature controlled the response of the fiber optic probe.

Visual inspection of the time series fiber data in Figures 27 and 29 (positions 5) in all runs shows that at 30 rpm the response for the polyethylene run is characterized by random sharp drops which are probably caused by wedging of the solid bed or complete filling of the flight channel with solid plastic. The polystyrene data are characterized by a more periodic fluctuation in every other flight or at one-half the screw speed frequency (Figure 29, run F1).

At 60 and 90 rpm, severe disruptions in the response of the probe are prominent in both the polyethylene (runs F9 and F10, Figure 27) and the polystyrene plots (runs F3 and F5 in Figure 29). The response could be caused by breaks in the solid bed helix or by severe pressure fluctuations. Also, the frequency of the disruption seems to decrease when the screw speed is increased from 60 to 90 rpm. Since the downstream pressure positions do not indicate a decrease in the fluctuations, it is assumed that the disturbance has moved downstream of
the probe. That is, from Tadmor and Klein's (49E) measurements, the size of the solid bed helix or length over the extruder in which the solid bed exists increases with screw speed. Also, the crystalline polyethylene will require an even longer length before complete melting has occurred. Since it appears that the disturbance is still occurring in the polyethylene run it must have moved downstream. For polystyrene, the frequency of the fluctuations increases as do the corresponding pressure fluctuations downstream of the probe.

Power spectral density plots confirm these observations. At 30 rpm (see Figures 47A and 49A), a very minor if not questionable peak occurs at .26 and .27 Hertz (location A, Figure 47A) in the polyethylene PSD plot. In the polystyrene run a strong dual peak occurs at .24 and .26 Hertz (location A, Figure 49A).

At 60 rpm (Figures 47B and 49B), both polymer runs exhibit two characteristic frequencies other than the screw speed frequency. In the polyethylene run very broad bands occur centered around .15 (location B) and .85 Hertz (location C). In the polystyrene run, two more distinct bands occur centered around .25 (location B) and .77 Hertz (location C). (See also Figures 48B and 50B.)

At 90 rpm, (Figures 47C and 49C), a similar situation occurs. Dual peaks appear in the polyethylene PSD centered around .15 (location D) and .85 (location E) (1.15 Hz aliased) and two strong single peaks occur in the polystyrene run at .36 (location D) and .85 Hertz (location E). (1.15 Hz aliased). (See also Figures 48C and 50C.)

In summary, at 30 rpm, the fiber optic system does not detect fluctuations other than a one-half screw speed fluctuation which appears
Figure 47A - Fiber PSD Plot, 30 rpm, Polyethylene, Slow

Figure 47B - Fiber PSD Plot, 60 rpm, Polyethylene, Slow

Figure 47C - Fiber PSD Plot, 90 rpm, Polyethylene, Slow
Figure 48C - Fiber PSD Plot, 90 rpm, Polyethylene, Fast

Figure 48B - Fiber PSD Plot, 60 rpm, Polyethylene, Fast

Figure 48A - Fiber PSD Plot, 30 rpm, Polyethylene, Fast
Figure 49A - Fiber PSD Plot, 30 rpm, Polystyrene, Slow

Figure 49B - Fiber PSD Plot, 60 rpm, Polystyrene, Slow

Figure 49C - Fiber PSD Plot, 90 rpm, Polystyrene, Slow
Figure 50A - Fiber PSD Plot, 30 rpm, Polystyrene, Fast

Figure 50B - Fiber PSD Plot, 60 rpm, Polystyrene, Fast

Figure 50C - Fiber PSD Plot, 90 rpm, Polystyrene, Fast
as a strong pulse in the polystyrene plot and as a very weak questionable pulse in the polyethylene plot. The difference in the amplitudes of the pulses may be due to a lower temperature differential between the solid and melt of the polyethylene. At 60 and 90 rpm, both polymers systems are characterized by two distinct frequencies other than the screw speed. Again the amplitude of the polyethylene pulses is much lower than those for the polystyrene. It appears that these frequencies are nearly symmetrically distributed about the one-half screw speed frequency which does not appear at 60 or 90 rpm.

Pressure

Six pressure transducer readings were recorded during the experimentation as described earlier. Analysis of the pressure transducers at positions 8 and 9--located after the valve and in the die head respectively--indicated in all runs that the responses from these positions were nearly equivalent. However, cross correlation analyses indicate that the response from these positions is only equivalent to about .7 Hertz. Figure 51 shows that the convergence and phase angle of the cross spectral density are equivalent below .7 Hertz (location A and B respectively) with some minor exceptions. That is, in this frequency range coherence is ~ 1.0 and phase angle is 0.0. Nevertheless, since the frequency range of interest--frequencies below that of the screw--were equivalent, only the fluctuations at position 8 were evaluated.

Visual inspection of the other pressure responses--positions 3, 4, 6, 7--indicates that generally, alternating pulses fluctuate. Also, at high rpm low frequency oscillations occur in the metering sections in the polyethylene run and in both the transition and the metering
Figure 51 - PSD and CSD, Polystyrene, 60 rpm, Fast Valve Pressure and Die Head Pressure

Coherence Plot

Cross Spectral -
(Phase angle)

Cross Spectral-
(Magnitude)

Die Head Pressure

Valve Pressure

Hz

Hz
sections in the polystyrene runs. (See Figures 27 and 29.)

At 30 rpm, the PSD plots for polyethylene and polystyrene for both the slow and fast data are shown in Figures 52 and 53, and 58 and 59 respectively. The arrangement of the plots places the results from position 3 in the bottom plot with those results from positions 4, 6, 7, and 8 placed above it respectively. In Figure 52, a minor peak at .28 Hz (location A) is shown to develop at position 6 in the extruder—the metering section. This frequency is approximately one-half that caused by the screw rotation. Similarly, Figure 58 shows that a dual peak occurs at .24 and .27 Hz (location A).

At 60 rpm (See Figures 54 and 55) pressure response PSDs for the polyethylene run indicate that a strong dual peak exists at .48 and .54 Hertz at positions 3 and 4 (location A). However, at position 6 (location B), the amplitude of this dual peak is attenuated and a much stronger low frequency component develops at .15 Hertz (location C). A broad frequency band also develops centered around .74 Hz (location D). All of the peaks are significantly attenuated at position 8—after the valve. In the 60 rpm polystyrene run (see Figures 60 and 61), minor peaks at .25, .5, and .77 Hz (locations A, B, C) already exist at position 3. However, at downstream positions (4, 6, 7, 8) it is very difficult to distinguish any specific frequencies because of the randomness of the signals generated. (See Figure 60.)

At 90 rpm, a similar situation occurs. At position 3 of the polyethylene run (see Figures 56 and 57) a strong fairly sharp peak exists at .76 Hertz (location A). This peak is almost completely attenuated at downstream positions in the extruder from which lower
Figure 52 - Pressure PSD Plots, 30 rpm, Polyethylene, Slow
Figure 53 - Pressure PSD Plots, 30 rov, Polyethylene, Fast
Figure 54 - Pressure PSD Plots, 60 rpm, Polyethylene, Slow
Figure 55 - Pressure PSD Plots, 60 rpm, Polyethylene, Fast
Figure 56 - Pressure PSD Plots, 90 rpm, Polyethylene, Slow
Figure 57 - Pressure PSD Plots, 90 rpm, Polyethylene, Fast
Figure 58 - Pressure PSD Plots, 30 rpm, Polystyrene, Slow
Figure 5 - Pressure PSD Plots, 30 rpm, Polystyrene, Fast
Figure 60 - Pressure PSD Plots, 60 rpm, Polystyrene, Slow
Figure 61 - Pressure PSD Plots, 60 rpm, Polystyrene, Fast
Figure 62 - Pressure PSD Plots, 90 rpm, Polystyrene, Slow
Figure 63 - Pressure PSD Plots, 90 rpm, Polystyrene, Fast
and higher broad frequency bands are detected centered at .21 (location B) and 1.3 Hertz (location C). In the polystyrene run (Figures 62 and 63) very distinct peaks occur at .35 and 1.15 Hertz. Again, it becomes very difficult to distinguish specific frequencies at downstream positions in the extruder although peaks at approximately 1/4, 1/2, and 3/4 the screw speed frequency appear to exist.

In summary, although in some runs it is difficult to state with certainty that specific frequencies exist, the plots do show that at most of the positions in the extruder distinct frequencies in terms of pressure pulses occur, indicating structure in polymer system. Also, the frequencies observed appear to shift with position in the system and the most important frequencies occur at 1/4, 1/2, and 3/4 the screw speed frequency.

The low frequency response of the extrusion system determined from both the fast and slow data can be used to characterize down channel fluctuations. At steady state, the profile passing a measuring element at any particular point in the extruder should be constant and consequently no low frequency (less than the screw frequency) components should be detected.

The low frequency most prevalent is the \( \frac{1}{2} \) screw speed frequency seen in many of the runs as previously described. The origin of this fluctuation must be in some periodic process occurring in the extruder.

There are three predictable periodic events occurring in the process continuously,

1. rotation of the screw
2. rotation of the polymer system helix
3. pressure pulsing in the solids conveying zone caused by the asymmetrical geometry of the feed inlet.
The \( \frac{1}{2} \) screw speed pulse is detected by the screw speed transducer, the pressure transducers and the fiber optic probe. The pulse is not an aliased frequency and it affects the polymer system and the mechanical operation of the screw.

Although the possibility that the perturbation is the result of a mechanical fluctuation cannot be completely ruled out, there are many reasons to discount it.

1. The fluctuation is not consistent throughout all runs as a mechanical fault would be expected to be.

2. The instability appears as dual peaks in the power spectral density in two runs and as a broad peak in another run. A mechanical pulse would be expected to cause a single sharp peak in the PSD.

3. The fluctuation is not consistent at all positions in the extruder in some runs. If the pulse were applied through the screw it would be expected that all positions would be affected.

4. Cross correlation results indicate that the pulse recorded in some of the runs at these \( \frac{1}{2} \) screw speed frequencies show no coherence with the screw speed response at those frequencies.

Assuming then that the pulse is not a result of the mechanical drive system it must be caused by the polymer system. In order for either the pressure transducers or the fiber optic probe to detect this fluctuation, alternate sections of the polymer helix must be substantially different.

Although Lovegrove (29) suggested that gravitational effects cause pulsing, another explanation which could account for very regular differences in the helix structure is related to the packing or compacting
effects at the entrance region of the extruder. That is, for one-half of the rotation at the entrance to the barrel the working pressure is equal to that of the head pressure. However, for the second half of the cycle an additional driving pressure is applied to the system as a result of the geometric design of the entrance region. Basically, the upper half of the screw is exposed to the open entrance region. When the compressive forces exceed the force developed by the head pressure circulation occurs—the circulation region. However, on the lower half of the screw in this section, circulation cannot occur and higher compressive forces are developed resulting in a more compacted section of the helix. The continuously alternating compressive force develops a continuously alternating helix structure. The actual magnitude of the compressive force difference can be calculated. The pressure developed may be calculated from

\[ P = P_0 e^{(-Az/D)} \]  

where

- \( P \) - pressure
- \( A \) - constant
- \( z \) - down channel length

For example, pressure forces in the polystyrene runs were calculated to be as much as 16 times greater on the lower portion of the screw compared with those pressure forces developed in the upper section. A calculated using Schneider's Equation (42).

The existence of this alternating structure, however, cannot account for the frequency response of the measuring elements unless it can be assumed that the bed is accelerated at some point in the extruder and further that this acceleration causes the weaker or less compacted
section of the helix structure to be elongated. As a result, the probes are exposed to different sections of the helix with each revolution.

Solid bed acceleration in an extruder has been the concern of several studies (40, 14, 1). Generally, the procedure involved in determining solid bed acceleration relies on screw push-out techniques and microsectioning. From the digital data collected in this study, the acceleration may be determined in situ. For example, by cross correlating the PSDs from adjacent positions the flow rate of instabilities may be quite accurately monitored—within the accuracy of the cross correlation procedure.

This procedure was used in run S3 (see Figure 30, slow data). In order to more clearly show the movement of instabilities during the extrusion of polystyrene the slow data were filtered through the FFT using a low pass filter which allowed only frequencies lower than .125 Hertz to pass. The filtered data are shown in Figures 64A and 64B. In order to determine flow rate through the extruder the residence time in each section was calculated through a cross correlation procedure. That is, the following positions were cross correlated:

1. Position 3 and position 4
2. Position 4 and position 5
3. Position 5 and position 6
4. Position 6 and position 7
5. Position 7 and position 8

The cross correlation plots are shown in Figure 65. The major peak indicates the point at which the highest correlation exists. For example, the third curve from the bottom is the result of the cross correlation between position 5 and position 6. The major peak (location A)
Figure 64A - A Low Pass Filtered Data (\(<.125\) Hz), 0 - 510 sec
60 rpm, Polystyrene, Single Stage Screw, Run S3
Figure 64B - Low Pass Filtered Data (< .125 Hz), 510 - 1020 sec
60 rpm, Polystyrene, Single Stage Screw, Run S3
Figure 65 - Cross Correlations, Polystyrene, Slow
60 rpm, Single Stage Screw
occurs at the fourteenth lag position. This means that there are fourteen time intervals between the best correlation point and time zero. For the slow data, the time interval is .5 sec and, therefore, position 4 lags position 5 by 7 seconds (accuracy is ± .5 sec). In a similar manner, all other lag values were calculated.

The flow rate through the transition and metering sections of the extruder was then calculated by simply dividing the distance between positions by the corresponding time lags. Results are shown in Figure 66.

The average flow rate through the solids conveying section was calculated by first determining the overall residence time of the extruder using a procedure described by Reber (41) this residence time was determined to be approximately 90 seconds for run S3. By subtracting the time needed for the flow to travel through the transition and metering sections, the residence time in the solids conveying section could be determined and then the flow rate through this section found. The flow rates are plotted in Figure 66. Strong acceleration occurs at the beginning of the transition. The plot is similar to those developed by Fenner (14) and Rahim (40) using screw push-out techniques. However, it is assumed that the plot presented in Figure 66 is somewhat more accurate since the flow rates obtained through the cross correlation procedure are more nearly true average flow rates. That is, screw push-outs can be used to measure only one event whereas the cross correlation results are averaged values of all the events which occur during the entire data collection period.

Finally, although all slow data sets do not show the same trends,
Figure 66 - Acceleration of Bed

\[ \Delta \] - Calculated
\[ 0 \] - Measured

in/min
Solid Bed Velocity

Inches from Feed

Figure 66 - Acceleration of Bed
this set does indicate that instabilities originate downstream or close to the first pressure transducer which is positioned at the end of the solids conveying section of the screw, indicating that in addition to the regular fluctuations at one-half the screw speed frequency which appear to develop in the solids conveying section, more important non-periodic frequencies may also develop. Then it is probable that the alternate helix structure is the cause of one-half screw speed fluctuations and non-periodic fluctuations.

The ability to detect and accurately measure the movement of instabilities in situ should be of value since it frees the experimentalist from the tedious and often unsuccessful method of using screw push-out techniques to determine the same quantities. In addition, many polymer systems which could not be examined using the push-out approach can be investigated using the frequency analysis approach.

At 60 and 90 rpm, frequencies at approximately 1/4 and 3/4 that of the screw are detected in many of the measuring elements. The 3/4 frequency is probably due to the rotation of the helix, that is, from residence time calculations, the rotational frequency of the polymer helix can be determined and was shown to be about 3/4 that of the screw. At this time, the cause of the 1/4 screw speed frequency can not be determined.

Finally, frequency analysis is useful for determining both cross channel fluctuations of the polymer system—the fast data collected can be used to characterize the cross channel regularity of the system at any particular point in the extruder. At true steady state the profile developed should be repeated with every rotation of the screw.
and the power spectral density calculated from this data should be characterized by a sharp peak at the frequency of the screw plus higher harmonics at integer multiples of this frequency. The variation in these higher harmonics can be directly linked to the viscoelastic properties of the melt system. That is, compared with temperature and/or pressure the frequency response of the polymer system fingerprints the system based on all its intrinsic properties and is therefore much more sensitive measure of the state of the system. Also, if the power spectral density has no distinct peaks then the polymer helix must be a random system indicating that severe break-up has occurred at or before this point. For example, the power spectral density plot for run #3 (see Figure 55) indicates that a random process is occurring at position 4 in the extruder, since the power spectral density plot shows no distinct frequencies to be present. Examination of the time series data (see Figure 29) confirms the fact that the flow past this point is very irregular compared to the other pressure transducer responses.

Although several major points of importance have been described, the interpretation of subtle changes involved in a frequency analysis procedure of this type can only be accurately determined by an expert in this field since the interpretation of the plots is somewhat of an art in itself. Therefore, the author has made no attempt to suggest the meaning of minor changes in the PSD plots and the frequency analysis in general.
Set Number 2--Two Stage Plasta Screw

The two stage screw used in this work was specifically designed for impact modified polystyrene. Understandably, then, this screw had the best overall performance for polystyrene. That is, output averaged 3.12 lbs/min or 187.2 lbs/hr at 90 rpm and die pressure fluctuations averaged .43% of average pressure. This screw also gave the best performance of the polyethylene runs. Flow rate averaged 3.52 lbs/min or 211.5 lbs/hr and die pressure fluctuations were .227% of average pressure.

Briefly, the fluctuating nature of the data recorded in these runs, although different from set number 1, indicates that similar processes are important in the system. Input fluctuations, screw speed fluctuations, and fiber fluctuations are similar to those of set #1. Pressure fluctuations are, however, quite different because of the two stage nature of the system--the instabilities of the system are radically modified as they pass from the first stage to the second. Nevertheless, visual examination of the slow data for these runs indicates that in spite of the second stage design, instabilities which originate in the solids conveying zone of the system are carried through the entire system. A more in-depth analysis of this data set should reveal the true nature of the system.

Set Number 3--Two Stage Plasta Screw

The feed screw used in this data set was specifically designed for low density polyethylene. At 90 rpm, the value for the polyethylene run was 2.56 lbs/min and the die head pressure fluctuation was .402% of total pressure. For the polystyrene runs the screw performed very
poorly with output at 2.39 lbs/m and pressure fluctuations of 4.02%.

The high density polyethylene used in this study ran well with this screw at thirty and sixty rpm. However, at ninety rpm the first stage of the screw was incapable of providing enough feed for the second stage with the result that quite severe pulsing occurred in the second stage. For the polystyrene runs the data indicate that the screw was completely unacceptable with very bad surging occurring even at 60 rpm.

In the single stage experiments it was determined that instabilities did affect the rotation of the screw. If this is true then the two stage concept should be re-examined since fluctuations imposed on the screw in the first stage will be transferred through the screw to all positions in the extruder, partially reducing the ability of the two stage design to separate and disperse instabilities in the melt flow system.
CONCLUSIONS

A system has been successfully developed to measure, display and analyze instabilities in the single screw extrusion process. Three common feed screw designs were evaluated at three different screw speeds for an amorphous and a crystalline polymer (impact modified polystyrene and high density polyethylene). In order to monitor the fluctuations during steady state operation of the system, input and output detection systems and a screw speed detection system were designed and built. The input flow rate detection system worked well and demonstrated that flow rate into the extruder could be continuously and accurately monitored. The screw speed detection system also performed well. However, the output flow rate transducer was subject to extraneous disturbances and results from the system were not considered reliable although they are presented.

A substantial amount of data has been presented in graphical form with accompanying statistically important qualities. Empirically, these data indicate that

1. The two stage screw design performed best for both polymers although it was designed specifically for impact modified polystyrene. That is, higher throughput rates were recorded at all of the screw speeds tested for this design and also die head fluctuations were within acceptable limits.

2. The two stage plastica screw performed worst. The screw was designed for low density polyethylene and the results indicated that
the second stage of the system was starved as a result of quite regular pulsing in the first stage. Although uniformity was considered acceptable for the polyethylene results with this screw, those for the polystyrene were considered unacceptable with head pressure fluctuations averaging greater than 4%.

3. The general purpose single stage screw performed adequately for both polymers in terms of head pressure fluctuations and output uniformity.

The data recorded from the single stage general purpose screw were analyzed for their frequency content. Results of this frequency analysis indicated

1. Periodic instabilities at approximately 1/4, 1/2, and 3/4 the frequency of the screw rotation were detected although all these frequencies did not occur in all the test runs. The fluctuations occurring at one-half the screw speed frequency were shown to result probably from cyclic compaction effects in the solids conveying zone, and those at 3/4 the screw speed frequency apparently are caused by the rotation of the polymer helix. However, the cause of the fluctuations at 1/4 the screw speed frequency could not be determined.

2. Many of the non-periodic instabilities occurring in the process originated at or before the beginning of the transition section of this screw.

3. Through cross correlation techniques, the mean residence time and acceleration through specific sections of the screw were determined quantitatively.

From the data presented, the occurrence, movement and significance
of instabilities in the extrusion process have been determined and qualitatively discussed. More importantly, an analysis procedure has been developed and demonstrated which yields quantitative information regarding these instabilities and should be useful for assessing the performance of existing screws and developing new designs.
RECOMMENDATIONS

The procedure demonstrated in this study has been used to examine the periodic and oscillatory nature of three plasticating feed screws. The following recommendations are suggested:

1. The dynamic characteristics of the fiber optic probe should be examined in more detail to determine the actual relationship which the response of the probe bears to the shear history and profile in the extruder.

2. A commercial load cell should be used for the input feed hopper and an integration circuit designed such that readings may be recorded as actual flow rates rather than voltages.

3. A more accurate, isolated system for the detection of output flow rate should be developed.

3. The data presented in this dissertation should be re-analyzed using a faster computer system with greater storage capability so that more averaging might be done and more accurate power spectral densities calculated.

4. The data from Sets 2 and 3 should be analyzed in detail using the frequency analysis techniques described.
REFERENCES CITED

1. Anastas, M. Y., Ph.D. Dissertation, The Ohio State University (1973)


   A) P2  B) Chap. 5  C) P110  D) Chap. 6  E) Chap. 8


APPENDIX A

Flow through the input hopper can be shown to effectively eliminate feed height fluctuations by supporting all of the weight of the polymer pellets regardless of height in the hopper. The derivation presented here follows closely that presented in McCabe and Smith (36).

Pressure at any particular height is given by

\[ P_z = \frac{F_z}{LW} \]  

(17)

For a rectangular duct and

\[ \frac{dP_z}{dz} = \frac{dF_z}{LW} \]

(18)

where \( dF_z = dF_z - dF_x \)

\[ dF_z = LW \rho_b \frac{g}{g_c} P_z - \mu (2Ldz + 2Wdz) P_L \]

(19)

where

- \( L \) - length
- \( W \) - width
- \( \rho_b \) - Density of bulk plastic
- \( g_c \) - Const. of proportionality
- \( \mu \) - coefficient of friction
- \( P_L \) - lateral pressure
- \( P_z \) - vertical pressure

Figure 67 A

\[ P_L/P_z = k' \]

(19)

\[ \frac{dP_z}{dz} = \rho_b \frac{g}{g_c} dz - \frac{\mu}{LW} (2Ldz + 2Wdz) P_L \]

(20)
\[ \frac{dP_z}{\rho \frac{g}{g_c} - \frac{2\mu}{LW} (L+W) P_z K'} = - \frac{dz}{P_z} \] 

(21)

\[ 1 - \frac{2\mu K'}{LW \rho g_c} (L+W) P_z = \exp \left[ z_T \left( \frac{1}{LW} \frac{1}{2\mu K' (L+W)} \right) \right] \]

(22)

\[ P_z = \frac{LW \rho g_c}{2\mu k' (L+W)} \left[ 1 - \exp \left( z_T \frac{2\mu K'}{LW} (L+W) \right) \right] \]

(23)

Substituting

\[ L = 4'' \]
\[ W = 1'' \]
\[ \mu = .527 \]
\[ \rho = 39 \text{ lb/ft}^3 \]
\[ K' = .521 \]
\[ P_z = 4.771 (1 - e^{-z_t (0.6812)}) \] (24)

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<td>7.0</td>
</tr>
<tr>
<td>4.75</td>
<td>8.0</td>
</tr>
<tr>
<td>4.76</td>
<td>9.0</td>
</tr>
<tr>
<td>4.765</td>
<td>10.0</td>
</tr>
</tbody>
</table>

Figure 67 B
In order to further reduce the base pressure, three 45° angles were added to the bottom of the hopper shown in Figure 67C. By not allowing the height of the pellets above (A) to drop below 7 inches \( P_{z1} = \text{const} \).

Also assuming that the 'No Flow' regions are filled with plastic and that the coefficient of friction for both the plastic and the steel are the same (11). The development follows that presented above very closely.

Defining the coordinate system as shown in Figure 67C where \( \alpha = 45° \)

\[
\Delta P_z = 3.373 \left(1 - e^{-\frac{z_t}{.9635}}\right) \quad (25)
\]

since \( z_t = 1.0 \) inches

\[ P_z = 2.086 \text{ lbf/ft}^2 \quad (26) \]

Therefore, the total pressure at (B) is 6.816 lbf/ft\(^2\) but by directing the flow through 90° at this point \( P_x = k'P_z = .521 \) (6.816)

\[ \therefore P_{xB} = 3.55 \text{ lbf/ft}^2 \quad (27) \]

which is a pressure drop from (A).

Now combining the effects of the two 45° additional angles assuming that the effects are additive

\[ P_{xG} = 5.636(.521) \quad (28) \]

Then

\[ P_x = 2.936 \text{ lbf/ft}^2 = .020 \text{ lbf/in}^2 \quad (29) \]

This force is const and negligibly small.
APPENDIX B

COMPUTER PROGRAMS

The computer programs used in this study are listed below. Because of the number of data sets involved in the analysis of this work these programs are necessarily specific for the type and format of the data collected.
STACAL

CALIBRATION ROUTINE FOR PRESSURE TRANSDUCERS

REAL LUN 52 TO T11 OR T12
REAL LUN 53 TO K50
REAL LUN 54 TO LP0

DOUBLE PRECISION SUM,SUM0

DIMENSION DATA1(100),DATA4(100).

COMMON NX,NXX,PRES,AVER,SPAN(8)

COMMON /DAT/SUM(5),DATA2(100),DATA3(100),SUM(5)

NX=0

DO 403 I=1,5

SUM(I)=0.000

SUM0(I)=0.000

CONTINUE

403 HOW MANY TRANSDUCERS WILL BE CALIBRATED--ONE OR TWO?

1 WRITE(53,200)

200 FORMAT(' DO YOU WISH TO CALIBRATE ONE (1) OR TWO (2)? ',/,' PRESSURE TRANSDUCERS? ') READ(52,205)ICAL

WRITE(53,201)ICAL

201 FORMAT(' THE NUMBER OF TRANSDUCERS TO BE CALIBRATED IS ',I1

1,',' OK? NO=0 YES=1 TERMINATE PROGRAM=2 ') READ(52,205)ANSW

IF(ANSW=1,2,75)

205 FORMAT(1)

2 IF (ICAL.EQ.2) GO TO 5

READ CHANNEL(S) AND RANGE THROUGH WHICH TRANSDUCER(S) WILL BE EXPOSED.

10 WRITE(53,210)

210 FORMAT(' CHANNEL(S) (13), RANGE (F7.1) ') READ(52,215)NCH,SPAN(1)

215 FORMAT(13,F6.1)

WRITE(53,220)NCH,SPAN(1)

220 FORMAT(' CHANNEL= ',I3,' RANGE= ',F7.1)

WRITE(53,225)

225 FORMAT(' OK? NO=0 YES=1 TERMINATE PROGRAM=2 ') READ(52,225)ANSW

IF(ANSW=1,10,15,75)

READS 50 VOLTAGES FROM THE CHANNEL(S) SELECTED

AND AVERAGES THEM, THIS AVERAGE IS THEN USED AS

THE DATA POINT.

15 CALL POINT(NCH)

DATA3(NX)=PRES

DATA2(NX)=AVER

WRITE(53,230)

230 FORMAT(' DO YOU WISH TO PROCEED WITH LEAST SQUARES?

1 NO=0 YES=1 TERMINATE PROGRAM=2 ') READ(52,230)ANSW

IF(ANSW=1,15,20,75)

5 WRITE(53,240)

READ(52,235)NCH1,NCH2,SPAN(1)
I CH1 = NCH1

235 FORMAT('I3,13,F6.1')
WRITE(53,240)NCH1,NCH2,SPAN(1)

240 FORMAT(' CHANNEL 1= ',13,', CHANNEL 2= ',13,' RANGE 
1= ',F7.1)
WRITE(53,225)
READ(52,205)IANSW
IF (IANSW, EQ, 0) GO TO 5

25 CALL POINT(NCH1)
DATA3(NX)=PRES
DATA2(NX)=AVER
NX=NX-1
CALL POINT(NCH2)
DATA4(NX)=PRES
DATA1(NX)=AVER
WRITE(53,230)
READ(52,205)IANSW
IF (IANSW-1)25,20,75

28 DO 400 I=1,NX
CALL MATRIX(NCH)
NCH=NCH2
DO 465 I=1,NX
DATA2(I)=DATA1(I)
DATA3(I)=DATA4(I)
465 CONTINUE

470 SUM(I)=SUM0(I)
480 CONTINUE
75 WRITE(53,285)
285 FORMAT(' TERMINATION REQUESTED')
80 CALL EXIT
END
SUBROUTINE POINT(NCH)

SUBROUTINE TO COLLECT THE DATA POINTS AND SUM THEM. THEY ARE THEN SENT TO THE MAIN PROGRAM.

LUN 52 TO TT1 OR TT2
LUN 53 TO KS0
LUN 54 TO LP0

DOUBLE PRECISION SUM,SUMB
DIMENSION MRATE(2),''
COMMON NX,NXX,PRES,AVER,SPAN(8)
COMMON /DAT/SUM(5),DATA2(100),DATA3(100),SUM0(5)
DATA MRATE/5.1/

DO 400 J=1,50
CALL RTIN(-1,NCH,DATA0,IEV)
CALL WAITFR(IEV)
SUM1=SUM1+DATA0
AVER=SUM1/50
CALL RTIN(-1.59,CHECK,IEV)
CALL WAITFR(IEV)
WRITE(53,200)AVER
FORMAT('1',F7,3)

CALL MARK(MRATE,IEV2)
CALL WAITFR(IEV2)
IF(CHECK.LT.4.0) GO TO 5
NX=NX+1
WRITE(53,205)NX
FORMAT(' POINT OK! NUMBER OF POINTS COLLECTED IS ',(I3))
WRITE(52,204)NX,AVER

WRITE(53,210)
FORMAT(' THE VOLTAGE FOR POINT NO'.13,' IS',F7.4)
READ(52,215)PRES
FORMAT('GUAGE PRESSURE (F10.5) ')
WRITE(53,220)PRES
FORMAT(' PRESSURE= ',F10.5)
WRITE(53,225)
FORMAT(' OK? YES=1 NO=0 ')
READ(52,230)IANS
FORMAT('11)
IF(IANS.EQ.0) GO TO 20

CALL MARK(MRATE,IEV2)

IF(NXX.EQ.0) GO TO 15
SUMB(1)=AVER*4*PRES+SUMB(1)
SUMB(2)=AVER*3*PRES+SUMB(2)
SUMB(3)=AVER*2*PRES+SUMB(3)
SUMB(4)=AVER*PRES+SUMB(4)
SUMB(5)=PRES+SUMB(5)
GO TO 25

SUM(1)=AVER*4*PRES+SUM(1)
SUM(2)=AVER*3*PRES+SUM(2)
SUM(3)=AVER*2*PRES+SUM(3)
SUM(4)=AVER*PRES+SUM(4)

15
SUBROUTINE HATRICE(NCH)

SUBROUTINE HATRICE DETERMINES THE COEFFICIENTS FOR EITHER A FIRST, SECOND, THIRD, OR FOURTH ORDER POLYNOMIAL. DATA ARE TRANSFERRED TO IT FROM THE MAIN PROGRAM.

REASSIGN

LUN 52 TO TT1 OR TT2
LUN 53 TO KSO
LUN 54 TO LP0

DOUBLe PRECISION DATA, SUM, SUM0
INTEGER ORDER
DIMENSION REF(8), OUT(8), DATA(5,6), Y1(100), TRANS(2), IDATE(6)
COMMON NX, NXX, PRES, AVER, SPAN(8)
COMMON /DAT/SUM(5), DATA2(100), DATA3(100), SUM0(8)
DATA THE, SUMX, C0, E/1, 0, 0, 0, 0/
SOLVES THE MATRIX BY STANDARD METHOD DESCRIBED BY GERALD--P.285

DO 405 J = 1, 5
N1 = 9 - J
DO 410 K = 1, 5
DATA(K, 6) = SUM(K)
DO 415 I = 1, NX
SUMX = SUMX + (DATA2(I) ** N1)
415 CONTINUE
DATA(I, K) = SUMX
SUMX = 0
N1 = N1 - 1
410 CONTINUE
405 CONTINUE

ASKS OPERATOR FOR ORDER OF POLYNOMIAL DESIRED.

WRITE(53, 250)
250 FORMAT(' ENTER ORDER AND TRANSDUCER NUMBER ') READ(52, 255) ORDER, TRANS(1), TRANS(2)
255 FORMAT(11, 1X, 2A5)
WRITE(53, 260) ORDER, TRANS(1), TRANS(2)
260 FORMAT(' ORDER=' ',I1,' TRANSUDER=' ',2A5)
WRITE(53, 225)
225 FORMAT(' RI, OK? YES=1 NO=0') READ(52, 265) IAN
IF (IAN, EQ., 8) GO TO 40
IF (ORDER, LE, NX) GO TO 41
ORDER = NX
WRITE(53, 226) NX
226 FORMAT(' ORDER IS TOO HIGH -- RESCHEDULE TO ', I1)

SOLVES MATRIX FOR THAT ORDER.

NORDER = ORDER
DO 420 K = ORDER + 1
DO 425 I = K, 4
R = DATA(I + 1, K) / DATA(K, K)
DO 430 J = K, 6
DATA(I + 1, J) = DATA(I + 1, J) - DATA(K, J) * R
CONTINUE
Continued

**LET** 5
DO 435 K=1,ORDER
KA=6-K
KB=LET-NORDER
DO 440 I=1,KB
IA=LET-I
R1=DATA(IA,KA)/DATA(KA,KA)
DO 445 J=LET,6,K
DATA(IA,J)=DATA(IA,J)-DATA(KA,J)*R1

**CONTINUE**

**LET**=LET-1
**CONTINUE**

DO 450 I=1,5
IB=6-I
DATA(IB,6)=DATA(IB,6)/DATA(IB,IB)

**CONTINUE**

Calculates Coefficients for the Polynomial,

\[ A = DATA(5\text{-ORDER}, 6) \]
\[ B = DATA(6\text{-ORDER}, 6) \]
\[ \text{IF}(\text{ORDER} \neq 1) \text{ GO TO 45} \]
\[ C = DATA(7\text{-ORDER}, 6) \]
\[ \text{IF}(\text{ORDER} \neq 2) \text{ GO TO 45} \]
\[ D = DATA(8\text{-ORDER}, 6) \]
\[ \text{IF}(\text{ORDER} \neq 3) \text{ GO TO 45} \]
\[ E = DATA(9\text{-ORDER}, 6) \]

**CALL DATE(1DATE)**
**WRITE**(52,265)A,B,C,E,NCH,TRANS,1DATE

**FORMAT**(10,' THE COEFFICIENTS ARE',6X,' A = ',F9.4)
10,' B = ',F9.4,6X,' C = ',F9.4,6X,' D = ',F9.4,6X,' E = ',F9.4

**CALL** (52,271)

**FORMAT**(10,' CALCU LATED',6X,' GU A GE VALUE',6X,'VALUE',6X)

**DO** 455 J=1,NX
**GO** TO(50,55,60,65,ORDER

Calculates Value Using Coefficients,

\[ Y_1(J) = A \times (DATA2(J)**2) \times B \times (DATA2(J)**3) \times C \times (DATA2(J)**2) \]
10,' DATA2(J)**2') + E
**GO** TO 70

\[ Y_1(J) = A \times (DATA2(J)**3) \times B \times (DATA2(J)**2) \times C \times DATA2(J)**2
**GO** TO 70

\[ Y_1(J) = A \times (DATA2(J)**2) \times B \times DATA2(J)**3
**GO** TO 70

**WRITE**(52,275)Y1(J),DATA3(J)

**CONTINUE**

Plot Both Calculated Value and Input Value

**WRITE**(53,272)

**FORMAT**(10,' DO YOU WISH TO PLOT? YES=1 NO=0')
**READ**(52,285)LANs
**IF**(LANs,EQ,0) **GO TO 71**
**DO** 465 J=1,NX

**WRITE**(53,272)

**FORMAT**(2X,F10.5,6X,F10.5)
**OUT**(1)=Y1(J)
**OUT**(2)=DATA3(J)
**REF**=148.
H L K r' I z H. 
SPAN (2) = SPAN (1) 
DO 460 K3 = 3, 8 
REF (K3) = 0, 
SPAN (K3) = 10, 
OUT (K3) = 10. 
460 CONTINUE 
CALL PLOT (SPAN, REF, OUT, TME) 
TME = TME + 1, 
465 CONTINUE 
71 C = 0, 
D = 0, 
E = 0, 
WRITE (53, 280) 
280 FORMAT (' DO YOU WISH TO TRY ANOTHER ORDER? 
YES = 1 NO = 0 ') 
READ (52, 205) IAW 
205 FORMAT (11) 
TME = 1, 
IF (IAW .EQ. 1) GO TO 30 
RETURN 
END
SUBROUTINE PLOT(S, R, OUT, TME)

PLOT SIMULATES AN 8 CHANNEL STRIP CHART RECORDER

DIMENSION S(8), R(8), OUT(8), IOUT(8), CODE(8), SPACE(101)

DEFINE WOLLERITH CONSTANTS

DATA CODE/1H1,1H2,1H3,1H4,1H5,1H6,1H7,1H8/
            BLANK/1H /, APOS/1H /, S/1H S/

CALCULATE POSITION ACROSS PAGE FOR EACH CHANNEL

DO 1 I = 1,8
    DEL = OUT(I) - REF(I)
    IOUT(I) = (DEL/SPLAN(I))*100.0 + 1.5
    IF(IOUT(I), GT, 101) IOUT(I) = 101
    IF(IOUT(I), LT, 1) IOUT(I) = 1
    CONTINUE

CLEAR LINE TO ALL BLANKS

DO 2 I = 1,101
    SPACE(I) = BLANK

MARK EACH 20 SPACES WITH AN APOSTROPHY

DO 3 I = 1,101,20
    SPACE(I) = APOS

CONSIDER EACH SPACE IN TURN

DO 4 I = 1,101
    ICTR = 0

CHECK EACH CHANNEL

DO 5 J = 1,8
    IF(IOUT(J), NE, I) GO TO 5
    SPACE(I) = CODE(J)
    ICTR = ICTR + 1
    CONTINUE

PRINT AN S IF TWO OR MORE CHANNELS COINCIDE

    IF(ICTR, GT, 1) SPACE(I) = S
    CONTINUE

OUTPUT THE LINE AND RETURN

WRITE(54,100) TME, (SPACE(K), K=1,101)

100 FORMAT(1H, F8.2, 10X, 101A1)

RETURN
END
CALI

This program collects data for the calibration of thermocouples.

REAL M, SUM, OLD, AVE, IMARK, IDATE

* This program collects data for the calibration of thermocouples.

LUN 50 TO RF0
LUN 52 TO TI1 OR TI2
LUN 53 TO KS0

IMPLICIT REAL(M)
DIMENSION ICHN(26), SUM(25), OLD(25), AVE(25), IMARK(2), IDATE(6)

SET CHANNELS TO BE SAMPLED

WRITE(53,5)
5 FORMAT('0', 'H1 THE CALIBRATION PROGRAM HAS BEEN REQUESTED')
CALL DATE(IDATE)
WRITE(52,6)(IDATE(I), I=1,6)
6 FORMAT('0', ' DATE ', IDATE)
WRITE(53,10)
10 FORMAT('1', ' INPUT NO. OF CHANNELS TO BE SAMPLED  MAX IS 25')
READ(52,20) N
20 FORMAT('15)
WRITE(53,30) N
30 FORMAT('1', ' ECHO', 115)

SET CHANNEL ASSIGNMENTS

DO 120 I=1,N
120 FORMAT('1', ' INPUT CHANNEL ASSIGNMENT NO. ', ICHN(I))
READ(52,20) ICHN(I)
WRITE(53,30) ICHN(I)
CONTINUE
100 CONTINUE
I珊瑚=1
140 FORMAT('1', ' ECHO', 112.5)

SET NUMBER OF RUNS

WRITE(53,160)
160 FORMAT('1', ' INPUT NUMBER OF RUNS DESIRED')
READ(52,20) NRUNS
WRITE(53,30) NRUNS

OPEN DATA FILE ON DISK

CALL ENTER(50, JHAPAD, JHDRAT, IEV)
CALL WAITFR(IEV)
DO 162 I=1,16
FDATE=IDATE(I)
WRITE(50,320) FDATE
162 CONTINUE
FN=N
WRITE(50,320) FN
FRUNS=NRUNS
WRITE(50,320) FRUNS
DO 165 I=1,N
ICHN(I)=ICHN(I)
WRITE(KA,399) FCHN
165 CONTINUE

CONTINUE

CLEAR ARRAYS

DO 180 I=1,N
   AVE(I)=0,
   SUM(I)=0,
   CONTINUE

COLLECT DATA 500 TIMES AND AVERAGE

DO 220 J=1,500
   DO 220 I=1,N
   NCNh=ICHn(I)
   CALL RTN(-1,NChH,XX,IEV)
   CALL WAITFR(IEV)
   SUM(I)=SUM(I)+XX
   CONTINUE
   DO 225 I=1,N
   AVE(I)=SUM(I)/500.
   CONTINUE

CHECK FOR DRIFT

MAXERR=-100.0
DO 230 II=1,N
   ERR=ABS((OLD(II)-AVE(II))/AVE(II))*100.
   OLD(II)=AVE(II)
   IF(ERR.GT.MAXERR) MAXERR=ERR
   CONTINUE

WRITE DATA TO SCOPE

WRITE(53,270)ICOUNT,MAXERR
270 FORMAT(1,14,' MAXERR= ',1F10.3)
WRITE(53,280)(AVE(I),I=1,N)
280 FORMAT(16F10.3)
   NCnH=59
   CALL RTN(-1,NChH,YChk,JEV)
   CALL WAITFR(JEV)
   YChk=ABS(YChk)
   IF(YChk.LT.4.) GO TO 170

READ PROCESS VARIABLE

WRITE(53,309)
309 FORMAT(1,' STEADY STATE HAS BEEN ACHIEVED')
310 FORMAT(1,' INPUT PROCESS VARIABLE')
305 WRITE(53,310)
   READ(52,320)YY
   WRITE(53,321)
   IF(YY.EQ.0) GO TO 320

IF PROCESS VARIABLE IS OK TYPE 1
IF NOT TYPE 2

READ(52,20)10K
IF(10K.NE.1) GO TO 305

OUTPUT TO DISK

WRITE(50,320)FCOUNT
320 FORMAT(1F12.5)
   FCOUNT=ICOUNT
   WRITE(50,320)FCOUNT
   WRITE(50,320)MAXERR
   WRITE(50,320)YY
   WRITE(50,320)(AVE(I),I=1,N,1)
   IF(FCOUNT.GE.1000000) GO TO 330

ICOUNT=ICOUNT+1
WRITE(53,325)
FORMAT('1 ',! ARE YOU READY? IF SO ENTER 1
1. TO TERMINATE RUN ENTER 2')
READ(52,20)IJ
IF(IJ.EQ.2) GO TO 330
329 IMARK(1)=15
IMARK(2)=2
CALL MARK(IMARK,IEV)
CALL WAITFRI(IEV)
GO TO 170
330 CALL CLOSE(50,3HPAD,3HOAT,IEV)
CALL WAITFRI(IEV)
WRITE(53,346)
340 FORMAT('10',! DONE WITH FINAL RUN')
CALL WAITFRI(IEV)
WRITE(53,350)
350 FORMAT('0',! ANALYSIS ROUTINE REQUESTED GOOD BYE')
CALL EXIT
END
PRINTS

THIS PROGRAM IS USED IN CONJUNCTION WITH CALI.
IT WILL READ FROM THE DISK THE DATA PLACED THEIR
BY CALI AND PRINT THE DATA TO A LINE PRINTER.
THEN PRINT3 WILL CALCULATE A 1ST ORDER LEAST
SQUARES POLYNOMIAL TO FIT THE DATA.
FINALLY THE POLYNOMIAL FIT, THE DIFFERENTIALS,
AND THE ROOT MEAN SQUARE ERROR WILL BE SENT
TO THE LINE PRINTER.

REASSIGN
LUN 50 TO RF0
LUN 52 TO TT1 OR TT2
LUN 53 TO KSP
LUN '54 TO LP0

DIMENSION X(25), ICHN(25), FDATE(6), IDATE(6), ERR(300)
1,SUM(25), SUMS0(25), SUMXY(25).
CALL SEEK(50,3HPAD,3HDAT,IEV)
CALL WAITF(IEV)
IF (IEV.LE.0) GO TO 1000
DO 5 I=1,6
READ(50,10) FDATE(I)
IDATE(I)=FDATE(I)
5 CONTINUE
WRITE(54,9) (IDATE(I), I=1,6)
READ(50,10) IFN
N=FN
WRITE(54,20) N
FORMAT(1F12,5)

20 FORMAT('0', ' THE NUMBER OF CHANNELS READ IS ',15)
READ(50,12) FRUNS
FRUNS=FRUNS
WRITE(54,21) NFRUNS
DO 30 J=1,N
READ(50,10) FCHN
ICHN(J)=FCHN
30 CONTINUE
WRITE(54,34)
34 FORMAT('0', ' CHANNEL NUMBER')
WRITE(54,35)(ICHN(I),I=1,N)

35 FORMAT('0', 'RUN', 'X', 'Y', '3X', '12110', '/9X', '12110', '/9X', '110)
DO 55 J=1,NFRUNS
READ(50,10) FCOUNT
ICOUNT=FCOUNT
READ(50,10) ERR(ICOUNT)
READ(50,10) Y
SUMY=SUMY+Y
DO 50 J=1, NFRUNS
READ(50,10) X(J)
SUM(J)=SUM(J)+X(J)
50 END
SU M XY(J)*X(J)*Y

50 CONTINUE
WRITE(54,60)ICOUNT,Y,(X(IJ),I,J=1,N)
CONTINUE
60 FORMAT('R',12,F10.3,12F10.5,13X,12F10.5,13X,1F10.5)
CALL CLOSE(50,3HPAD,3HDAT,IEV)
CALL WAITFR(IEV)
IF(IEV.LE.P) GO TO 1000
WRITE(54,80)
80 FORMAT('R', 'RUN MAXERR')
WRITE(54,90)(I,ERR(I),I=1,NRUNS)
90 FORMAT('R',13,1F10.4)
DO 400 I=1,N
TOTAL=R=0
WRITE(54,310)ICHN(I)
SLOPE=(SUM*SUM(I)-SUMXY(I)*FRUNS)/(SUM(I)**2-SUMSQ(I)*FRUNS)
310 FORMAT('R', 'LEAST SQUARES FIT CHANNEL NO.',I3)
B=(SUM*SUMSQ(I)-SUMXY(I)*SUM(I))/(SUMSQ(I)-SUM(I)**2)
WRITE(54,320)
320 FORMAT('R',9X,'X',15X,'Y',11X,'YCALC',13X,'DIFF')
CALL SEEK(52,3HPAD,3HDAT,IEV)
CALL WAITFR(IEV)
IF(IEV.LT.P) GO TO 1000
DO 330 J=1,6
READ(59,10)FDATE(I)
CONTINUE
READ(59,10)FN
READ(59,10)FRUNS
DO 330 J=1,N
READ(59,10)FCHN
CONTINUE
DO 330 J=1,N
READ(59,10)FCOUNT
READ(59,10)FXERR
READ(59,10)FRUNS
READ(59,10)Y
DO 340 K=1,N
READ(59,10)FCOUNT
CONTINUE
YCALC=SLOPE*X(I)*B
DIFF=YCALC-Y
TOTAL=TOTAL+DIFF**2
WRITE(54,345)Y,YCALC,DIFF
345 FORMAT('R',4F15.5)
CONTINUE
CALL CLOSE(50,3HPAD,3HDAT,IEV)
CALL WAITFR(IEV)
IF(IEV.LT.P) GO TO 1000
RMS=SQRT(TOTAL/NRUNS)
WRITE(54,360)SLOPE,B,RMS
360 CONTINUE
WRITE(54,365)R,R,
SLOPE=',1F15.5,' THE INTERCEPT=',1F15.5,' THE ROOT MEAN SQUARE ERROR=',1F15.5)
CALL EXIT
1000 WRITE(54,1001)IEV
1001 FORMAT('R', 'IEV=',I5)
CALL EXIT
END
DATA

TASK FOR OBTAINING DATA FROM TEN INPUT CHANNELS.

THIS TASK MUST BE FIXED IN CORE.

NORMAL TERMINATION OF THIS TASK IS BY SETTING CHANNEL 59 TO LESS THAN 5.0 VOLTS.

DATA ARE STORED ON DISK IN OPERATOR SPECIFIED FILES, IN BLOCKS OF 32 WORDS. THERE IS NO HEADER BLOCK, AND NO TERMINAL BLOCK. IN READING THE TAPE, USE THE END* OPTION WITH THE READ STATEMENT.

THIS TASK CONSISTS OF THE RESIDENT DRIVER (THIS CODE) AND TWO SUBROUTINES WHICH OVERLAY EACH OTHER. THE FIRST SUBROUTINE, DATA1 IS FOR INITIALIZATION, TERMINATION, AND CONTAINS ALL CHARACTER (FORMATTED) INPUT AND OUTPUT. DATA1 IS CALLED BY THE DRIVER AND BY THE OTHER SUBROUTINE. SUBROUTINE DATA2, THE SECOND OVERLAY, IS CALLED BY DATA1, AND CONTAINS CODE FOR DATA COLLECTION AND TRANSFER TO DISK.

REASSIGN

LUN 50 TO RF0
LUN 52 TO TT1 OR TT2
LUN 53 TO KS0

COMMON /PARAM/ IERR1, IERR2, IERR3, FILE1
IERR1 = 0
CALL DATA1
END
SUBROUTINE DATA1

SUBROUTINE DATA1, FIRST OF TWO OVERLAYERED SUBROUTINES FOR TASK
DATA. THIS SUBROUTINE HANDLES ALL CHARACTER (FORMATTED)
INPUT AND OUTPUT REQUIRED FOR INITIALIZATION AND ERROR
DIAGNOSTICS. SUBROUTINE DATA2 IS CALLED BY THIS SUBROUTINE FOR
COLLECTION OF DATA. THIS SUBROUTINE IS
CALLED BY THE DRIVER FOR INITIALIZATION AND BY SUBROUTINE
DATA2 FOR TERMINATION, WHETHER IN RESPONSE TO AN ERROR OR
BY OPERATOR REQUEST.

DIMENSION ICHAN(10)
COMMON /PARAM/ IERR1, IERR2, IERR3, FILE1
IF (IERR1) 101, 182, 183

CALL IS FOR INITIALIZATION.

102 WRITE (52,1)
1 FORMAT (52,1)
1 WRITE (52,16) IFAST
16 FORMAT (I1)
1 WRITE (52,17)
17 FORMAT ('0', ' ENTER FILE NAME(S)'
)
READ (52,2) FILE1, FAST
2 FORMAT (A5, 1X, A5)
WRITE (52,10)
10 FORMAT ('ENTER TEN (10) CHANNELS AND FREQUENCY,' )
READ (52,11) (ICHAN(I), I=1, 10 ), IFQ
11 FORMAT (I2, 10(I1, X, I2))
WRITE (52,12) FAST, FILE1, FAST, (ICHAN(I), I=1, 10), IFQ
12 FORMAT ('0', 11, 1X, A5, 3X, A5, 1X, 10(I1, X, I2), 1X, I2)
WRITE (52,13)
13 FORMAT ('0', ' OK YES=1 NO=0')
READ (52,14) IANS
14 FORMAT (I2)
LIMIT=64
IF (IANS = 1) 102, 15, 15
15 CALL ENTER (50, FILE1, 3HPAD, IEV)
CALL WAITFR (IEV)
1 IF (IEV) 111, 111, 112
111 WRITE (52,3) IEV
GO TO 198
3 FORMAT ('*** TAPE FILES CANNOT BE OPENED,' )
GO TO 199
198 CALL UNFIX (40, DATA)
GO TO 199
19 CALL DATA2 (ICHAN, IFQ, LIMIT)

ERROR DETECTED BY SUBROUTINE DATA2.

103 IF (IERR1 = 3) 121, 121, 101
101 WRITE (52, 4) IERR1
4 FORMAT ('*** ERROR, UNIDENTIFIED, IERR1=', I5)
10 GO TO 198
121 GO TO (131, 132, 133), IERR1
131 WRITE (52, 5) IERR2
5 FORMAT ('*** ERROR RETURNED BY RTSET, EVENT
1 VARIABLE=', I5)
GO TO 198
WHILE (B2.7) FILE1
FORMAT (" *** WRITE ERROR OCCURED. TAPE FILE ", A5, ' PAD'.")
GO TO 197

NORMAL TERMINATION, BY OPERATOR REQUEST,

WRITE (52,8)
FORMAT (" NORMAL OPERATOR TERMINATION REQUESTED.")
IF(IFAST.EQ.0.OR.IFO.EQ.1) GO TO 197
CALL CLOSE(50;FILE1;HHPAD;IEV)
CALL WAITFR(IEV)
IF (IEV) 141,141,142
IF0=1
FILE1=FAST
LIMIT=110
GO TO 15

CALL CLOSE (50, FILE1,3HPAD,IEV)
CALL WAITFR (IEV)
CALL UNFIX (4HDATA)
IF (IEV) 141,141,199

WRITE (52,9)IEV
FORMAT (" *** ERROR IN CLOSING TAPE FILE
1 EVENT VARIABLE1", I5)

CALL EXIT
END
SUBROUTINE DATA2(ICHAN, IFQ, LIMIT)

SUBROUTINE DATA2, SECOND OF TWO OVERLAYERED SUBROUTINES FOR TASK
DATA. THIS SUBROUTINE IS CALLED BY SUBROUTINE DATA1 FOR
COLLECTING DATA AND STORING THEM ON DISK. THIS
SUBROUTINE EXITS TO SUBROUTINE DATA1 UPON DETECTION OF AN
ERROR CONDITION OR OPERATOR TERMINATION REQUEST.

DIMENSION IT(2), KEEP(64, 10), ICHAN(10), POINT(64)
2, 13(256), 12(256)
3, 14(256), 15(256), 16(256), 17(256), 18(256)
4, 19(256), 110(256)

COMMON /PARAM/ IERR1, IERR2, IERR3, FILE1

COMMON IDT(256, 10)

EQUIVALENCE (ICHAN(1), IDT(1, 1)), (ICHAN(2), IDT(1, 2)), (ICHAN(3), IDT(1, 3))
ICHAN(4), IDT(1, 4)), (ICHAN(5), IDT(1, 5)), (ICHAN(6), IDT(1, 6)), (ICHAN(7), IDT(1, 7))
ICHAN(8), IDT(1, 8)), (ICHAN(9), IDT(1, 9)), (ICHAN(10), IDT(1, 10)), (POINT, KEEP(1, 1))

DATA IT/1, 2/

KOUNT=0

IDT(64, 10)=0

IDT(125:10)=0

IDT(256:10)=0

IPOS1=0

IPOS2=64

IPOS3=128

IPOS4=192

J=0

IA=ICHAN(1)

IB=ICHAN(2)

IC=ICHAN(3)

ID=ICHAN(4)

IE=ICHAN(5)

IF=ICHAN(6)

IG=ICHAN(7)

IH=ICHAN(8)

II=ICHAN(9)

IJ=ICHAN(10)

INITIALIZE CONSTANTS

CALL RTOUX(0, 0, 10)

CALL MARK(1, IV)

CALL WAIT(1, IV)

CALL RTINX(-2.59, VOLT)

IF(VOLT, GT, 4.0) GO TO 2

GO TO 1

CALL RTSET(I, IFQ, 11)

CALL RTSET(18, IFQ, 12)

CALL RTSET(16, IFQ, 13)

CALL RTSET(16, IFQ, 14)

CALL RTSET(15, IFQ, 15)

CALL RTSET(14, IFQ, 16)

CALL RTSET(13, IFQ, 17)

CALL RTSET(12, IFQ, 18)

CALL RTSET(11, IFQ, 19)

CALL RTSET(10, IFQ, 20, IERR2)

CALL WAIT(1, IV)

IERR=0
GO TO 103
15 CALL RTRY2(IERR2)
CALL WAITF2(IEV)
IF(IERR2)25.25.45
25 IERR1=2
GO TO 103
45 IF(I10(64),EQ,0)GO TO 45
CALL AVER(I1,POINT,J,IP051)
118(64)=0
55 IF(I10(128),EQ,0)GO TO 55
J=M+2
CALL AVER(I1,POINT,J,IP052)
118(128)=0
65 IF(I10(192),EQ,0)GO TO 65
J=M+2
CALL AVER(I1,POINT,J,IP053)
118(192)=0
75 IF(I10(256),EQ,0)GO TO 75
J=M+2
CALL AVER(I1,POINT,J,IP054)
J=M+2
118(256)=0
IF(J,NE,32,AND,J,NE,64)GO TO 45
K1=J-31
KOUNT=KOUNT+1
WRITE(50) (KEEP(L,M),M=1,10),L=K1,J
IF(J,EQ,64)J=0
IF(KOUNT.LT,LIMIT)GO TO 45
C
C  OPERATOR TERMINATION.
C
113 IERR1 = 3
103 CALL RTUX (0,0,0)
CALL DATA1
C
C  WRITE ERROR DETECTED.
C
301 IERR1 = 2
GO TO 103
END
.GLOBL AVER,,DA

AVER 0 /ENTRY POINT
JMS* ,DA /GENERAL GET ARGUMENT (OTS)
JMP *4+1 /JUMP ARROUND ARGUMENTS
ARRY1 ,DSA 0 /ARGUMENT 1
ARRY2 ,DSA 0 /ARGUMENT 2
POS1 ,DSA 0 /INCREMENT BETWEEN CALLS
POS2 ,DSA 0 /INCREMENT BETWEEN CALLS CALLS
LAC ARRAY2 /LOAD ADDRESS OF OUTPUT ARRAY
TAD* POS1
DAC ARRAY2 /LOAD ADDRESS OF INPUT ARRAY
LAC ARRAY1
TAD* POS2
DAC ARRAY1
LAC INPUT
LAW =2
DAC NUM4 /SET COUNTER 4
LOOP3 LAW =12 /SET COUNTER 3
DAC NUM3
LOOP2 DZM* PARAM /DEPOSIT ZERO AT PARAM
DZM TEMP /DEPOSIT ZERO IN ADDER
LAW =4 /SET COUNTER 2
DAC NUM2
LAW =10 /SET COUNTER 1
DAC NUM1
LAC* INPUT
LOOP RTL
RTL LRS 4
TAD TEMP /STORAGE FOR LOOP 1
DAC TEMP
IS2 NUM1 /CHECK COUNTER 1
JMP NEW /OK? YES - GET NEW WORD
RAL
LRS 4
TAD PARAM
DAC* PARAM /STORE AT ADDRESS OF PARAM
IS2 NUM2 /CHECK COUNTER 2
JMP NEW1 /OK? YES - GET NEW SET OF WORDS
RAL
LRS 3
DAC PARAM
IS2 NUM3 /CHECK COUNTER 3
JMP NEW2 /OK? YES - GET NEW VARIABLE
IS2 NUM4 /NO - CHECK COUNTER 4
JMP NEW3 /OK? YES - DO SECOND SET OF VARIABLES
JMP* AVER /NO - JUMP TO CALLING PROGRAM
NEW3 LAC ARRAY2 /LOAD ORIGIONAL ADDRESS
AAC +1
DAC PARAM
LAC ARRAY1 /TAKE SECOND 32 POINTS
AAC +40
DAC INPUT
JMP LOOP3
NEW2 LAC PARAM /RESET DUMMY TD NEW ARRAY
AAC +100
DAC PARAM
IAP INPUT

AVER -
AAC: *341
DAC: INPUT
JMP: LOOP2
NEW1: LAW =10 /RESTORE COUNTER 1
DA: NUM1
DIZ: TEMP /RESTORE ADDER
NEW2: LAC* INPUT /INCREMENT THE MEMORY
JMP: LOOP /JUMP TO LOOP
TEMP: 0 /TEMPORARY STORAGE FOR ADDER
NUM1: 0 /COUNTER 1
NUM2: 0 /COUNTER 2
NUM3: 0 /COUNTER 3
NUM4: 0 /COUNTER 4
PARAM: 0 /DUMMY ADDRESS
INPUT: 0 /DUMMY ADDRESS
.END
COLLECTION ROUTINE DTRANS

THIS COLLECTION ROUTINE TRANSFERS DATA FROM THE DISK TO A STORAGE DECTAPE. THE DATA ARE TRANSFERED INTO TEN FILES.

DIMENSION KEEP(32,10),TRANS(10)
DATA TRANS/5HPRZ5,5HPRZ5,5HPRZ5,5HPRZ5,5HPRZ5,2HIN,3HOUT,5HSCREW,5HINSERT/,DATA/40DATA/
WRITE(52,110)
110 FORMAT('0', 'ENTER FILE NAME AND OUTPUT EXTENSION')
READ(52,115)TEST,EXT
115 FORMAT(AS15,0),AS3)
WRITE(52,120)TEST,EXT
120 FORMAT('0', 'THE FILE TO BE TRANSFERED IS ',AS
 1.,'/', 'THE OUTPUT EXTENSION IS ',AS
 2.,'/', 'OK? NO=0 YES=1')
READ(52,125)IANS
125 FORMAT(11)
IF(IANS.EQ.0)GO TO 1
DO 480 I=1,10
C OPENS FILES AND TRANSFERS DATA
CALL SEEK(52,TEST,3HPAD,IEV)
CALL WAITFR(IEV)
DATA=TRANS(I)
CALL ENTER(51,DATA,EXT,IEV)
CALL WAITFR(IEV)
5 READ(50,END=10,ERR=25)((KEEP(L,M),M=1,10),L=1,32)
WRITE(51,END=20,ERR=25)((KEEP(L1),L=1,32)
GO TO 5
10 WRITE(51,END=20,ERR=25)((KEEP(L1),L=1,32)
20 CALL CLOSE(51,DATA,EXT,IEV)
CALL WAITFR(IEV)
CALL CLOSE(50,TEST,PA.D,IEV)
CALL WAITFR(IEV)
480 CONTINUE
WRITE(52,100)
100 FORMAT('0', 'DATA TRANSFER COMPLETED')
GO TO 30
25 WRITE(52,105)
C EXITS ON ERROR CONDITION.
105 FORMAT('0', 'ERROR IN WRITING TO THE TAPE OR IN READING 1 FROM THE FILE')
CALL CLOSE(51,DATA,PA.D,IEV)
CALL WAITFR(IEV)
CALL CLOSE(50,TEST,PA.D,IEV)
CALL WAITFR(IEV)
30 CALL EXIT
END
COLLECTION ROUTINE PRINT

THIS ROUTINE PRINTS THE DATA COLLECTED ON DISK.
ONLY EVERY EIGHTH POINT IS PRINTED. THIS SERVES AS
A QUICK METHOD TO SCAN THE DATA.

DIMENSION IDATA(32,10),IDATE(6)
WRITE(52,105)
105 FORMAT('WRITE DATA COLLECTION NAME')
READ(52,110)TEST
110 FORMAT(A5)
WRITE(52,111)
111 FORMAT(/,'WRITE RUN NUMBER AND CONDITIONS')
READ(52,112)RUN1,RUN2,RUN3,RUN4,RUN5
112 FORMAT(A5)
WRITE(52,115)TEST,RUN1,RUN2,RUN3,RUN4,RUN5
115 FORMAT('OK? NO=0 YES=1')
READ(52,120)IANS
120 FORMAT(A11)
IF(IANS.EQ.0)GO TO 1
CALL DATE(IDATE)
WRITE(54,116)IDATE,RUN1,RUN2,RUN3,RUN4,RUN5
116 FORMAT('OK? NO=0 YES=1')
DATA ARE WRITTEN TO THE LINE PRINTER.
CALL SEEK(58,TEST,3HPAD,IEV)
CALL WAITFRI(IEV)
DO 400 I=1,110
READ(58,END=10)((IDATA(L,K),K=1,10),L=1,32)
WRITE(54,100)((IDATA(L,K),K=1,10),L=1,25,8)
400 CONTINUE
10 CALL CLOSE(55,TEST,PAD,IEV)
CALL WAITFRI(IEV)
CALL EXIT
END
THIS IS THE MONITOR ROUTINE FOR DATA
DISPLAY DURING OPERATION, THIS ROUTINE
SAVES NO DATA AND USES DIGITAL FILTERING
DURING OPERATION, PROCESS PRESSURES, TEMPERATURES
MASS FLOW RATES AND SCREW SPEED ARE DISPLAYED.

DIMENSION ICHAN(18),DATA(18),OLD(18),IT(2)
DIMENSION C2(18),C3(18),IDATE(6)
DATA IT/1,2/,ALPHA/32/,KOUNT/0/
DO 410 I=1,18
READ(56,105)ICHAN(1),C2(I),C3(I)
105 FORMAT(12,1X,F7.3,1X,F7.3)
410 CONTINUE
WRITE(53,118)(ICHAN(I),C2(I),C3(I),I=1,18)
118 FORMAT('THE CHANNELS AND THE COEFFICIENTS ARE',/
1,18(/,1X,2X,F8.3,1X,F8.3)/)

READS ONE POINT FOR EACH CHANNEL AND DIGITALLY FILTERS IT.

DO 15 I=1,18
CALL RTIN(-1.59,VOLT)
IF(VOLT.GT.4.0)GO TO 20
CALL MARK(IT,IEV)
CALL WAITF(REV)
GO TO 15

DO 20 I=1,18
CALL RTIN(1.59,VOLT)
IF(VOLT.GT.4.0)GO TO 20
CALL MARK(IT,IEV)
CALL WAITF(REV)
GO TO 15

5 DO 420 J=1,18
DO 405 J=1,4
CALL RTIN(18,ICHAN,DATA,IEV)
CALL WAITF(REV)
DO 405 J=1,18
DATA(J)=0.
CALL RTIN(18,ICHAN,DATA,IEV)
CALL WAITF(REV)

DO 400 I=1,18
DATA(I)=ALPHA*DATA(I)+(1-ALPHA)*OLD(I)
400 OLD(I)=DATA(I)
CALL MARK(IT,IEV)
405 CALL WAITF(REV)
DO 415 J=1,18
DATA(J)=C2(J)*DATA(J)*C3(J)

NOW CONVERTS RAW VOLTAGE VALUE TO PRESSURE
TEMPERATURE, FLOW RATE, OR SCREW SPEED.

WRITE(53,108)(DATA(J),J=1,18)
108 FORMAT('1,'PRESSURES (PSIG)',6(2X,F7.2)/
1,' TEMPERATURES (C)',6(2X,F5.1)/
2,' FIBER OPTIC PROBE (V)',2X,F6.3,/
3,' SCREW SPEED (RPM)',2X,F6.2,/
4,' FLOW RATES (V)',2(2X,F6.3))
CALL RTIN(-1.49,VIN)
```
IF(VOLT,LT,4,0)GO TO 25
GO TO 5
25  KOUNT=KOUNT+1
WRITE(52,100)(DATA(J),J=1,10)
IF(KOUNT,GT,3)GO TO 30
GO TO 5
30  WRITE(52,155)RUN1,RUN2,RUN3,RUN4,RUN5
155  FORMAT(' ',///,3X,5AS)
CALL DATE(DATE)
WRITE(52,150)DATE
150  FORMAT(' ',///,6(2X,I3),///)
CALL RESST(4HDATA,1,IEV)
CALL WAITFRI(IEV)
10  CALL EXIT
END
```
ANALYSIS ROUTINE ORGN


REASSIGN

185

LUN 52 TO KSP
LUN 53 TO KSP
LUN 51 TO DT
LUN 54 TO LPS

DIMENSION KEEP(32), FILES(10), SMX(10), SMN(10), EXI(5)
1, C1(10), C2(10), IVAR(10), IDATE(6), IK(2), IC(2), ICUT(7)
COMMON /KEEP2(PS/P)
DATA FILES/SHS CCM, SHPRES6, SHPRES5, SHFIBER
1, SHPRES4, SHPRES3, SHPRES2, SHPRES1, SHOUT /
2, PAD/SHS, C1/10*1, . . . , C2/10*1, . . .
DATA EXI/3HS20, 3HS60, 3HSM3, 3HSM2, 3HSM1
DATA SMX/10*(-11.0), SMN/10*(-11.0)
WRITE(52,10)

102 FORMAT(' ', 'ENTER THE FILE EXTENSION?', /,
1. THE NUMBER OF VALUES TO BE SKIPPED?', /,
2. THE NUMBER OF SETS TO BE PLOTTED?', /,
3. THE NUMBER OF POINTS PER SET?', /,
4. THE STARTING SET?', /,
5. THE FREQUENCY CUT OFFS AND FILTER TYPE?', /,
6. THE BREAK POINTS ARE?', /,
7. THE NUMBER OF VARIABLES?', /,
8. THE SLOW DATA?', /,
9. HISTOGRAM?', /)
READ(52,10) EXI, ISKIP, ISET, IPOINT, ISTART, ICUT, IK, IC, ISL, IN
FORMAT(1X, 12, 1X, 11, 1X, 12, 5(1X, 11), 7(1X, 11), 1X, 12, 1X, 11, 1X, 11)
WRITE(52,10) EXI, ISKIP, ISET, IPOINT, ISTART, ICUT, IK, IC, ISL, ISN

105 FORMAT (' ', 'THE FILE EXTENSION IS ', 'AS?', ' THE NUMBER OF POINTS TO BE SKIPPED IS ', '14, /
3. THE NUMBER OF POINTS TO BE PLOTTED IS ', '13, /
4. THE STARTING SET IS ', '15, /
5. THE FILTERS ', '12, 2X, ' THE CUT OFFS ', '15, 3X, 15, 3X, 15, /
7, 4(5X, 15), ', THE NUMBER OF VARIABLES IS ', '14, /
8, SLOW DATA?', '13, /
9, HISTOGRAM?', '13, /
8, OK? NO=0 YES=1+)
READ(52,115) ANS

115 FORMAT(I1)
IF (AI(5, EQ. 0)) GO TO 1
NUM=IPOINT*ISET
ISET=2*IPOINT
IPOINT=2*IPOINT
NUM=NUM/32
DO 402 II=1,10
142 IVAR(II)=II
1PLOT=38P
130 FORMAT(' , ', ENTER THE PLOT SPAN')
READ(53,135)PLOT
135 FORMAT(15)
WRITE(53,135)PLOT
120 FORMAT(' , ', ENTER THE ORDER OF PLOTTING')
NO 401 I=1,10
READ(53,129)IVAR(I)
125 FORMAT(12)
CONTINUE
WRITE(53,135)PLOT
150 FORMAT(' , ', THE PLOTTING SPAN IS',I6)
NO 403 IREP=1,10
WRITE(53,151)IVAR(IREP)
151 FORMAT(' , ', THE VARIABLE IS',I3)
CONTINUE
WRITE(53,153)
153 FORMAT(' , ', OK? NO=0 YES=1')
READ(53,115)IANS
IF(IANS.EQ.9)GO TO 2
DO 404 II=1,10
C ADJUST VARIABLE ORDER
I=IVAR(I1)
READ(56,101)C1(I),C2(I),FILES(I)
FORMAT(F8.3,1X,F8.3,1X,A5)
WRITE(53,102)C1(I),C2(I),FILES(I)
FORMAT(F8.3,1X,F8.3,1X,A5)
101 FORMAT(F8.3,1X,F8.3,1X,A5)
102 FORMAT(F8.3,1X,F8.3,1X,A5)
104 ISAV=ISkip
DO 403 II=1,10
ISkip=ISAV
ICUT=ICUT(1)
ISTOP=ICUT(1)
DO 400 K7=1,ISTOP
IF(K7.NE.11)ICUT(2)=2
ISkip=(K7-1)*8
100 CONTINUE
C CORRECT SIGN
I=IVAR(I1)
101 SIG1=1
102 IF(I.ME.10)GO TO 6
103 IK1=ICK(1)
104 IK2=ICK(2)
6 GO TO(9,7,7,7,6,7,7,7,7,8),I
7 IF(SIG1.EQ.1)
8 FILE=FILES(I)
K2=1
CALL SEEK(51,FILE,EXT,IEV)
CALL WAITF(IEV)
C SKIP INITIAL VALUES IF REQUESTED
10 IF(ISkip.EQ.0)GO TO 10
DO 427 M=1,ISkip
420 READ(51)KEEP
10 DD 405 K=1,NUM
READ(51)KEEP
DD 426 K1=1,32
CALL AOCNV(KEEP(K1),KEEP(K2))
KEEP(K2)=KEEP(K2)*ISign
K2=K2+1
CONTINUE
CALL CLOSE(51,FILE,EXT,IEV)
CHANGE VALUES FOR IN AND OUT TO DIFFERENTIAL VALUES

IF(I.EQ.2.AND.1.NE.10.AND.ISLOW.NE.1)GO TO 490
GO TO (11,12,13,14,15,13,13,13,12,1)

11 CALL LINE1(NUM,C,GO)
IFS=1
CALL FILTR(AKEEP,MUM,IFS,IERR)
CALL BAND(ICUT,NUM)
IFS=1
CALL FILTR(AKEEP,MUM,NUM,IERR)
C=G,0
GO TO 20

12 CALL RCOMP(IBK,MUM,NUM,ICUT)
CALL INOUT(NUM)
C=G,0
C=G,0,0
GO TO 20

13 CALL LINE1(NUM,C,GO)
IFS=-1
IERR=""
CALL FILTR(AKEEP,MUM,IFS,IERR)
CALL BAND(ICUT,NUM)
IFS=1
CALL FILTR(AKEEP,MUM,IFS,IERR)
GO TO 20

14 CALL LINE1(NUM,C,GO)
IFS=-1
CALL FILTR(AKEEP,MUM,IFS,IERR)
CALL BAND(ICUT,NUM)
IFS=1
CALL FILTR(AKEEP,MUM,IFS,IERR)

20 EX=EX1(K)
CALL ENTFR(55,FILE,EXK,IEV)
CALL WAITFR(IEV)
IF(I.EQ.2.OR.1.EQ.10)CALL LINE1(NUM,C,GO)
WRITE(55)(AKEEP(K),K,FILE,EXK,IEV)
CALL CLOSE(55,FILE,EXK,IEV)
CALL WAITFR(IEV)

492 CONTINUE
GO TO 412
M=1,NUM

412 AKEEP(M)=AKEEP(M)+C*FLOAT(M)+GO
CALL ENTER(50,FILE,PAD,IEV)
CALL WAITFR(IEV)
CALL STAT(NUM,1,SMAK,SMIN,DIF,AMAIN,SD,VAR,C1,C2,PX,PN)
GO TO 415
L1=1,NUM
DO 416 L1=1,32
L2=L1+(L-1)*32

416 KEFP(L1)=AINT(AKEEP(L2)*IPLOT)
WRITE(54,140)FILE,EXK,AMAIN,PX,PN,SD,VAR

415 CALL CLOSE(55,FILE,PAD,IEV)
CALL WAITFR(IEV)
WRITE(54,140)FILE,EXK,AMAIN,PX,PN,SD,VAR

144 FORMAT(*:THE FILE AND EXTENSION ARE 'A5,2X,A3,///
1,' THE AVERAGE VALUE IS '1PE12.4,' THE MAXIMUM VALUE
2 IS '2X,1PE12.4,' THE MINIMUM VALUE IS '2X,1PE12.4,' THE
3 DIFFERENCE IS '2X,1PE12.4,' THE STANDARD
4 DEVIATION IS '1PE12.4,' THE VARIANCE IS '1PE12.4,///)
IF(I.EQ.0)GO TO 490
CALL HIST(PX,PN,NUM,1,C1,C2)
CONTINUE
ISKIP=((ISTART-1)*IPOINT)/32
DO 460 K=ISTART,ISET
CALL LABEL(K,10)
DO 455 I=1,10
I=VAR(I)
FILE=FILES(I)
CALL SEEK(59,FILE,PAD,IEV)
CALL WAI TP(IEV)
CALL ORAW2(ISKIP,I,IPOINT,I,IPL0T)
... 
CALL CLOSE(5P,FILE,PAD,IEV)
CALL WAITFR(IEV)
CONTINUE
CALL HPL0T(8,999,9999)
IF(K.EQ.ISET)GO TO 460
ISKIP=ISKIP+(IPOINT/32)
WRITE(52,155)
155 FORMAT(' PLOTTING COMPLETED - CHANGE PAPER AND PEN'
' Y/N? OK? NO=2 YES=1')
READ(52,175)IANS
175 FORMAT(1I1)
IF(IANS.EQ.0)GO TO 30
CONTINUE
WRITE(52,180)
IANS FORMAT(1P', 'DATA TRANSFER COMPLETED')
CALL EXIT
END
ANALYSIS ROUTINE DRAW2

THIS ROUTINE normalizes values sent to it from DRAW1 and positions them on the plotter.

SUBROUTINE DRAW2(ISKIP, I, IPOINT, II, IPLOT)
DIMENSION KEEP(32)
IF(ISKIP.EQ.0)GO TO 5
DO 415 H=1,ISKIP
415 READ(5P)KEEP
IP=IPOINT/32
DO 445 K=1,IP
READ(5P)KEEP
IF(K.GT.1)GO TO 10
Y=(II-1)*(IPOINT+80)+199
IY=IPOINT(Y)+KEEP(I)
K3=9216/IPOINT
L1=K3*IPOINT
IY=IPOINT(Y)+(IPOINT+80)/2
CALL HPLLOT(0,0,1,Y)
CALL DRAW4(L1)
CALL HPLLOT(0,0,0,1)
CALL DRAW3(KEEP,K,K3)
10 CONTINUE
RETURN
END

ANALYSIS ROUTINE DRAW3

THIS ROUTINE draws vectors between the values sent to it from DRAW2.

SUBROUTINE DRAW3(KEEP,K,K3)
DIMENSION KEEP(32)
ISTART=1
IF(K.GT.1)GO TO 5
IOLD=KEEP(1)
ISTART=2
5 DO 400 J=ISTART,32
IY=KEEP(J)+IOLD
CALL HPLLOT(1,1,K3,Y)
IOLD=KEEP(J)
400 RETURN
END

ANALYSIS ROUTINE DRAW4

THIS ROUTINE draws a center line at the average value.

SUBROUTINE DRAW4(L1)
CALL HPLLOT(1,1,L1,0)
RETURN
END
SUBROUTINE FORT (A,M,S,IFS,IFERR)

FORT. ONE-DIMENSIONAL FINITE COMPLEX FOURIER TRANSFORM,
FOURIER TRANSFORMING SUBROUTINE, TAKEN FROM IBM SHARE LIBRARY.

DOES EITHER FOURIER SYNTHESIS, I.E., COMPUTES COMPLEX FOURIER
SERIES GIVEN A VECTOR OF N COMPLEX FOURIER AMPLEUS, OR,
GIVEN A VECTOR OF COMPLEX DATA X, DOES FOURIER ANALYSIS,
COMPETING AMPLEUS.

A IS A COMPLEX VECTOR OF LENGTH N = 2**M COMPLEX NUMBERS OR
2**N REAL NUMBERS. A IS TO BE SET BY THE USER.
M IS AN INTEGER 2<K<11, SET BY THE USER.
S IS A VECTOR S(J) = SIN(2*PI*J/NP), J = 1, 2, ..., NP/4-1,
COMPUTED BY THE PROGRAM.
IFS IS A PARAMETER TO BE SET BY THE USER AS follows-
IFS = 0 TO SET NP = 2**M AND SET UP SINE TABLE.
IFS = 1 TO SET N = NP = 2**M, SET UP SINE TABLE, AND DO
FOURIER SYNTHESIS, REPLACING THE VECTOR A BY
X(J) = SUM OVER K = 0, N-1 OF A(K)*EXP(2*PI*I/N)*E(J*K),
J = 3, N-1, WHERE I = SORT(-1)
THE A'S ARE STORED WITH REA(X(J)) IN CELL 2*J+1 AND IM(X(J))
IN CELL 2*J+2 FOR J = 0, 1, 2, ..., N-1.
THE A'S ARE STORED IN THE SAME MANNER.
IFS = -1 TO SET N = NP = 2**M, SET UP SINE TABLE, AND DO
FOURIER ANALYSIS, TAKING THE INPUT VECTOR A AS X AND REPLACING
IT BY THE A SATISFYING THE ABOVE FOURIER SERIES.
IFS = +2 TO DO FOURIER SYNTHESIS ONLY, WITH A PRE-COMPUTED S,
IFS = -2 TO DO FOURIER ANALYSIS ONLY, WITH A PRE-COMPUTED S,
IFS IS SET BY THE PROGRAM TO-
= 0 IF NO ERROR DETECTED.
= 1 IF M IS OUT OF RANGE, OR, WHEN IFS = +2 OR -2, THE
PRE-COMPUTED S TABLE IS NOT LARGE ENOUGH.
= -1 WHEN IFS = +1 OR -1, MEANS ONE IS RECOMPUTING S TABLE
UNNECESSARILY.

NOTE- IT MAY BE NECESSARY TO IMPOSE A LOWER MAXIMUM BOUND ON
M, DEPENDING ON THE CORE AVAILABLE FOR STORAGE. ALSO, IT MAY
POSSIBLE TO INCORPORATE A HIGHER VALUE BY EXTENDING THE K
ARRAY AND ADDING MORE "DO 30 ..." LOOPS.

DIMENSION A(1),S(1),K(12)
EQUIVALENCE (K(1),K1), (K(10),K2), (K(9),K3), (K(8),K4),
1 (K(7),K5), (K(6),K6), (K(5),K7), (K(4),K8), (K(3),K9),
2 (K(2),K10), (K(1),K11,N2)
IF (M) 2, 2, 3
IF (M-11) 5, 5, 2
2 IFERR=1
1 RETURN
5 IFERR=4
10 M=IABS(IFS)-1
C WE ARE DOING TRANSFORM ONLY. SEE IF PRE-COMPUTED S TABLE
C IS SUFFICIENTLY LARGE.
12 IFERR = 1
GO TO 200
C SCRAMBLE A, BY SANDE'S METHOD.
20 K(1) = 2*N
DO 22 L = 2,M
22 K(L) = K(L-1)/2
DO 24 L = M-1,0
24 K(L+1) = 2
1. BINARY

DO 30 J1 = 2, K1, 2
J1 = 2

30 IF (J1 = K1) 331, 331, 431
C

331 J2 = J1

332 IF (J2 = K2) 332, 332, 432

331 J2 = J1

332 IF (J2 = K2) 331, 332, 431

C

333 J3 = J2, K3, K2
DO 33 3P J4 = J3, K4, K3
DO 33 3P J5 = J4, K5, K4
DO 33 3P J6 = J5, K6, K5
DO 33 3P J7 = J6, K7, K6

332 IF (J1 = J2) 28, 30, 30

28 T = A(J1-1)

A(J1-1) = A(J1-1)
A(J1) = T

30 IF (J1 = J2) 28, 30, 30

30 J1 = J1 + 2
J2 = J2 + K1
GO TO 531

432 J1 = J1 + 2
GO TO 532

431 IF (J1 = J2) 32, 2, 36

C DOING FOURIER ANALYSIS, SO DIVIDE BY N AND CONJUGATE.

32 FN = N
DO 34 I = 1, N
A(2*I-1) = A(2*I-1) / FN
A(2*I) = (-A(2*I)) / FN

C SPECIAL CASE - L = 1

34 DO 40 I = 1, N/2
T = A(2*I-1)
A(2*I-1) = T * A(2*I-1)
A(2*I) = T * A(2*I)

40 IF (N = 1) 21, 1, 50

C SET FOR L = 2

50 LEXP1 = 2
C
LEXP1 = 2**((L-1))
LEXP = 8
C
NPL = NP = 2**((-L))

60 DO 13 I = 2, M

C SPECIAL CASE - J = 0

70 DO 80 I = 2, N/2, LEXP
I1 = I * LEXP1
I2 = I1 + LEXP1
I3 = I2 + LEXP1
T = A(I1)
A(I1) = T * A(I2-1)
A(I2-1) = T * A(I2-1)
T = A(I1)
A(I1) = T * A(I2)
A(I2) = T * A(I2)
T = (-A(I3))
T = A(I3)
A(I3) = A(I1-1) - T

80
A(13) = A(11) + T
A(11-1) = A(11-1) + T
A(1) = A(1) + T
IF (L-2) .120, 120, 90
KLAST = N - LEXP
JJ=NPJ
DO 110 J = 4, LEXP, 2
NPJJ = NT - JJ
UR = S(NPJJ)
UL = S(JJ)
LAST = J + KLAST
DO 120 I = J, ILAST, LEXP
I1 = I - LEXP1
I2 = I1 - LEXP1
I3 = I2 - LEXP1
T = A(I2-1)*UR - A(I2)*UL
T1 = A(I2-1)*UL + A(I2)*UR
A(I2-1) = A(I2-1) - T
A(I2) = A(I2) - T
A(I2-1) = A(I2-1) + T
A(I2) = A(I2) + T
IF (I-1) .120, 120, 90
110 CONTINUE
120 LEXP = LEXP1
C END OF J LOOP.
130 NPJ = NPJ/2
C END OF I LOOP.
C MAKE TABLE OF S(J) = SIN(2*PI*J/NT), J = 1, 2, ..., NT-1, NT = NP/4
220 NP = N
NP = M
NT = N/4
MT = M - 2
IF (MT) 260, 260, 220
205 THETA0 = .73539816
C Theta = PI/2***(L+1) FOR L=1
210 JSTEP = NT
C JSTEP = 2**(MT-L-1) FOR L=1
220 IF (L) 250, 250, 220
S(JSTEP) = SIN(THETA0)
220 IF (L) 250, 250, 220
DO 250 L = 2, MT
THETA = THETA0/2
JSTEP = JSTEP+JSTEP2
JSTEP = JSTEP2+JSTEP
JSTEP = JDIF
220 JSTEP = JSTEP+JSTEP2
250 CONTINUE
C JDIF = 2**(MT-L-1) FOR L=1
S(JDIF) = SIN(THETA)
JDIF = JDIF+2
S(JDIF) = SIN(THETA)
JC = NT - JDIF
S(JC) = COS(THETA)
LAST = NT - JLAST
230 CONTINUE
JC=VT-J
JD=J+JDIF
240  S(JD)=S(J)*S(JC1)*S(JDIF)*S(JC)
250  CONTINUE
260  IF(IFS) 20,1,20
END

ONE-DIMENSIONAL REAL FINITE FOURIER TRANSFORM,

FOURIER TRANSFORM SUBROUTINE FOR REAL DATA. TAKEN FROM
IBM SHARE LIBRARY.

THIS PROGRAM USES THE SUBROUTINE FORT TO COMPUTE COMPLEX
FOURIER TRANSFORMS OF REAL DATA.

THE FOURIER SERIES IS
\[ X(j) = \sum_{k=0}^{N-1} C(k) \cdot \exp(-2\pi i j k / N) \]
WHERE \( i = \sqrt{-1} \) AND WHERE \( C(k) \) IS COMPLEX.

SINCE \( X(j) \) IS REAL, \( C(k) = \text{CONJ} (\text{CONJ}(N-k)) \). THEREFORE ONLY
\( C(k), k = 0, 1, \ldots, N/2 \) ARE COMPUTED AND/OR USED.

ARGUMENTS -
A IS INITIALLY THE INPUT ARRAY, \( X \), WHEN COMPUTING A FOURIER
TRANSFORM AND \( C \) WHEN COMPUTING A FOURIER SERIES. A IS RE-
PLACED BY THE OUTPUT ARRAY, \( C \), ON THE FORMER CASE, \( X \) ON THE
LATTER. THE \( X \) VECTOR CONTAINS THE REAL DATA \( X(p), X(1), \ldots, X(N-1) \).
\( C \) VECTOR CONTAINS THE COMPLEX FOURIER
ANALYSIS \( C(0), C(1), \ldots, C(N/2) \). THE COMPLEX VECTOR \( C \)
IS STORED ACCORDING TO THE NORMAL FORTRAN IV CONVENTION FOR
STORING COMPLEX NUMBERS, I.E., REAL PARTS IN ALTERNATE CELLS
STARTING WITH THE FIRST, IMAGINARY PARTS IN ALTERNATE CELLS
STARTING WITH THE SECOND, TO ADHERE TO FORTRAN RULES. \( X(0), X(1), \ldots \) ARE REFERRED TO AS \( X(1), X(2), \ldots \) RESPECTIVELY
IN THE PROGRAMS. ALSO, \( C(0), C(1), \ldots \) ARE REFERRED TO AS
\( C(1), C(2), \ldots \) RESPECTIVELY, IF \( C \) IS DESIGNATED AS COMPLEX
IN A TYPE STATEMENT.

M GIVES N=2**M

THE ARGUMENTS \( S, IFS, \) AND IFERR ARE THE SAME AS IN SUB-
ROUTINE FORT AND THE USER IS REFERRED TO COMMENT LINES
IN FORT FOR THEIR EXPLANATION.

DIMENSION STATEMENTS - THE DIMENSIONS OF ARRAYS A AND S SHOULD
BE \( N/2 \) AND \( N/4 \), RESPECTIVELY FOR THE LARGEST \( N \) USED. FOR
EXAMPLE, IF THE LARGEST \( M \) IS 11, THEN \( N=2048 \) AND ONE SHOULD
HAVE THE DIMENSION STATEMENT -
DIMENSION A(2050), S(512)

IF ONE WISHES TO SPECIFY A TO BE COMPLEX BY A TYPE STATEMENT,
ONE SHOULD GIVE IT A DIMENSION OF \( N/2*1 \), FOR THE LARGEST \( N \).

\[ \text{DIMENSION } A(1), S(1) \]
\[ \text{IFERR}=0 \]
\[ N=2**M \]
\[ NV=2^N/2 \]
\[ NV4M=2^N/4-1 \]
\[ MM=2^M-1 \]
\[ IF(ABS(IFS)=1) 10,10,5 \]
\[ IF(MP=M) 6,20,20 \]
\[ IFERR=1 \]

COMPUTE SINE TABLE

\[ \text{CALL FORT } (A, M, S, 0, IFERR1) \]
\[ \text{IFERRS}=\text{IFERRS+IFERR1} \]
**COMPUTE FOURIER TRANSFORM.**

```fortran
20  KD=NP/N
    KT=KD
    NP4=NP/4
    IF(IF)30,50,60

C
C
30  CALL FOR T (A,M,N,2,IFERR2)
    IFERRS=IFERRS+IFERR2
    DO 42 K=1,NV4M1
       J=NV2-K
       A1P=A((2*K+1)+A(2*J+1))
       A1I=A((2*K+2)-A(2*J+2))
       A2I=A((2*J+1)-A(2*K+1))
       KKT=NPV4-KT
       AWR=A2P*5(KKT)+A2I*5(KT)
       AWR=A2I*5(KKT)-A2R*5(KT)
       A(2*K+1)=A(2*J+1)/4,
       A(2*J+2)=(A(2*K+2))/4,
       A(2*J+1)=(A1P-A4I)/4,
       KT=KT+K
       T=I(1)
       A(2**1)=(T-A(2))**2,
       A(2**2)=(T-A(2))**2,
       A(2**3)=T,
       A(2**4)=T
       A(NV2+1)=0.5*A(NV2+1)
       A(NV2+2)=(-2.5*A(NV2+2))

40  KT=K*N
    DO 50 K=1,NV4M1
       J=NV2-K
       A1P=A((2*K+1)+A(2*J+1))
       A1I=A((2*K+2)-A(2*J+2))
       A2I=A((2*J+1)-A(2*K+1))
       KKT=NPV4-KT
       AWR=A2P*5(KKT)-A2I*5(KT)
       AWR=A2I*5(KKT)+A2R*5(KT)
       A(2*K+1)=A(2*J+1)/4,
       A(2*J+2)=(A(2*K+2))/4,
       A(2*J+1)=(A1P-A4I)/4,
       KT=KT+K
       T=I(I)
       A(2**1)=(T-A(2))**2,
       A(2**2)=(T-A(2))**2,
       A(2**3)=T,
       A(2**4)=T
       A(NV2+1)=0.5*A(NV2+1)
       A(NV2+2)=(-2.5*A(NV2+2))

50  IFERRS=IFERRS+IFERR2
    RETURN
C
C
COMPUTE FOURIER SERIES.

70  DO 80 K=1,NV4M1
       J=NV2-K
       A1P=A((2*K+1)+A(2*J+1))
       A1I=A((2*K+2)-A(2*J+2))
       AWR=A2P*5(KKT)+A2I*5(KT)
       AWR=A2I*5(KKT)-A2R*5(KT)
       A(2*K+1)=A1R-A2I
       A(2*K+2)=A1I+A2R
       A(2*J+1)=A2R-A1I
       KT=K*N
       T=I(1)
       A(2**1)=T-A(1)**1
       A(2**2)=T-A(1)**1
       A(NV2+1)=2.5*A(NV2+1)
       A(NV2+2)=(-2.5*A(NV2+2))
       CALL FHT (A,M,1,5,2,IFERR2)
       IFERRS=IFERRS+IFERR2
    GO TO 50
    END
```
SUBROUTINE COSTP(Y,NS,R,IERR,INV)
   DIMENSION Y(1)
   EQUIVALENCE (T,WINDOW)
   IERR=0

   CHECK TO SEE IF DATA WINDOW IS WITHIN THE PRESCRIBED LIMITS AS SET
   FORTH ABOVE. IF NOT, ERROR FLAG IS SET.
   IF (NS) 1010,1010,1011
   1011 IF (R-0.05) 1012,1013,1013
   1012 R = 0.1
       IERR = 1
       GO TO 1014
   1013 IF (R-0.5) 1014,1010,1010
   SET UP APPROPRIATE CONSTANTS TO MINIMIZE CALCULATIONS WITHIN THE
   DO LOOP.
   1014 R = FLOAT(NS)*R + 0.01
       IR = R
       IF (IR) 1010,1010,1020
   1020 C1 = 3.141593/R
       NS1 = NS + 1
       DO 30 I=1,IR
           T = 1
           TMHAF=T-0.5

   TAPER WEIGHT FORMED
   C1A = C1*TMHAF
   WINDOW = 0.5-0.5*COS(C1A)
   IF(INV) 12,11,12
   12 WINDOW = 1./WINDOW

   APPLY TAPER TO BOTH ENDS OF DATA
   11 Y(I) = WINDOW*Y(I)
       J = NS1-I
   30 Y(J) = WINDOW*Y(J)
   100 RETURN
   1010 IERR = 1
       GO TO 100
END
SUBROUTINE STAT(NUM,I,SMAX,SMIN,DIF,AMEAN,SD,VAR,C1,C2,PIX,PN)

THIS ROUTINE CALCULATES STATISTICAL DATA, THE MEAN, STANDARD
DEVIATION, VARIANCE, MAXIMUM AND MINIMUM ARE CALCULATED.

DOUBLE PRECISION AMEAN,SD1
DIMENSION C1(10),C2(10),SMAX(10),SMIN(10)
COMMON AKEEP(3072)
SMAX(I)=11.0
SMIN(I)=11.0
AMEAN=0.000
SD1=0.000
DO 402 K=1,NUM
IF(AKEEP(K).GT.SMAX(I))SMAX(I)=AKEEP(K)
IF(AKEEP(K).LT.SMIN(I))SMIN(I)=AKEEP(K)
402 AMEAN=AMEAN+AKEEP(K)
AMEAN=AMEAN/NUM
DO 405 K=1,NUM
EF=0=AKEEP(K)-AMEAN
AMEAN=AMEAN/NUM
SD1=SD1+(AKEEP(K)-AMEAN)*EF
405 AMEAN=AMEAN*(SMAX(I)-SMIN(I))
IF(SMIN(I).EQ.0.000)GO TO 5
1 SD1=SD1+(C1(I)+C2(I))
AMEAN=AMEAN*C1(I)+C2(I)
VAR=SD1/NUM
SD=VAR**.5
5 PX=C1(I)*SMAX(I)+C2(I)
PN=C1(I)*SMIN(I)+C2(I)
DIF=PX-PN
RETURN
END

SUBROUTINE LABEL(K,IO)

SUBROUTINE LABEL DRAWS A BOX AROUND THE PLOTTED
DATA AND PUTS IN HASH MARKS.

DIMENSION LINE(184).
DATA LINE/0.5*1.0,1.0,1.0,1.0,1.0,1.0,1.0,1.0,1.0,1.0,1.0,1.0,1.0,1.0,
1.0,1.0,1.0,1.0,1.0,1.0,1.0,1.0,1.0,1.0,1.0,1.0,
2.1,0.1,0.1,460,9217,0,59217,9217,9416,9416,
3.9217,9217,9416,9416,9217,9217,9416,9416,9416,
4.9217,9416,9416,9416,9217,9217,9416,9416,9217,
5.9416,9001,9201,8101,7201,7201,6301,6301,
6.9001,5401,5501,5401,3601,3401,2701,2701,1801,
7.1801,9001,9001,9001,9001,9001,9001,9001,9001,
8.9001,8901,8801,8709,7059,7059,6879,6879,5899,
9.5401,4119,3139,3139,2159,2159,1179,1179,199,
1.199,199,0.0,199,199,0.0,199,199,0.0,199,199,
2.0,8.199,199,199
IF(IO.NE.18)GO TO 5
DO 408 I=1,46
IUP=LINE(I)
IAB=LINE(I+46)
IX=LINE(I+92)
IY=LINE(I+138)
408 IF(I.GT.26)IX=IX-(216*(K-1))
CALL HPLOT(IUP,IAB,IX,IY)
CALL HPLOT(8,8,9999,9999)
5 RETURN
END
SUBROUTINE LINE1(NUM, C1, C0)

SUBROUTINE TO REMOVE THE LINEAR TREND FROM THE DATA.

DOUBLE PRECISION AVG, AVGR
COMMON AKEEP(250)
AK=0,
AK1=0,
AVG=P, PD
AVGR=0, 000
DO 40 I=1, NUM
AVG=AVG+AKEEP(I)
AVGR=AVGR+(AKEEP(I)*AK)
AK=AK+I,
10 C0=-(4,0DB*AK+7,2DB)*AVG-6,0DB*AVGR)/((AK+1,0DB)*(AK+2,0DB))
C1=(12,0DB*AVGR-6,0DB*AK*AVG)/(AK*(AK+1,0)*(AK+2,0))
C CALCULATE THE COEFFICIENTS NECESSARY TO REMOVE THE TREND.
NO 405 I=1, NUM
AKEEP(I)=(AKEEP(I)-C0-C1*AK1)
C ADJUSTS THE DATA
C 405 AK1=AK1+1,
RETURN
END
SUBROUTINE BAND(icut,num)
C THIS SUBROUTINE DETERMINES HOW THE DATA SENT TO IT THROUGH THE COMMON STATEMENT WILL BE FILTERED. FILTERING IS ACCOMPLISHED BY SETTING THE COMPLEX FOURIER COEFFICIENTS TO ZERO OVER THE DESIRED RANGES.
C
DIMENSION IP1(10),IP2(10),ICUT(7)
COMMON AKEEP(2050)
IF(icut.eq.0)GO TO 1
5 WRITE(53,100)
100 FORMAT('0',' HOW MANY SETS?')
READ(52,105)ISET
105 FORMAT(11)
DO 425 I=1,ISET
WRITE(53,110)
110 FORMAT('C',' ENTER CUT OFFS')
READ(50,115)IP1(I),IP2(I)
115 FORMAT(14,1X,14)
425 CONTINUE
DO 425 I=1,ISET
WRITE(53,125)
125 FORMAT('C',' OK? NO=0 YES=1')
READ(52,130)IANS
130 FORMAT(11)
IF(IANS.EQ.0)GO TO 5
1 DO 415 J=1,ISET
KP1=IP1(J)
KP2=IP2(J)
415 AKEEP(J)=0.0
410 CONTINUE
RETURN
END

SUBROUTINE FILTR(X,M,ISAV,IERR)
C THIS SUBROUTINE CALLS THE IBM FAST FOURIER ROUTINE RFOPT.
C
DIMENSION S(512),X(2050)
CALL RFOPT(X,M,S,ISAV,IERR)
RETURN
END
SUBROUTINE HIST

THIS ROUTINE CALCULATES THE HISTOGRAM
FOR THE DATA SENT TO IT FROM DRAH1.

SUBROUTINE HIST(PX,PN,NUM,I,C1,C2)
DIMENSION C1(10),C2(10)
COMMON AKEEP(2050)
WRITE(54,100)PX,PN
100 FORMAT('6','',' THE EVENLY SPACED DISTRIBUTION OF VALUES',/ 
1' BETWEEN '','F8.3,' AND '','F8.3,' IS',/)
VAL=1,
SD1=0.
X4=0.
X2=0.
AMEAN=.5
DO 440 K=1,11
AINC=VAL/11.
X2=X2+1.
TEST1=AMEAN+((6.5-X2)*AINC)
TEST=TEST1-AINC
DO 445 J=1,NUM
IF(K.EQ.11)GO TO 15
IF(AKEEP(J),GT,TEST.AND.AKEEP(J),LE.TEST1)X1=1,
GO TO 20
15 IF(AKEEP(J),GE,TEST.AND.AKEEP(J),LE.TEST1)X1=1,
20 X4=X4+X1
X1=0.
445 CONTINUE
WRITE(54,150)X4
150 FORMAT(1,'5X,F6.1)
440 X4=0.
RETURN
END

SUBROUTINE INOUT(NUM)

THIS SUBROUTINE FITS THE DATA PASSED TO IT THROUGH THE
COMMON STATEMENT WITH A STRAIGHT LINE IN SETS OF 40 POINTS
TO DETERMINE THE SLOPE.

DOUBLE PRECISION AVG,AVGR
DIMENSION SLOPE(40)
COMMON AKEEP(2050)
DO 480 I=1,40
480 SLOPE(I)=AKEEP(I)
DO 410 K=1,NUM
AVG=0.000
AVGR=0.000
DO 405 I=1,39
AVG=AVG+SLOPE(I)
AVGR=AVGR+(SLOPE(I)*(I-1))
405 SLOPE(I)=SLOPE(I-1)
AVG=AVG-AKEEP(K)
AVGR=AVGR-(AKEEP(K)*39.000)
SLOPE(39)=AKEEP(K)
AKEEP(K)=((12.000*AVGR-234.000*AVG)/63968.000)
410 IF(AKEEP(K),LT,0.)AKEEP(K)=0.
DO 415 K=1,39
415 AKEEP(K)=AKEEP(40)
RETURN
END
SUBROUTINE RCOMP(IBK,M,NUM,ICUT)

THIS SUBROUTINE IS CALLED WHEN THE VARIABLE IS
EITHER INPUT OR OUTPUT. IT FITS THE DATA TO A SECOND
ORDER CURVE AND SUBTRACTS OUT THIS TREND. FILTERING
CAN BE ACCOMPLISHED THROUGH THE FOURIER TRANSFORM IF DESIRED.

DOUBLE PRECISION AMEN1,AMEN2
DIMENSION IBK(2)
COMMON AKEEP(2050)
AMEN1=0.0D0
AMEN2=0.0D0
AK=0.
AK1=0.
IB1=1
IB2=IBK(1)
IB3=IBK(1)+1
IB4=IBK(2)
IB5=IBK(2)+1
IB6=NUM
DO 400 I=IB1,IB2
AMEN1=AMEN1*AKEEP(I)
400 AKEEP(I)=0.
AMEN1=AMEN1/FLOAT(IB2).
CALL POLY(IB3,IB4,A,B,C)
DO 405 I=IB3,IB4
AK=AK*1.
405 AKEEP(I)=AKEEP(I)-((A*AK+B*AK*C))
DO 410 I=IB5,IB6
AMEN2=AMEN2*AKEEP(I)
410 AKEEP(I)=0.0
CALL COSTP(AKEEP,NUM,,1,IERR,0)
AMEN2=AMEN2/FLOAT(IB6-IB4)
IFS=1
CALL FILTR(AKEEP,M,IFS,IERR)
CALL BAND(ICUT,NUM)
IFS=1
CALL FILTR(AKEEP,M,IFS,IERR)
DO 435 I=IB1,IB2
435 AKEEP(I)=AMEN2
DO 450 I=IB1,IB4
AKEEP(I)=AKEEP(I)*(AMEN2-AMEN1)/(FLOAT(IB4-IB2))*AK1*AMEN1
450 AK1=AK1*1.
DO 455 I=IB5,IB6
455 AKEEP(I)=AMEN2
RETURN
END
SUBROUTINE POLY(IB3, IB4, A, B, C)

THIS SUBROUTINE DETERMINES A SECOND ORDER FIT TO THE DATA PASSED TO IT THROUGH THE COMMON STATEMENT.

DOUBLE PRECISION SUM, PSUM, DATA

DIMENSION SUM(3), PSUM(5), DATA(IS, 4)

COMMON AKEEP(2058)

AK = 0.
DO 415 K = 1, 3
415 SUM(K) = 0.0D0
DO 421 K = 1, 5
421 PSUM(K) = 0.0D0
DO 400 J = IB3, IB4
400 AK = AK + 1.
SUM2 = AKEEP(J) * AK
SUM1 = SUM2 * AK
SUM(1) = SUM1 * SUM1
SUM(2) = SUM2 * SUM2
SUM(3) = SUM3 * AKEEP(J)
PSUM2 = AK
PSUM3 = PSUM2 * AK
PSUM4 = PSUM3 * AK
PSUM5 = PSUM4 * AK
PSUM(2) = PSUM(2) * PSUM2
PSUM(3) = PSUM(3) * PSUM3
PSUM(4) = PSUM(4) * PSUM4
480 PSUM(5) = PSUM(5) * PSUM5
PSUM(1) = AK
DO 405 K = 1, 3
405 DATA(K, 4) = SUM(K)
DO 412 K = 1, 3
412 J = 1, 3
IPICK = K + J
410 DATA(K, J) = PSUM(7 - IPICK)
DO 420 K = 1, 2
420 DATA(I1, K) = DATA(K, K)
DO 430 J = K, 4
430 DATA(I1, J) = DATA(I1, J) - DATA(K, J) * R
430 CONTINUE
425 CONTINUE
420 CONTINUE

LET = 3
DO 435 K = 1, 2
435 KA = 4 - K
KB = LET - 1
DO 440 I1 = 1, KB
440 IA = LET - 1
R1 = DATA(I1, KA) / DATA(KA, KA)
DO 445 J = LET - 4 + K
445 DATA(I1, J) = DATA(I1, J) - DATA(KA, J) * R1
445 CONTINUE
440 CONTINUE
435 CONTINUE
450 DATA(IB, 4) = DATA(IB, 4) / DATA(IB, IB)

LET = LET - 1
450 CONTINUE
A = DATA(1, 4)
B = DATA(2, 4)
C = DATA(3, 4)
RETURN

END
ANALYSIS ROUTINE CORR

THIS ROUTINE IS CAPABLE OF CALCULATING AND PLOTTING
POWER SPECTRAL DENSITIES, AUTOCORRELATIONS, CROSS CORRELATIONS
CROSS SPECTRAL DENSITIES, AND COVARIANCE. BECAUSE OF THE
LIMITED STORAGE OF THE PDP-15 USED IN THIS WORK, THE
PROGRAMS ARE RELATIVELY SLOW.

DIMENSION S(512)
COMMON /DATA1/X(2050)
COMMON /DATA2/Y(2050)
COMMON /DATA3/GXY(2050)
DATA FILE1,EX1,FILE2,EX2/5HFILES,3HEXT,5HFILE,3HEX /
WRITE(53,100)

100 FORMAT('8',ENTER DATAN')
READ(92,105)FILE1,KP1,FILE2,KP2,IA1,IA2,IP1,IP2,ICC
 1.IC5,ICO,ISPAN,M

ENTER PARAMETERS

105 FORMAT('A5,1X,11,1X,A5,1X,11,7(1X,I1),1X,I4,1X,I2)
WRITE(53,110)FILE1,KP1,FILE2,KP2,IA1,IA2,IP1,IP2,ICC
 1,ICS,ICO,ISPAN,M

110 FORMAT('8',THE FIRST FILE AND NUMBER IS ',A5,3X,I2,/,,
 1'THE SECOND FILE AND NUMBER IS ',A5,3X,I2,/,,
 2'AUTOCORRELATION ',I2,3X,I2,/,,
 3'POWER SPECTRAL ANALYSIS ',I2,3X,I2,/,,
 4'CROSS CORRELATION ',I2,/,,
 5'CROSS SPECTRAL ANALYSIS ',I2,/,,
 6'COVARIANCE ',I2,/,,
 7'SPAN ',I3,/,,
 8'NUMBER OF VALUES ',I3,/,,
 9'OK? YES=1 NO=0')
READ(52,115)IANS

115 FORMAT(I2)
IF(IANS.EQ.0)GO TO 5
K=R
NUM=(2**M+2)
NUM2=NUM/2
ISKP=1
IQUAD=0
I1=0
IBG=0
ISTART=200

FOURIER TRANSFORMS THE DATA AND AVERAGES COEFFICIENTS

CALL COLL(FILE1,ISKP,FILE2,KP1,M)
CALL ENTER(58,2HXY,3HSPE,IEV)
CALL WAITFR(IEV)
WRITE(50)(GXY(I),I=1,NUM)
CALL CLOSE(58,2HXY,3HSPE,IEV)
CALL WAITFR(IEV)
DO 407 I=1,NUM

SCALES DATA TO INCREASE RANGE

407 X(I)=GXY(I)
GXY(I)=ALOG(GXY(I))
IF(IP1.EQ.0)GO TO 15
ISTART=ISTART+ISPAN+IBG
IBG=1

PLOTS DATA IF REQUIRED FOR POWER SPECTRAL DENSITY,
CALL DXY(XY,ISTART,ISPN,IQUAD,M)
CALL HPLT(0,0,9999,9999)

15 IF(IA1.EQ.0)GO TO 10
CALL RFDT(X,M,S,1,IER1)
ISTART=ISTART+ISPN*IBG
IBG=1
CALL DXY(XY,ISTART,ISPN,IQUAD,M)

PLOTS DATA IF REQUIRED FOR POWER SPECTRAL DENSITY.

10 DO 406 I=1,NUM1
Y(I)=GXY(I*NUM2)
406 GXY(I)=ALOG(GXY(I+NUM2))
IF(IP2.EQ.0)GO TO 25
ISTART=ISTART+ISPN*IBG
IBG=1
CALL DXY(XY,ISTART,ISPN,IQUAD,M)

PLOTS DATA IF REQUIRED FOR AUTOCORRELATION.

25 IF(IA2.EQ.0)GO TO 20
CALL RFDT(Y,M,S,1,IER1)
ISTART=ISTART+ISPN*IBG
IBG=1
CALL DXY(Y,ISTART,ISPN,IQUAD,M)

PLOTS DATA IF REQUIRED FOR AUTOCORRELATION.

20 IF(ICC.EQ.0.AND.WAY.EQ.0.AND.ICO.EQ.0)GO TO 30
DO 408 I=1,NUM
408 GXY(I)=0.0

CALCULATES CROSS CORRELATION.

искп=0
CALL C0LL(FILE1,искп,FILE2,KP2,M)
IF(ICS.EQ.0)GO TO 35
DO 415 I=1,NUM,2
K=K+1
C1=GXY(I)
C2=GXY(I+1)

CALCULATES THE QUADRATURE AND SPECTRAL DENSITY FUNCTIONS.

X(K)=SORT(GXY(I)*C1+GXY(I+1)*C2)
IF(C1.EQ.0)GO TO 51
Y(K)=ATAN(C2/C1)
GO TO 415
51 Y(K)=0.
415 CONTINUE

MANN FILTERS THE DATA IF REQUIRED.

CALL MANN(Y,M)
IF(ICC.EQ.0)GO TO 40
CALL RFDT(GXY,M,S,1,IER1)
ISTART=ISTART+ISPN*IBG
IBG=1
IQUAD=3
CALL DXY(GXY,ISTART,ISPN,IQUAD,M)
IQUAD=8
CALL HPLT(0,0,9999,9999).
IF(ICS.EQ.0) GO TO 30
ISTART=ISTART+ISPA+IBG
IBG=1
DO 428 I=1,NUM
GXY(I)=X(I)
428 X(I)=ALOG(X(I))
CALL DM(X,ISTART,ISPAN,IONAD,M)
CALL H PLOT(0.0,9999,9999)
ISTART=ISTART+ISPAN
IONAD=1
CALL DM(Y,ISTART,ISPAN,IONAD,M)
IONAD=0
CALL H PLOT(0.0,9999,9999)
IF(ICO.EQ.0) GO TO 30
CALL HANN(GXY,M)
DO 425 I=1,NUM
C1=GXY(I)
425 GXY(I)=GXY(I)*C1
CALL SEEK(50.2HXY,3HSPE,IEV)
CALL WAITF(IEV)
READ(50) (X(I),Y(I),1=1,NUM)
CALL CLOSE(50.2HXY,3HSPE,IEV)
CALL WAITF(IEV)
DO 435 I=1,NUM
Y(I)=X(I)+NUM
CALL HANN(X,M)
CALL HANN(Y,M)
DO 433 I=1,NUM
Y(I)=GXY(I)/X(I)*Y(I))
430 IF(Y(I),GT.1.0) Y(I)=1.0
IONAD=2
ISTART=ISTART+ISPA
CALL DM(Y,ISTART,ISPAN,IONAD,M)
CALL H PLOT(0.0,9999,9999)
30 CALL EXIT
END
SUBROUTINE COLL(FILE1,ISKP,FILE2,KPI)

SUBROUTINE COLL CONVERTS FLOATING POINT DATA
STORED ON DISK TO THE FREQUENCY DOMAIN THROUGH THE
FOURIER TRANSFORM, THE COEFFICIENTS OBTAINED MAY BE
AVERAGED (5 MAXIMUM).

DIMENSION EX0(5)
DIMENSION S(512)
COMMON /DATA1/X(2050)
COMMON /DATA2/Y(2050)
COMMON /DATA3/GXY(2050)
DATA EX0/3HS00,3HS0B,3HS16,3HS24,3HS32/
DO 400 I=1,KPI
EX1=EX0(I)
CALL SEEK(55,FILE1,EX1,IEV)
CALL OPEN(55,FIELD,EX1,IEV)
CALL WAITFR(IEV)
READ(55)X
CALL CLOSE(55,FILE1,EX1,IEV)
CALL WAITFR(IEV)

COSINE TAPERS THE DATA
CALL CDSTP(X,2048,1,IERR1,0)
CALL RFORT(X,11,S,-1,IERR1)
CALL SEEK(55,FILE2,EX1,IEV)
CALL WAITFR(IEV)
READ(55)Y
CALL CDSTP(Y,2048,1,IERR1,0)
CALL RFORT(Y,11,S,-1,IERR1)
IF(ISKP,EQ,0)GO TO 10
DO 405 K=1,2050,2
B1=X(K)
B2=X(K+1)
C1=Y(K)
C2=Y(K+1)
I=I+1

GOES THROUGH THE AVERAGING SCHEME
GXY(I1)=GXY(I1)*X(K)+B1*X(K+1)+B2
GXY(I1+1025)=GXY(I1+1025)+Y(K)+C1*Y(K+1)+C2
GO TO 400
10 DO 415 L=1,2050,2
GXY(L)=GXY(L)*X(L)*Y(L)+X(L+1)*Y(L+1)
415 GXY(L+1)=GXY(L+1)*(-1)*X(L+1)*Y(L+1)*X(L)
400 I=0
DO 420 L=1,2050
GXY(I)=(GXY(I)/FLOAT(KPI))*1.14285
X(I)=0.0
Y(I)=0.0
RETURN
END
SUBROUTINE OH(S,ISTART,ISPAN,IQUAD)

SUBROUTINE OH PLOTS DATA SUBJECT TO THE PARAMETERS SENT TO IT FROM CORR.

DIMENSION KEEP(32)
DIMENSION S(1)
K2=32
K3=9
IF(IQUAD.EQ.3)K2=16
K1=8
IF(IQUAD.EQ.3)K3=18
AMIN=11.
AMAX=-11.
IF(IQUAD.NE.1)GO TO 5
AMAX=1.57078
AMIN=-1.57078
GO TO 20
5 IF(IQUAD.NE.2)GO TO 6
AMIN=0.0
AMAX=1.0
GO TO 20
6 DO 410 IMM=1,1024
IF(S(IMM),LT,AMIN)AMIN=S(IMM)
410 IF(S(IMM),GT,AMAX)AMAX=S(IMM)
20 SPAN=AMAX-AMIN
WRITE(54,105)AMAX,AMIN
105 FORMAT(' '1,'//,' THE MAXIMUM VALUE IS ',1PE12.4,/'
1,' THE MINIMUM VALUE IS ',1PE12.4,/')
WRITE(54,100)(S(I),I=1,512)
100 FORMAT(51(16(1X,1PE12.4),//),2(1X,1PE12.4))
CALL HPLOT(0,0,9,ISTART)
CALL HPLOT(1,0,0,ISTART)
IF(ISPAN,EQ.0)GO TO 10
DO 400 K=1,K2
DO 405 I=1,32
K1=K1+1
405 KEEP(I)=INT((S(K1)-AMIN)*ISPAN/(ISPAN-50))
IF(K1.GT.1)GO TO 15
CALL HPLOT(0,1,0,KEEP(I))
15 CALL DRAW3(KEEP,K,K3)
400 CONTINUE
10 RETURN
END
SUBROUTINE HANN(S)

THIS SUBROUTINE HANN FILTERS THE DATA SENT TO IT.

DIMENSION S(1)
S(1)=S(1)*.5*S(2)*.5
DO 406 I=2,1023
S(I)=S(I-1)*.25+S(1)*.5+S(I-1)*.25
S(1024)=S(1024)*.5+S(1023)*.5
RETURN
END
APPENDIX C

EXPERIMENTAL AND STATISTICAL DATA

The following figures (Figures 68 through 103) are enlarged portions of Figures 28 through 37. For example, Figure 28 is identical to the composite of Figures 68A, 68B, 69A and 69B, and 70A, 70B. In addition, the average and range are listed for each plot in each of the following figures.
Figure 68A - Polyethylene, 90 rpm, Single Stage Screw, Fast, Run F10 0 - 51 sec
Figure 68B - Polyethylene, 90 rpm, Single Stage Screw, Fast, Run F10, 51 - 102 sec
Figure 69A - Polyethylene, 60 rpm, Single Stage Screw, Fast, Run F9, 0-51 sec
Figure 69B - Polyethylene, 60 rpm, Single Stage Screw, Fast, Run F9, 51-102 sec
Figure 70A - Polyethylene, 30 rpm, Single Stage Screw, Fast, Run F11, 0-51 sec
Figure 70B - Polyethylene, 30 rpm, Single Stage Screw, Fast, Run F11, 51-102 sec
Figure 71A - Polyethylene, 90 rpm, Single Stage Screw, Slow, Run S10, 0-510 sec
Figure 71B - Polyethylene, 90 rpm, Single Stage Screw, Slow, Run S10, 510-1020 sec
Figure 72A - Polyethylene, 60 rpm, Single Stage Screw, Slow, Run S9, 0-510 sec
Figure 72B - Polyethylene, 60 rpm, Single Stage Screw, Slow, Run S9, 510-1020 sec
Figure 73A - Polyethylene, 30 rpm, Single Stage Screw, Slow, Run S11, 0-51C sec
Figure 73B - Polyethylene, 30 rpm, Single Stage Screw, Slow, Run S11, 510-1020 sec
Figure 74A - Polystyrene, 90 rpm, Single Stage Screw, Fast, Run F5, 0-51 sec
Figure 74B - Polystyrene, 90 rpm, Single Stage Screw, Fast, Run F5, 51-102 sec
Figure 75A - Polystyrene, 60 rpm, Single Stage Screw, Fast, Run F3, 0-51 sec
Figure 75B - Polystyrene, 60 rpm, Single Stage Screw, Fast, Run F3, 51-102 sec
Figure 76A - Polystyrene, 30 rpm, Single Stage Screw, Fast, Run F1, 0-51 sec
Figure 76B - Polystyrene, 30 rpm, Single Stage Screw, Fast, Run F1; 51-102 sec
Figure 77A - Polystyrene, 90 rpm, Single Stage Screw, Slow, Run S5, 0-510 sec
Figure 77B - Polysytrene, 90 rpm, Single Stage Screw, Slow, Run S5, 510-1020 sec
Figure 78A - Polystyrene, 60 rpm, Single Stage Screw, Slow, Run S3, 0-510 sec
Figure 78B - Polystyrene, 60 rpm, Single Stage Screw, Slow, Run S3, 510-1020 sec
Figure 79A - Polystyrene, 30 rpm, Single Stage Screw, Slow, Run S1, 0-510 sec
Figure 79B - Polystyrene, 30 rpm, Single Stage Screw, Slow, Run S1, 510-1020 sec
Figure 80A - Polyethylene, 90 rpm, Single Stage Screw, Fast, Run F27, 0-51 sec
Figure 80B - Polyethylene, 90 rpm, Single Stage Screw, Fast, Run F27, 51-102 sec
Figure 81A - Polyethylene, 60 rpm, Two Stage Screw, Fast, Run F26, 0-51 sec

0.35 lb/min, 2.26  
875 psi, 17  
2026 psi, 304  
1407 psi, 405  
673 psi, 428  
185.0 psi, 6.3  
908 psi, 497  
1836 psi, 590  
2.14 lb/min, 2.5  
61.1 rpm, .8
Figure 81B - Polyethylene, 60 rpm, Two Stage Screw, Fast, Run F26, 51-102 sec
Figure 82A - Polyethylene, 30 rpm, Two Stage Screw, Fast, Run F25, 0-51 sec
Figure 82B - Polyethylene, 30 rpm, Two Stage Screw, Fast, Run F25, 51-102 sec
Figure 85A - Polyethylene, 90 rpm, Two Stage Screw, Slow, Run S27, 0-510 sec
Figure 83B - Polyethylene, 90 rpm, Two Stage Screw, Slow, Run S27, 510-1020 sec
Figure 84A - Polystyrene, 60 rpm, Two Stage Screw, Slow, Run S26, 0-510 sec
Figure 848 - Polystyrene, 60 rpm, Two Stage Screw, Slow, Run S26, 510-1020 sec
Figure 85A - Polyethylene, 30 rpm, Two Stage Screw, Slow, Run S25, 0-510 sec
Figure 85B - Polyethylene, 30 rpm, Two Stage Screw, Slow Run S25, 510-1020 sec
Figure 86A - Polystyrene, 90 rpm, Two Stage Screw, Fast, Run F32, 0-51 sec
Figure 86B - Polystyrene, 90 rpm, Two Stage Screw, Fast, Run F32, 51-102 sec
Figure 87A - Polystyrene, 60 rpm, Two Stage Screw, Fast, Run F30, 0-51 sec
Figure 87B - Polystyrene, 60 rpm, Two Stage Screw, Fast, Run F30, 51-102 sec
Figure 88A - Polystyrene, 30 rpm, Two Stage Screw, Fast, Run F29, 0-51 sec
Figure 88B - Polystyrene, 30 rpm, Two Stage Screw, Fast, Run F29, 51-102 sec
Figure 89A - Polystyrene, 90 rpm, Two Stage Screw, Slow, Run S32, 0-510 sec
Figure 89B - Polystyrene, 90 rpm, Two Stage Screw, Slow, Run S32, 510-1020 sec
Figure 90A - Polystyrene, 60 rpm, Two Stage Screw, Slow, Run S30, 0-510 sec
Figure 90B - Polystyrene, 60 rpm, Two Stage Screw, Slow, Run S30, 510-1020 sec
Figure 91A - Polystyrene, 30 rpm, Two Stage Screw, Slow, Run S29, 0-510 sec
Figure 91B - Polystyrene, 30 rpm, Two Stage Screw, Slow, Run S29, 510-1020 sec
Figure 92A - Polyethylene, 90 rpm, Two Stage Planta Screw, Fast, Run F16, 0-51 sec
Figure 92B - Polyethylene, 90 rpm, Two Stage Plasta Screw, Fast, Run F16, 51-102 sec
Figure 93A - Polyethylene, 60 rpm, Two Stage Plasta Screw, Fast, Run F13, 0-51 sec
Figure 93B - Polyethylene, 60 rpm, Two Stage Plasta Screw, Fast, Run F13, 51-102 sec
Figure 94A - Polyethylene, 30 rpm, Two Stage Plasta Screw, Fast, Run F15, 0-51 sec
Figure 94B - Polyethylene, 30 rpm, Two Stage Plasta Screw, Fast, Run F15, 51-102 sec
Figure 95A - Polyethylene, 90 rpm, Two Stage Plasta Screw, Slow, Run S16, 0-510 sec
Figure 95B - Polyethylene, 90 rpm, Two Stage Plasta Screw, Slow, Run S16, 510-1020 sec
<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>195.3</th>
<th>198.3</th>
<th>201.3</th>
<th>204.3</th>
<th>207.3</th>
<th>210.3</th>
<th>213.3</th>
<th>216.3</th>
<th>219.3</th>
<th>222.3</th>
<th>225.3</th>
<th>228.3</th>
</tr>
</thead>
<tbody>
<tr>
<td>rpm</td>
<td>61.2</td>
<td>62.2</td>
<td>63.2</td>
<td>64.2</td>
<td>65.2</td>
<td>66.2</td>
<td>67.2</td>
<td>68.2</td>
<td>69.2</td>
<td>70.2</td>
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</tr>
<tr>
<td>psi</td>
<td>312</td>
<td>326</td>
<td>340</td>
<td>354</td>
<td>368</td>
<td>382</td>
<td>396</td>
<td>410</td>
<td>424</td>
<td>438</td>
<td>452</td>
<td>466</td>
</tr>
<tr>
<td>lb/min</td>
<td>0.22</td>
<td>0.22</td>
<td>0.22</td>
<td>0.22</td>
<td>0.22</td>
<td>0.22</td>
<td>0.22</td>
<td>0.22</td>
<td>0.22</td>
<td>0.22</td>
<td>0.22</td>
<td>0.22</td>
</tr>
</tbody>
</table>

**Figure 96A - Polyethylene, 60 rpm, Two Stage Planta Screw, Slow, Run S13, 0.5 sec to 500 sec**
Figure 96B - Polyethylene, 60 rpm, Two Stage Plasta Screw, Slow, Run S13, 510-1020 sec
Figure 97A - Polyethylene, 30 rpm, Two Stage Plasta Screw, Slow, Run S15, 0-51C sec
Figure 97B - Polyethylene, 30 rpm, Two Stage Plasta Screw, Slow, Run S15, 510-1020 sec
Figure 98A - Polystyrene, 90 rpm, Two Stage Plasta Screw, Fast, Run F23, 0-51 sec
Figure 98B - Polystyrene, 90 rpm, Two Stage Plasta Screw, Fast, Run F23, 51-102 sec
Figure 99A - Polystyrene, 60 rpm, Two Stage Plasta Screw, Fast, Run F21, 0-51 sec

- 0.22 lb/min
- 1.14
- 249 psi
- 59
- 156 psi
- 474
- 4 psi
- 53
- 13 psi
- 18
- 197.9 °C
- 5.2
- 36 psi
- 71
- 143 psi
- 131
- 1.67 lb/min
- 1.63
- 60.9 rpm
- .7
Figure 99B - Polystyrene, 60 rpm, Two Stage Plasta Screw, Fast, Run F21, 51-102 sec
Figure 100A - Polystyrene, 30 rpm, Two Stage Plasta Screw, Fast, Run F24, 0-51 sec
Figure 100B - Polystyrene, 30 rpm, Two Stage Plasta Screw, Fast, Run F24, 51-102 sec
Figure 101A - Polystyrene, 90 rpm, Two Stage Plasta Screw, Slow, Run S23, 0-510 sec
Figure 101R - Polystyrene, 90 rpm, Two Stage Plasta Screw, Slow, Run S23, 510-1020 sec
Figure 102A - Polystyrene, 60 rpm, Two Stage Plasta Screw, Slow, Run S21, 0-510 sec
Figure 102B - Polystyrene, 60 rpm, Two Stage Plasta Screw, Slow, Run S21, 510-1020 sec.
Figure 103A - Polystyrene, 30 rpm, Two Stage Plasta Screw, Slow, Run S24, 0-510 sec
APPENDIX D

INITIAL RUN CONDITIONS

The following tables list values for the initial run conditions. Before data collection was started the extruder was allowed to equilibrate for approximately one-half hour. Once "steady state" had been attained four sets of variable values were printed. These values are average readings spaced approximately 15 sec apart.
Figure 105 - Placement of Measuring Elements--Two Stage Screw and Plasta Screw
Table 5
Initial Conditions - Runs 10, 9, 11 Slow and Fast

P = Pressure -- psi  T = Temperature -- °C  S = Screw Speed -- rpm

<table>
<thead>
<tr>
<th>Run</th>
<th>P1</th>
<th>P2</th>
<th>P3</th>
<th>P4</th>
<th>P5</th>
<th>P6</th>
<th>T1</th>
<th>T2</th>
<th>T3</th>
<th>T4</th>
<th>T5</th>
<th>T6</th>
<th>T7^</th>
<th>T8^</th>
<th>S</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>950.01</td>
<td>1217.54</td>
<td>2476.37</td>
<td>3548.43</td>
<td>2985.68</td>
<td>2398.74</td>
<td>225.2</td>
<td>218.4</td>
<td>215.7</td>
<td>218.4</td>
<td>204.2</td>
<td>207.9</td>
<td>32.0</td>
<td>28.8</td>
<td>90.48</td>
</tr>
<tr>
<td>9</td>
<td>950.01</td>
<td>1219.22</td>
<td>2478.76</td>
<td>3555.99</td>
<td>2985.77</td>
<td>2403.77</td>
<td>225.1</td>
<td>218.4</td>
<td>216.0</td>
<td>218.4</td>
<td>204.3</td>
<td>207.8</td>
<td>32.0</td>
<td>28.8</td>
<td>90.48</td>
</tr>
<tr>
<td>11</td>
<td>950.01</td>
<td>1218.64</td>
<td>2479.20</td>
<td>3618.37</td>
<td>2985.46</td>
<td>2353.49</td>
<td>225.0</td>
<td>218.4</td>
<td>216.3</td>
<td>218.4</td>
<td>204.5</td>
<td>208.3</td>
<td>31.9</td>
<td>28.9</td>
<td>90.48</td>
</tr>
<tr>
<td>9</td>
<td>950.01</td>
<td>1220.49</td>
<td>2469.75</td>
<td>3643.02</td>
<td>2985.71</td>
<td>2285.15</td>
<td>225.1</td>
<td>218.4</td>
<td>215.5</td>
<td>218.4</td>
<td>204.5</td>
<td>208.6</td>
<td>31.9</td>
<td>28.8</td>
<td>90.53</td>
</tr>
<tr>
<td>11</td>
<td>852.68</td>
<td>1041.68</td>
<td>2102.88</td>
<td>3272.60</td>
<td>2857.14</td>
<td>2213.97</td>
<td>223.4</td>
<td>218.4</td>
<td>215.8</td>
<td>215.8</td>
<td>205.0</td>
<td>205.3</td>
<td>33.3</td>
<td>29.2</td>
<td>61.07</td>
</tr>
<tr>
<td>9</td>
<td>853.48</td>
<td>1042.63</td>
<td>2086.00</td>
<td>3339.20</td>
<td>2959.33</td>
<td>1979.55</td>
<td>224.0</td>
<td>218.4</td>
<td>216.0</td>
<td>215.6</td>
<td>205.0</td>
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^a - T 7 and T8 monitor operating temp of input and output load cells respectively.
Table 6

Initial Conditions - Runs 5, 3, 1 Slow and Fast

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\(^a\) - T7 and T8 monitor operating temp of input and output load cells respectively.
Figure 104 - Placement of Measuring Elements, Single Stage Screw
### Table 7

**Initial Conditions - Runs 27, 28, 25 Slow and Fast**

\[ P = \text{Pressure} - \text{psi} \quad T = \text{Temperature} - ^\circ\text{C} \quad S = \text{Screw Speed} - \text{rpm} \]

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\( ^a \) - T7 and T8 Monitor Operating Temp of Input and Output Load Cells.
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a - T7 and T8 monitor temp of input and output load cells.
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| 13  | 873.90 | 1703.71 | 1210.58 | 409.99 | 647.19 | 1263.80 | 216.3 | 215.1 | 218.0 | 213.0 | 215.4 | 189.5 | 29.5 | 32.0 | 61.49 |
|     | 873.46 | 1699.35 | 1096.79 | 506.84 | 347.43 | 1136.43 | 216.4 | 215.2 | 218.0 | 213.2 | 215.6 | 188.9 | 30.1 | 32.0 | 60.82 |
|     | 872.91 | 1638.05 | 1223.84 | 417.52 | 568.60 | 1122.80 | 216.4 | 215.4 | 218.0 | 213.5 | 215.9 | 188.3 | 30.1 | 32.0 | 61.55 |
|     | 872.81 | 1715.51 | 1115.03 | 451.20 | 435.37 | 1238.08 | 216.5 | 215.2 | 218.0 | 213.7 | 216.1 | 188.1 | 33.3 | 32.0 | 60.98 |

| 15  | 641.05 | 1200.60 | 839.46 | 351.48 | 246.07 | 577.76 | 217.3 | 219.4 | 218.0 | 216.6 | 218.4 | 197.1 | 32.6 | 31.7 | 30.14 |
|     | 643.13 | 1188.26 | 834.44 | 358.92 | 246.55 | 598.69 | 217.2 | 219.4 | 218.0 | 216.5 | 218.4 | 197.2 | 32.1 | 31.6 | 30.11 |
|     | 642.21 | 1182.37 | 840.52 | 394.98 | 232.02 | 629.54 | 217.2 | 219.4 | 218.0 | 216.4 | 218.4 | 197.1 | 31.9 | 31.6 | 30.19 |
|     | 642.70 | 1184.38 | 890.20 | 385.88 | 237.40 | 548.12 | 217.2 | 219.4 | 218.0 | 216.2 | 218.4 | 197.1 | 34.1 | 31.6 | 30.19 |

\^a - T7 and T8 monitor temp of input and output load cells.
Table 10

Initial Conditions - Runs 23, 21, 24 Slow and Fast.

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T7 and T8 monitor temp of input and output load cells.
APPENDIX E

WIRING DIAGRAMS
Figure 106 - Extruder Pressure Transducer Power Supply and Amplifier/Filter
Figure 107 - Pressure Transducer Amplifier
Figure 108 - Typical Interconnection of Transducer Power Supplies
Figure 109 - Frequency to Voltage Converter