I, Liran Oren, hereby submit this original work as part of the requirements for the degree of Doctor of Philosophy in Aerospace Engineering.

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Fluid dynamics of pulsating jets and voice

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Fluid dynamics of pulsating jets and voice

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Abstract

Vortical structure plays a significant role in flow mechanisms that impact our everyday life. This work is focused on two types of flow that are characterized and dominated by vortical structures. The first part of this work focuses on a particular type of jet known as a synthetic jet. This jet is formed by the time harmonic motion of a vibrating element that encloses a cavity with an orifice. The current work explored the characteristics synthetic jets using circular, slot, and triangular orifices (all having the same equivalent diameters). The results showed that merging of successive vortex pairs can occur between $4.0 < x/D < 6.5$, a process previous thought not to exist in synthetic jets. Comparison of the current data with others showed that the spreading rate is actually independent of the $St_D$ when the latter is calculated in the normal way. The characteristics of these jets show that the pulsatile nature of the jet dominates near the orifice, and further upstream the synthetic jets behave in a similar manner as conventional turbulent jets. Axis switching and entrainment enhancement were observed in the non-circular cases. The second part of this work was directed on the characteristics of the flow that pass between the vibrating vocal folds, which serve as the acoustic source for the human voice. In the current work, intraglottal velocity fields were measured using PIV and used to compute the corresponding pressure distribution between the folds. The results showed that when the flow separates from the divergent glottal walls during closing, the vortices that are formed in the
separated region of the glottis create negative pressure near the superior aspect of the folds. The magnitude of the negative pressure is proportional to the subglottal pressure.
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A final and special thanks goes to my family for their love and devotion. My parents, Ze’ev and Osnat, who always encouraged my curiosity as a child and tried their best to answer my many questions and made me who I am. My sons, Liam and Jordan, who remind me everyday what things really matter in life. And to my wonderful wife, Jessica, who always believed in me, even when I did not. Without her support, sacrifice, and most of all, love, none of this would have been possible.
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\langle u \rangle, \langle u_x \rangle total axial fluctuations of the velocity
$\bar{u}, \bar{u}_x$ deterministic axial fluctuations of the velocity
$u', u'_x$ random axial fluctuations of the velocity
\langle u_r \rangle total radial fluctuations of the velocity
$\bar{u}_r$ deterministic radial fluctuations of the velocity
$u'_r$ random radial fluctuations of the velocity
$V$ transverse velocity
\langle v \rangle total transverse fluctuations of the velocity
$\bar{v}$ deterministic transverse fluctuations of the velocity
$v'$ random transverse fluctuations of the velocity
$x$ axial direction
$y$ transverse direction, major axis (slot)
$y_{1/2}$ transverse half width of the jet
$z$ minor axis (slot orifice)

**Greek Symbols**

$\delta$ shear layer thickness
$\varepsilon$ strain
$\eta$ half cycle length, $F_o/2$
$\theta$ cycle phase
$\lambda$ wavelength, POD spatial energy
$\mu$ dynamic viscosity
$\nu$ Poisson’s ratio
$\rho$ density
$\sigma$ stress
$\tau_p$ particle time scale
$\tau_f$ flow time scale
$\Phi$ POD mode
$\Omega$ vorticity
Vortical structures play a significant role in flow mechanisms that are concerned with our everyday life. Some naturally occurring examples of such structures include: weather (tornado, whirlpool), blood flow, magnetic fields, air flowing around and behind an airplane, and flow that produces sound (e.g. noise).

Flow can coalesce into vortical structures by pressure perturbations that are caused by acoustical or aeroelastic means. The latter channel the formation of the vortical structures via the interaction between the dynamic changes in the surface (i.e. elastic deformation) and the aerodynamic forces in the flow that passes by the surface.

One prominent example of flow that is dominated by vortical structure is a forced jet. These jets are often excited by acoustical means, which produce vortices in the flow. These vortices play a significant role in shaping the flow characteristics of the forced jet. Forced jets are considered to be a leading solution in flow control (methods used to direct and manipulate fluid flow).

The mechanism for flow control can be passive or active. The passive systems are (normally) optimized for a narrow range of flow conditions and cannot be adjusted for changes in the flow. Examples of passive flow control systems include: riblets, vortex generators, and non-circular jets. The different flow dynamics of the latter
makes them a preferable solution for applications such as jet noise, heat transfer, and combustion (Gutmark and Grinstein [1]). As their name implied, these jets are produced from orifices with shape other than the circular (i.e. square, slot, elliptic slot, triangle, etc.), and their flow characteristics will also vary based on the orifice geometry (i.e. aspect ratio, sharp corners, etc.).

Systems that are based on active flow control are more flexible, can operate in a wide range of flow conditions and can be adjusted for changes in the flow. Examples of systems that are based on active flow control include: deforming surfaces, active suction, bleed, MEMS, and pulsed jets. The latter are characterized by the formation of vortical structures at the orifice exit and by the dominance of the fluctuations in the flow near the orifice. Further downstream vortex dynamics transition the pulsed jet into a continuous turbulent jet.

At certain conditions strong forcing (of a pulsed jet) can produce a feature in the flow where the mass of the slug of fluid that exits the orifice is equal to the mass of the slug of fluid that entrains back into the orifice. This zero-net-mass-flux characteristic across the orifice grants the name synthetic jet. These type of jet has shown much promise as an active flow control mechanism [2].

Former studies on synthetic jets concluded that their flow characteristics are independent of the Reynolds number [3, 4, 5], but are dependent on the actuator stroke length (which is inverse to the Strouhal number) [4, 5, 6] of the jet. These studies also showed that the jet transitions into a continuous turbulent jet via a vortex decay mechanism, and without the merging of successive vortex pairs [3, 7].

Inconsistency in the published data for synthetic jets is evident when studies are compared within and against each other. For example, the centerline velocity data
from NASA’s CFD validation workshop on synthetic jets [8] varies greatly based on the measurement technique (i.e. hot-wire vs. PIV). Similarly the centerline velocity (for an axisymmetric jet) varies greatly between the data shown by Smith et al. [4] and Shuster and Smith [5] although the parameters of their jet (i.e. stroke length and Re numbers) are similar.

The first part of this dissertation aims to investigate the flow properties of synthetic jet and address the discrepancy that exists in the published data. It also explores the instabilities that develop in the jet and its transition into a continuous turbulent jet. The flow characteristics of the synthetic jet are reexamined and assessed using time-resolved PIV. This method gives a new window for understanding how the spatial and temporal characteristics of the flow in synthetic jet mesh together.

No work has been published to-date about the flow characteristics of non-circular synthetic jets. The majority of the data that is available in the literature comes from studies about axisymmetric and 2-D (i.e. slot with large AR) jets. The current work also studies the flow characteristics of non-circular synthetic jets and considers the cases of a slot (with small aspect ratio) and triangular (equilateral) jets. The results are compared against (counterpart) excited and conventional jet.
Chapter 2: Background - vortical structures in flow control

The following sections are intended to review the current knowledge about the characteristics of jet flows that are dominated by vortical structures. The chapter reviews axisymmetric and non-circular jets and focuses on the previous work that was done on the flow characteristics of synthetic jets. It also includes a section that reviews the publish work on the geometry and dynamics of the synthetic jets actuator, which was needed in order to design the actuators used in the current study.

This background chapter concludes with sections that review the process of vortex merging in the jet and methods to compute the exit velocity of the jet. These are the two cardinal points that make the current work novel and significant.

Jet flow describes movement of fluid into a medium that is either at motion or at rest. Jet flows exist in many shapes and forms and their variations mainly depend on the Reynolds and the Mach numbers of the jet. The Reynolds number is defined as: 

\[ Re = \frac{\rho UD}{\mu}, \]

where \( \rho \) is the density of the flow, \( \mu \) is the viscosity of the flow, and \( U \) and \( D \) are the characteristic velocity and diameter of the jet, respectively. The Reynolds number describes the ratio of the inertial forces to the viscous forces in the jet. The Mach number is defined as: 

\[ M = \frac{U}{c}, \]

where \( U \) is the characteristic velocity and \( c \) is the speed of sound.
There are two main regions that characterize the initial formation of turbulent jets. The initial development occurs near the orifice and is characterized by the diminishing of the potential core of the jet and the development of the velocity profiles. Further downstream, the jet becomes fully developed with self-preserving velocity profiles (Figure 2.1).

Vortical structures in jet flow play an important role as they shape the jet characteristics and ultimately determine its potential use in flow control applications. The dynamics of the vortical structure can be changed based on the initial conditions of the jet, such as the shape of its orifice.
2.1 Axisymmetric jets

Wygnanski and Fiedler [9] investigated the flow characteristics of circular jets using hot-wire anemometry. The majority of their measurements were obtained for $x/D > 70$ and showed self-similarity of the profiles for the mean velocity and its fluctuations. Their experimental data had moderate agreement with the numerical models that were available at the time.

The transition of an excited jet into a continuous turbulent jet, which occurs in the boundary layer of an excited jet, was investigated by Freymuth [10] using hot-wire anemometry and smoke visualization. Freymuth [10] suggested that the transition process occurs in four regions: The first region is the transformation region that occurs at the nozzle exit where the boundary layer changes from its wall conditions to a free jet conditions. The second region occurs just downstream of the nozzle exit where the disturbances in the flow roll-up into vortices. The third region is characterized by a jet that is dominated by the vortical flow, and the last region occurs downstream after the vortex breakdown where the jet is turbulent. Freymuth [10] suggested that the breakdown process is governed by the vortex interaction in the flow.

Crow and Champange [11] showed that the instability process that characterizes excited jets is governed by the dynamic formation and merging of the Kelvin-Helmholtz vortices that are formed in the shear layer. Their study showed that preferred mode of the jet, where the most amplification occurred, was at a Strouhal number of: $St = fD/U_o = 0.3$. They also showed that the entrainment in the flow, measured by the volume flux, can increase by 32% compared with an equivalent unforced jet.
Hasan and Hussain [12] compared the flow characteristics in the near field of an excited axisymmetric jet with the flow characteristics of an equivalent conventional jet. They showed that the spreading and the decay rates of the jet are increased when the jet is excited. They also showed that due to the excitation of the jet (which occurred inside the nozzle) the fluctuations near the orifice were higher, but converged to the same level as in the non-excited jet further downstream. They also noted that exciting the jet also increased the volume flux in the jet, which is advantageous for applications where entrainment control is desirable.

Michalke and Hermann [13] analyzed numerically the instability process that occurs in the axisymmetric jet. Their model showed that the excited jet does not follow the same aspects as conventional jets because the tendency of the jet to follow the disturbance of the excitation. They showed that the jet becomes more stable downstream as the ratio of its width to its momentum thickness decreases.

Hussain and Zaman [14] showed that excitation of the jet at its preferred mode cannot sustain the coherent structures beyond eight diameters of the jet. They showed that near the orifice the coherent Reynolds stress dominated the flow compared with the random turbulence. Further downstream the dominance of the stress is decreased, and near \( x/D \approx 8.0 \) the jet is predominantly turbulent. Their study also observed lack of paring between the coherent structures.

The variance in the preferred mode of the axisymmetric jets was summarized by Gutmark and Ho [15] who attribute the differences to low-level upstream disturbances, which are facility dependent and affect the downstream conditions of the jet. The same conclusion was made about the differences that were reported in the spreading
rates of these jets. They showed that the reported Strouhal numbers in the literature for the preferred mode of axisymmetric jet varied between 0.24 to 0.64.

The flow characteristics of an axisymmetric pulsed jet (10Hz) was studied by Bremhorst and Hollis [16]. Their jet was produced using a solenoid valve. Their study showed that in the initial region where the pulsed jet is dominated by the periodic component in the flow, the jet was characterized with higher entrainment and slower centerline decay rate compared with a conventional jet. Further downstream ($x/D > 50$) where the periodic component in the jet was lessened, the magnitude of these quantities matched conventional jets.

The aforementioned studies about axisymmetric jets showed that excited jet are initially dominated by their coherent structures, but further downstream they transition into continuous turbulent jets. The flow characteristics of an excited jet differ from the characteristics of the continuous turbulent jet. The characteristics do not differ much based on the Reynolds number of the jets and vary more based on their Strouhal number.

### 2.2 Non-circular jets

The chief advantage of non-circular jets is that they can passively increase the entrainment in the flow due to the different growth rates that occur between the sides of the jet, a process which is known as axis switching.

Gutmark and Grinstein [1] showed that the flow characteristics of non-circular jets are subject to its orifice configuration; slot jets will vary based on their aspect ratio, an elliptical jet will vary from a sharp corners slot, an equilateral triangle will vary from an isosceles triangle, etc. Miller et al. [17] compared computationally several cases of
continuous (turbulent) non-circular jets having the same equivalent diameters. They considered a square, an elliptical (AR=2), a rectangular slot (AR=2), an equilateral triangle, and an isosceles triangle (AR=2). All cases were compared with each other and with the circular jet. They observed that the decay of the centerline velocity was the highest in the triangular jet and lowest in (both) slot configurations. They observed one axis switching for the slot cases and two cases of axis switching for the triangular cases. The highest entrainment was observed in the case of the isosceles triangle.

The process of axis switching occurs when the higher growth rate on one side of the jet shifts to the other side, which is due to the Biot-Savart deformation of the vortex ring (Gutmark and Grinstein [1]). This deformation is caused by having parts of the vortex with smaller radius of curvature (such as in a vertex) move faster downstream than the other elements of the vortex ring. Zaman [18] showed that an additional mechanism for axis switching can come from the induced velocity of the streamwise vortex pair. If the streamwise vortices rotate in a manner that will move them in the direction of the minor axis, then axis switching will occur. Contrary, if the streamwise vortices rotate in a manner that move them in the direction of the major axis, then the jet will elongate, and axis switching will not occur. Other dynamics in the flow that characterize non-circular jets tend to be more specific based on the orifice configuration of the jet.

2.2.1 Slot orifice

The slotted jet can actually be divided into two main categories consisting of rectangular and elliptical jets. The dynamics of the two cases vary based on the
existence of sharp or round corners in the jet orifice. The following reviews some of the work done on both cases.

Gutmark and Wygnanski [19] investigated the flow characteristics of a planar jet and found it to be similar to the axisymmetric jet in its mean velocity profiles and turbulence quantities. They observed that self-similarity in the jet developed at $x/h \geq 40$, where $h$ is the slot width.

Ho and Gutmark [20] (AR=3) showed that the entrainment in the flow increase (compared with equivalent axisymmetric case), and that the majority of the entrainment was attained on the minor axis. Their study attributed the increase to the azimuthal deformation of the elliptic vortex. Their study also examined how the instability process developed in the shear of the major and minor planes of the jet. They observed excitation of subharmonics frequencies in the downstream of the jet, which they attribute to the vortex merging process that occurs. Ho and Gutmark [20] also showed that the turbulence properties of the elliptic jet vary between its major and minor axis, which reflects the changes that occur with axis switching. They showed that the peaks in the turbulence quantities occurred at different axial locations for the minor and major axes. Similar results for axis switching and turbulence quantities were obtained by Quinn [21] (AR=5) and Quinn [22] (AR=2) for elliptic jets.

The process of axis switching in a slot occurs because the growth rate of the jet in the minor plane is higher than the growth rate in the major plane of the jet. The location of the axis switching will vary based on the Reynolds number of the jet, the upstream conditions of the jet (i.e. temperature and spectral content), the aspect ratio and geometry of the nozzle, and the initial distribution of the shear layer thickness (Gutmark and Grinstein [1]). Further downstream the slot jet attains an
axisymmetric shape. Hussain and Husain [23] looked at different elliptical jets and showed that the location and the number of axis switches depends on the initial conditions, the aspect ratio of the slot, and the Strouhal number of the jet. They showed that at low aspect ratio the jet is comparable to an axisymmetric jet, but at high aspect ratio (AR ≥ 8) the jet behaves like a 2-D jet. They also showed that the location for the axis switching moved upstream as the forcing of the jet was increased.

The computational work by Grinstein [24] showed that the rectangular vortex ring goes through (two) repeated axis switches before the bifurcation of the vortex occurs. The bifurcation is the first step in the decay process of the vortex, and marks the beginning of the decay process of the coherent structure in the flow. The split of the vortex corresponds to the formation of rib vortices that interact with the corner regions of the jet. Further downstream his simulations showed that the jet contains slender, tube-like filament vortices, which characterize a fully-developed turbulent jet.

2.2.2 Triangular orifice

Schadow et al. [25] explained that triangular jets can provide a good method for passive flow control due to the asymmetry that characterizes their evolution. Their study showed that the dynamics of the jet in its flat side are very different compared with its vertex side. The flow along the flat edge is dominated with coherent structures, while the flow in the vertex is more turbulent. This occurs due to higher order modes getting amplified on the vertex side, making the jet more unstable on this side. The difference in the formation mechanism along the two sides of the jet is preferable for applications that can benefit from increasing fine scale mixing, while reducing coherent structures (say in a jet engine).
Koshigoe et al. [26] showed that the underlying mechanism of axis switching in triangular jets depends on the localized eigenfunctions of the jet, the amplification rate of the eigenmodes of the jet, and the phase speed difference between the eigenmodes. Miller et al. [17] showed computationally and Quinn [27] experimentally that the switching process repeats itself several times downstream of the orifice. Quinn [27] also showed that the spreading rate of triangular jets is faster than circular jets having the same equivalent diameter.

2.3 The synthetic jet

Synthetic jets are a special case of pulsed jets having zero-net-mass-flux across the orifice. Along with this unique characteristic, their flow properties and their interactions with adjacent flow render them to be one of the preferred actuators for active flow control. Their current and potential applications vary from flight control (Amitay et al. [28], Amitay et al. [29], Andres et al. [2], Greenblatt and Wygnanski [30], and Wygnanski and Seifert [31]), to thermal management (Campbell et al. [32], Mahalingam and Glezer [33], and Mahalingam and Glezer [34]), and enhancement of mixing (Gad-el-Hak [35] and Tamburello and Amitay [36]). Synthetic jets eliminate the need for sophisticated or heavy support systems (e.g. hydraulics, piping, air supply, connections, and compressor pumps) and offer an ideal solution at a relatively low cost.

Synthetic jets are formed from the time harmonic motion of a vibrating element that encloses a cavity with an orifice. During each cycle, the vibrating element moves towards the orifice and a slug of fluid is ejected out of the cavity. A vortex sheet is formed at the edge of the orifice, which depending on the shape of the orifice, roles
into a vortex pair or a ring. The vortex pair/ring then advects downstream under its own induced velocity [37]. When the vibrating element moves away from the orifice a pressure drop occurs inside the cavity and flow enters. The vortex pair/ring is removed enough from the orifice not to be affected by the entrained flow. The mass of the fluid slug that exits the orifice is equal to the mass that enters, which gives synthetic jets their zero-net-mass-flux characteristic.

The zero-net-mass-flux at the orifice of synthetic jet occurs due to the reversal of the flow. Smith found that this zero-net-mass-flux characteristic of a synthetic jet did not translate into equal momentum of the flow across the orifice. Using hot-wire measurements, he observed zero timed average velocity at the center of the orifice exit for the 2-D synthetic jet [3], but not for the circular synthetic jet [4]. These studies showed that the duration and magnitude of the velocity are equal during the ejection and entrainment cycles for 2-D synthetic jet, but vary for the circular jet. Smith initially suggested that these differences could result from the measurement location (x/h=0 for the 2-D case, and x/D=0.1 for the circular case), but he later noted that the asymmetry of circular case occurred at the exit [38].

Previous studies that aimed to compare synthetic and continuous jets (Smith and Swift [38], and Cater and Soria [39]) showed that the main difficulty of doing so stems from the difference between the velocity scales that are used to normalize the flow. These velocity scales are normally based on the jets exit velocity or their centerline velocity, which have irregular behavior in synthetic jets. The time averaging process, which intends to determine the flow characteristics, is more involve for synthetic jets. Depending on the axial location, synthetic jets observe partial or complete flow reversal, and the averaging process of the velocity can include negative values.
2.3.1 The jet actuator

The main variation in the actuators that are capable of producing synthetic jets is in the mechanism/element that creates the vibrations. These actuators can be based on mechanical means (Mednikov and Novitskii [40]), loudspeakers (Smith and Swift [41] Müller et al. [6]), plasma (Santhanakrishnan and Jacob [42]), or piezoelectric means. The latter mechanism is the most commonly used where a piezoelectric material is connected to a metal diaphragm (See Figure 3.1b). The type of vibrating element determines the forcing frequency range of the jet.

Gallas et al. [43] created a lumped element model, which showed that varying the actuator geometry will vary the forcing frequency of the jet since it changes the Helmholtz frequency of the actuator. They showed that increasing the cavity volume caused an increase in the acoustic compliance and decreased the overall broadband amplitude. They also showed that the orifice is related to the acoustic mass of the actuator and that increasing the orifice diameter causes the forcing frequency of the jet to increase. In contrast, increasing the orifice length causes the forcing frequency to decrease. Gallas et al. [43] also modeled the material properties of a vibrating piezoelectric element and demonstrated that the performance of the actuator (measured by the peak velocity of the jet) is optimized when the forcing frequency is near the mechanical resonance of the piezoelectric diaphragm and the acoustic (Helmholtz) resonance of the cavity and the orifice, which is due to the coupling that occurs.

Liang et al. [44] investigated how changing the current that drives the actuator would affect its performance. They showed that the deformation magnitude of the vibrating piezoelectric material is directly related to the magnitude of the current
being applied, which stems from the capacitor characteristic of the piezoelectric material. Thus higher current values generate bigger slugs of fluid that move across the orifice, translating into bigger stroke lengths of the jets. Liang et al. [44] also found that non-symmetric displacement of the piezoelectric material occurs with greater displacement of the material occurring when positive current is applied.

Chen et al. [45] looked at improving the actuator performance by changing the material and geometry of the piezoelectric diaphragm. They found that the material performance (i.e. its durability during prolong use) depend on the type, bond strength, and the glass transition temperature of the adhesive material used to connect the piezoelectric to the metal plate. They also found that the performance of their actuator increased with the area of the piezoelectric material and the thickness of the metal material, but decreased with the thickness of the piezoelectric material.

The geometrical parameters of the synthetic jet actuator were investigated by Gomes et al. [46] (for a circular orifice), and found that the actuator performance was reduced with the heights of its cavity and orifice. As the cavity height increases, the momentum of the swept volume (fluid displaced by the vibrating element) gets damped inside the cavity and less gets transferred into the orifice. As similar mechanism exists in the orifice but the damping effect accelerates the flow. In contrast, the boundary layer that develops inside the orifice decelerate the flow. Gomes et al. [46] showed that optimization of the actuator occurs when the ratio of the orifice height to its diameter ($L_o/d$) is 1.25.

Ugrina et al. [47] investigated the shape effect of the orifice and the shape of the vibrating element of the actuator. They observed higher peak velocity for slot orifices (aspect ratio was varied from 9 to 28) compared with circular orifices (with the same
equivalent diameter), which they attributed to the higher resistance that exist in
the circular orifice. Ugrina et al. [47] also reported that the actuator performance
had increased when using rectangular piezoelectric material (compared with circular
elements) for the vibrating element, which they ascribed to the greater displacement
that occurs with the rectangular element. A similar study was done by Mossi et al.
[48] who looked at the affect of using a biomorph vibrating element that has two of
its sides covered with piezoelectric material. They observed that using the biomorph
material increased the actuator performance, but noted that such improvement was
not proportional to the increase in cost that was associated with the new design.

Zhong et al. [49] looked at the effect of an inclined circular orifice and observed
that the skewness (asymmetry) of the velocity profiles was proportional to the angle
of inclination of the jet. Their study also found that the peak velocity of the synthetic
jet increased as the inclination angle of the orifice increased, which they attributed
to the asymmetry in the shear layer formed in the orifice. The inclination creates a
side with a reduced shear layer, which accelerates the flow. The acceleration is not
negated by deceleration that occurs on the other side.

The edge configuration of the orifice was investigated by Holman et al. [50] who
showed in a numerical and computational model that fillet radius at the exit of the
orifice delayed the formation of the vortex pair/ring and that a smaller exit diameter
of the jet will form when the orifice exit is sharp.

### 2.3.2 Axisymmetric jets

The synthetic jet is similar to the excited jet with respect to its dependence on
the Strouhal number. Shuster and Smith [5] examined the flow characteristics of
axisymmetric jet, and showed that in the near field, the jet characteristics such as centerline velocity, jet width, turbulent quantities, and the trajectory of the jet, is scaled with the actuator stroke length. The actuator stroke length is a quantity that measures the slug of fluid that is ejected out of the orifice during each cycle. Holman et al. [50] showed that the dimensionless slug length, $L_o/D$, corresponds to the inverse of the jet Strouhal number. Similar results of the jet scaling with the actuator stroke length were shown by Smith et al. [4]. To estimate the exit velocity of the jet Shuster and Smith [5] used a sinusoidal equation, which amounted to net-zero-mass-flux across the orifice. Di Cicca and Iuso [51] varied the Reynolds number of the jet, while keeping its Strouhal number and also observed that the jet characteristics were not influenced by the former.

Cater and Soria [39] compared the characteristics of an axisymmetric synthetic jet to a conventional turbulent jet produced by the same apparatus. They observed similarity of the cross-stream velocity profiles between the two jets, but greater spreading and decay rates for the synthetic jet. The differences occurred in the near field and stemmed from the structural differences of the jets in this region. Higher volume flow rate was also observed for the synthetic jet compared with the continuous jet, although the difference shown between their jets was minimal.

All the aforementioned studies for axisymmetric synthetic jet were experimental and the data was taken using PIV. Mallinson and Reizes [52] used a computational model to look at the characteristics of the axisymmetric synthetic jet and compare their results with hot-wire measurements. It should be noted that hot-wire anemometry cannot differentiate negative and positive velocities, which occur near the orifice of the jet. The practice instead is to invert the velocity measurements (Bruun [53]).
Mallinson and Reizes [52] varied the dimensions of the actuator and showed that the peak velocity of the jet depends on the ratio of the displacement volume from the cavity and the boundary layer that is formed within the orifice. The characteristics of their jet were overall similar to the previous characteristics mentioned above.

2.3.3 Non-circular jets

Smith and Glezer [3] used hot-wire anemometry and Schlieren images to study the formation mechanism of a 2-D synthetic jet (AR=150). They showed that the coherence of the jet is dominated in the near field, but further downstream the jet transitions into a continuous turbulent jet. Smith and Glezer [3] noted the lack of interaction between successive vortex pairs and suggested that the transition into a turbulent jet occurs via the decay of the vortex pair into small scale structures. They noted higher decay rate of the centerline velocity (compared with 2-D continuous jets). They also showed that although the change in volume flow rate, \( \frac{dQ}{dx} \), is lower than the conventional 2-D jet, the overall flow rate of the jet is several time higher than the equivalent turbulent jet.

Béra et al. [54] compared their jet (AR=100) with an equivalent excited jet (using moderate forcing), and showed that for the latter the expansion of the jet is delayed and occurs further downstream of the orifice. They showed that further downstream the vortex pair is no longer in phase with the forcing frequency of the jet, therefore appearing at different axial locations when phase-locked velocity fields were taken (using PIV).

Amitay and Cannelle [7] showed, using planar PIV, that a vortex pair from the same cycle collide and destroy each other, which they attributed to be the process that
governs the development of the synthetic jet further downstream. Similar to Smith and Glezer [3] they did not observe interaction of successive vortex pairs. Their study also showed that increasing the aspect ratio of the slot decreases the spreading rate of the jet, which they attribute to the reduction in the induced velocity at the higher AR jets.

The lack of interaction between successive vortices was also shown numerically by Kotapati et al [55]. Their study showed that the jet transitioned into a continuous jet via breakdown of the vortex pair, which they attributed to the rapid growth of the spanwise instabilities in the jet. The results of Kotapati et al. [55] had good agreement with experimental data only near the orifice.

Smith and Glezer [56] showed the existence of a saddle point in the slot synthetic jet, which marks the axial location (i.e. border) between the region in the flow that is affected by the suction phase and the one that is not. They showed that the location of the saddle point varies during the suction phase, and that its maximum depends on the Strouhal number of the jet. The existence of these two regions is the fundamental mechanism that enables synthetic jet to act as a flow control mechanism for adjacent jets. Di Cicca and Iuso [51] showed that such a saddle point exists in axisymmetric synthetic jets too.

2.4 Vortex merging

Vortex merging in the flow leads to two possible outcomes: either complete destruction of the vortices, which reduce the coherence of the jet, or formation of a new vortex. Ho and Huang [57] showed that the location of the merge depends on the
initial conditions and the Strouhal number of the jet. They showed that the subharmonics in the jet act as a catalyst for the process. Ho and Huang [57] observed that concurrent to the vortex merging the following also occurred in the jet: a peak in the energy of the subharmonics, alignment of the vortices, and constant spreading rate. The process of vortex merging is known to govern the growth of the mixing layer (Ho and Huerre [58]).

2.5 Exit velocity

The exit velocity of the jet is an important characteristic as it is often used to normalize the velocity of the jet for the purpose of comparison with jets under different flow conditions. The exit velocity of the jet is commonly used to calculate the Reynolds and Strouhal numbers of the jet.

For conventional turbulent jets the velocity scale is normally taken from the time-averaged velocity at the orifice exit:

$$U_o = \frac{1}{T} \int_0^T u_o(t) dt$$  \hspace{1cm} (2.1)

Here $u_o$ is the centerline velocity at the exit, and $T$ is the integration time. Equation 2.1 is the standard equation used to compute the time-averaged velocity values, regardless of the flow direction. When reverse flow is present (i.e. negative velocity) it leads to underestimation of the true magnitude of the forward velocity. For synthetic jets, the largest fallacy in the mean velocity occurs near the orifice where large magnitudes of negative velocity exist.

Smith and Glezer [3] suggested that the exit velocity for synthetic jets should be based on the positive velocity at the orifice exit, averaged over the entire cycle:

$$U_o = \frac{1}{T} \int_0^\eta u_o(t) dt$$ \hspace{1cm} (2.2)
Where the forcing frequency of the jet is $F_o = 1/T$, and $\eta = F_o/2$. $u_o$ is the centerline velocity at the exit. The equation intends to better describe the forward momentum of the flow in synthetic jet. The majority of studies on synthetic jets use Equation 2.2 (or some derivation of it) as a method to compute the exit velocity of the jet.

The foremost information from the literature review given in this chapter is that the flow characteristics of synthetic jets are independent of the Reynolds number, but vary based on the Strouhal number of the jet. The exit velocity of the jet is used to compute both these numbers; hence its computation method is central for the purpose of comparing different jets. If it is expected that jets with similar Strouhal numbers would be comparable with each other, then care must be taken to ensure that the exit velocity is calculated in the same manner for comparative jets.
Chapter 3: Methodology - synthetic jets

3.1 The synthetic jet actuators

The synthetic jets were generated from an actuator having orifice height of $L_o/D = 0.7$, cavity diameter of $D_c/D = 12.3$ and cavity height of $L_c/D = 0.4$. The orifice of the actuator was positioned across from the vibrating element (Figure 3.1a). The diameter of orifice for the axisymmetric (circular) case was $D=3.9\text{mm}$. The slot (AR=3) and the equilateral triangle had the same dimensions for the actuator and the same equivalent diameter for the orifice. The vibrating element in the actuators was a piezoelectric diaphragm plate having 50mm diameter (APC International, FT-50T-2.6A). A back-plate was used to mount the diaphragm to the orifice-plate. Both the orifice-plate and the back-plate were made of (anodized) aluminum (Figure 3.1b) and were held together using eight equi-spaced screws near their perimeters. The diaphragm was operated at $100V_{pp}$, sine waveform, generated by a function generator (Agilent, 33220A) connected to a x50 amplifier (Tegam, 2350).

The driving voltage of the diaphragm was chosen such that it would generate a substantial jet, but would not cause re-polarization of the piezoelectric material. Increasing the voltage amplitude would increase the deflection of the diaphragm, which would sweep more volume from the cavity and thus increase the jet velocity [46]. The
maximum voltage that can be safely applied to the diaphragm was determined by the dielectric properties of the piezoelectric material. Excessive voltage can cause repolarization of the piezoelectric material and subsequently reduce its effectiveness (i.e. by reducing how much the diaphragm deflects). Large deflections of the diaphragm that exceed the yielding point of the piezoelectric material can lead to cracking of this (very) brittle material.

The frequency response of the actuators, based on peak velocity of the jets taken one diameter length above the orifice using hot-wire are shown in Figure 3.2. Hot-wire measurements were collected using an anemometer (A. A. Lab Systems, AN-1005) taken at 25kHz sampling rate for a total of 100k data points. The forcing frequency of all the synthetic jets was set to 700Hz. The Strouhal numbers for the different cases (based on equivalent exit diameter) are summarized in Table 3.1
Figure 3.2: Frequency response of the synthetic jet actuators. Data is based on peak velocity taken one diameter above the orifice. Forcing frequency of the jets was set to 700Hz.

Table 3.1: Initial conditions for the jets in the current study

<table>
<thead>
<tr>
<th>Synthetic jet</th>
<th>$St_D = F \cdot D_e/U_o$</th>
<th>$Re_D = U_o \cdot D_e/\nu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Circular</td>
<td>$U_o \rightarrow$ Eqn 2.1</td>
<td>$U_o \rightarrow$ Eqn 3.1</td>
</tr>
<tr>
<td>Circular</td>
<td>0.26</td>
<td>2562</td>
</tr>
<tr>
<td>Circular</td>
<td>0.12</td>
<td>5472</td>
</tr>
<tr>
<td>Slot</td>
<td>0.23</td>
<td>2935</td>
</tr>
<tr>
<td>Slot</td>
<td>0.13</td>
<td>5086</td>
</tr>
<tr>
<td>Triangular</td>
<td>0.24</td>
<td>2811</td>
</tr>
<tr>
<td>Triangular</td>
<td>0.16</td>
<td>4228</td>
</tr>
</tbody>
</table>
3.2 Instrumentation

3.2.1 Hot-wire anemometry

Hot-wire anemometry (HWA) is used to measure velocity of a fluid. The method is based on placing a hair-thin wire (or film) into the flow and quantifying the convective heat transfer between the wire and the flow. The wire is constantly heated and thus any changes in the flow conditions (i.e. its velocity, temperature, concentrations, etc.) will affect the heat transfer from the wire, which can be measured and quantified into some measurable engineering unit.

The two main advantages of HWA are the relatively low cost (compared with LDV systems) and the fast frequency response of the wire (which relates to the temporal resolution of the measurement). The two main disadvantages of this method are the low spatial resolution (although it is still much higher than LDV), and the higher inaccuracies when the flow is highly turbulent (Bruun [53]). The latter stems from the inability to discern the flow direction using single wire measurement. Flow measurements in a highly turbulent flow can be significantly improved if the data is taken using multiple wires.

The fundamental principle of HWA was proposed by King [59] who showed that the heat transfer from a heated (infinite) wire placed into the flow will depend on the properties of the flow (i.e. density, viscosity, thermal conductivity, etc.) and the characteristics of the flow (i.e. velocity, temperature, pressure, etc.). The HWA method defined these relationships via different correlations of the Nusselt, Reynolds, Prandtl, Grashof, and Mach numbers. The actual value for the correlations varied based on the medium being measured and its conditions.
The practical hot-wire method is based on modification of the relationships that were developed for the infinite wire by taking the wire to be of a finite length. The wire is held in space between two prongs, which are significantly bigger than the wire. The wire is then heated by a current to a constant temperature that is significantly higher than the temperature of the flow, which also creates conductive heat transfer towards the prongs. This leads to a temperature gradient within the wire. In order to achieve a uniform temperature distribution profile along the wire, there must be some minimal length to diameter ratio of the wire (Bruun [53]). The airflow that passes over the heated wire has a cooling effect, which changes the resistance of the wire. The velocity of the flow is estimated by calibrating the wire resistance to known velocity values.

The hot-wire method that is based on constant temperature anemometer, CTA, is operated by keeping the resistance of the hot-wire constant. The resistance of the wire will tend to fluctuate with the fluctuations of the flow and thus the current running through the wire is measured and made to increase or decrease to compensate and keep the resistance constant. The current adjustments are made via servo amplifier with a very high frequency response.

3.2.1.1 Flow measurements in synthetic jets

Velocity measurements using hot-wire anemometry were collected for the synthetic jet experiments using a single component 1mm hot-wire probe connected to an anemometer. The data was taken at 25kHz sampling rate for a total of 100k data points. All measurements were taken one diameter length above the orifice. Sample data from the hot-wire signal is shown in Figure 3.3. Assessing the forcing frequency of the synthetic jets (Figure 3.2) was done based on averaging the peak velocities.
3.2.2 Particle Image Velocimetry

The Particle Image Velocimetry (PIV) method is a non-intrusive velocity measurements technique. The technique is most advantageous where spatial information about the flow field is of interest. Other flow derivatives (such as turbulence, vorticity, pressure, etc.) can be extracted from the PIV velocity measurements.

The principle of the PIV method is based on measuring the particle displacement in the seeded flow between two light pulses. The light pulses illuminate the flow field with some known predetermined time interval. A digital camera then capture each illumination of the flow field in a separate frame. Each frame is divided into interrogation windows, which are cross-correlated between the two frames. The displacement of the particles inside the widow are determined from the highest (i.e. strongest)
Figure 3.4: Measurement planes in the synthetic jets experiments.

correlation peak from the correlation function. Because the known time interval, $dt$, between the two frames, each correlation window produces a velocity vector. The velocity field is obtained by applying interrogation windows (with some overlap) for the entire flow field. Advance algorithms for PIV use adaptive shape for the interrogation windows, which gives high fidelity flow vectors in large gradient flows (e.g. vortex).

3.2.2.1 Flow measurements in synthetic jets

PIV measurements of synthetic jets were taken by mounting the actuators on a vise inside a chamber (measured 50x50x50cm) made of clear acrylic walls. The bottom of the chamber, below the vise, was open to the atmosphere. The inside of the chamber was seeded using DEHS oil (Alfa Aesar, Bis(2-ethylhexyl) sebacate) generated by an atomizer (TSI, 9306). The flow field was illuminated from above the orifice. The measurement planes for the different orifice configurations is shown in Figure 3.4. Cross-sectional measurements were acquired in the case of a slot orifice and were taken by illuminating the flow field from the side, parallel to the synthetic jet actuator, at different axial stations.
Time resolved PIV data was collected by illuminating the jet using a high repetition rate, dual cavity, Nd:YLF laser system (Litron, LDY304) synchronized with a high speed video camera (Photron, FASTCAM SA5). The camera was fitted with a Nikon 85mm F/1.4 lens and a 527nm bandpass filter. An area of 512x992 pixels corresponding to 21.2x40.9mm in the physical space was captured for each image by connecting a 20mm extension tube to the lens. Image pairs were taken at a time interval of 8µsec. Post processing of the images was done using DAVIS® 8.1 software (from LaVision Inc) with a multi-pass decreasing window size (64x64 to 32x32) and adaptive interrogation window with 50% overlap.

The acquisition of the PIV data was triggered by the driving signal of the actuator. Phase locked data was obtained using a sampling rate of 7kHz for the PIV. Using a trigger delay (Stanford Research, DG535), total of 50 phases were collected to ensemble phase averaged data. Each phase was computed by averaging the results from 720 image pairs. Convergence of the PIV data was confirmed by comparing the ensemble average from 720 realizations with a trial of 1000 realizations, which showed less than 1% deviation in the turbulent quantities. The time-average data was calculated from averaging 1200 image pairs, taken at a sampling rate of 6250Hz. A-synchronizing the sampling rate of the PIV to the forcing frequency of the jet (700Hz) gave a sample population of the flow field data that can be considered as random (Figure 3.5).
3.3 Data Processing

3.3.1 Proper orthogonal decomposition

The proper orthogonal decomposition method (POD) can be used to investigate the most dominant structures of the jet (Berkooz, et al. [60]). The method extracts the most energetic modes from the flow by assuming that high-energy structures are associated with the different modes of the flow. The method forms an ortho-normal set of eigenvectors fields (i.e. modes) and eigenvalues (i.e. energy) based on a correlation tensor: \( R\Phi_n = \lambda_n \Phi_n \), where \( \Phi \) is an eigenvector field, \( \lambda \) is the eigenvalue, \( R \) is a correlation tensor, and \( n \) is the mode number. The extraction of the POD modes for the synthetic jet was followed by the snap shot method by Sirovich [61], which gives the same number of modes as the total number of PIV images that were used in the
computation. For each snapshot of the velocity field the modal amplitude is obtained by projecting the PIV image onto the eigenvector: \( a_{i,n}(t) = \int u'(\vec{x}, t) \Phi_i^*(\vec{x}) d\vec{x} \).

### 3.3.2 Exit velocity of the synthetic jets

The exit velocity in synthetic jets was calculated according to Equation 2.1 and Equation 2.2. The exit velocity was also computed by integrating the positive velocity, and averaging its duration:

\[
U_o = \frac{1}{T^*} \int_0^{T^*} u_o(t) dt
\]  

(3.1)

where \( u_o \) is the centerline velocity at the exit and \( T^* \) is the period of positive velocity in the cycle measured on the centerline of the jet.

### 3.4 Experimental uncertainty estimation

The Stokes number, defined as: \( S = \tau_p/\tau_f \), can measure how closely the seeding particles can follow the flow. Here \( \tau_p = \rho_p D_p/18\mu \) and \( \tau_f = \delta_o/U_o \), where \( \rho_p \) and \( D_p \) are the particle density and diameter, respectively. \( \mu \) is the absolute viscosity of air, \( \delta_o \) is the thickness of the shear layer at the orifice (measured as the distance where the velocity drops to 80% of its value along at the centerline), and \( U_o \) is the average centerline velocity of the jet at the orifice exit. Crowe et al. [62] and Chein and Chung [63] showed that for a seeding particle to follow an incompressible flow, the Stokes number should be less than 0.2. The upper bound in the synthetic jet experiments was \( S = 0.0015 \), which set the estimated errors due to the Stoke number effect at less than 2%. The mean particle size in the study was 0.3\( \mu m \) (per atomizer specifications), which gave a particle response of 10kHz based on its scattering properties (Melling [64]).
The uncertainty of the experimental parameters comes from the basis that the flow properties are not measured directly, but instead are determined from a combination of other quantities (i.e., parameters). The combination of all the uncertainties that are associated with the system parameters are assumed to have equal contribution, and are summed together to give the overall error of the measurement system [65]. The error is given by:

\[ E \equiv \sqrt{\left( \Delta u_1 \frac{\partial f}{\partial u_1} \right)^2 + \left( \Delta u_2 \frac{\partial f}{\partial u_2} \right)^2 + \ldots + \left( \Delta u_n \frac{\partial f}{\partial u_n} \right)^2} \]  

(3.2)

The two main parameters that affect the uncertainties of velocity measurements from PIV come from the uncertainty in the particle displacement (estimated to be in the order of 0.1 pixel), and the uncertainty of the timing for the laser pulse (estimated to be in the order of 1 nsec).

The time interval for each image pair in the synthetic jet experiments was set at 8 \( \mu \) sec. The highest displacement of particles occurred near the orifice where the velocity was at its maximum. For the current data this corresponded to 8.7 pixels, which according to Eqn. 3.2 yields an estimated error of 1.1%. The rapid decay of the jet produced different uncertainty of the velocity measurements further downstream. Based on the mean velocity of the jets, the uncertainty of the data near \( x/D=5.0 \) was estimated to be 4.2%-4.5% and 8.0%-9.2% near \( x/D=10 \).

The velocity measurements on the centerline of the jet at \( x/D=1.0 \) were compared between the PIV and the hot-wire data. It showed an average difference of 2.0% in the peak velocities with a standard deviation of \( \pm 2.8 \text{m/s (4.3\%)} \). The difference in the mean velocity was 0.3 m/s (0.5%). The mean velocity data from hot-wire was computed after inverting the velocities corresponding to the entrainment flow.
Chapter 4: Results - flow characteristics in synthetic jet

4.1 Axisymmetric synthetic jet

4.1.1 Instantaneous and mean velocity

A sequence of consecutive instantaneous velocity fields taken 1.6msec apart (every \( t/T = 0.11 \) ) are shown in Figure 4.1. The sequence covers a little more than a cycle (from \( t/T = 0.3 \) until \( t/T = 1.53 \) ) and shows the formation and development of the same vortex ring. The ejection phase occurs in Figures 4.1a to 4.1c and 4.1i to 4.1k and the ejected flow is characterized with a forward momentum (i.e. positive axial velocity). The suction phase occurs in Figures 4.1d to 4.1h and 4.1l. Near the orifice the flow is dominated by the entrainment that enters the cavity of the actuator (i.e. negative axial velocity). Such complete reversal of the flow near the orifice is the chief characteristic of synthetic jets, which separates them from continuous (forced or unforced) jets. This characteristic also challenges how the time averaged velocity characteristics of the jet are determined. The images show that the vorticity magnitude and the magnitude of the axial velocity in the middle in the vortex ring are constantly decreasing as the vortex ring is convecting downstream from the orifice. Finally, merging of successive vortex rings is observed in Figures 4.1h to 4.1k and will be discussed in Section 4.1.3.
The time-averaged axial velocity field is shown in Figure 4.2. The first image shows the mean velocity field computed in a traditional way (i.e. Eqn. 2.1). It suggests that the flow is accelerating downstream of the orifice, which is known to occur in continuous jets due to the vena contracta effect (Figure 4.2a). The second image shows the mean velocity field based on the forward momentum of the jet (Eqn. 3.1). It shows that the highest velocity magnitude occurs near the orifice and the forward momentum of the jet is constantly decaying downstream of the orifice (Figure 4.2b). The spreading pattern of the jet near the orifice is also different than the spreading pattern of the jet in Figure 4.2a. The third image is the mean axial velocity field based on the negative velocity. It shows that the highest magnitude occurs at the orifice and that the jet is spreading more laterally because more entrainment gets pulled into the cavity from the sides of the orifice (Figure 4.2c). The complementariness of the positive and negative velocity fields makes the positive velocity near the orifice depreciated by the magnitude of the negative velocity and give the flow field that is shown in Figure 4.2a.
Figure 4.1: Consecutive instantaneous velocity fields with the vorticity shown. a) t/T=0.3, b) t/T=0.41, c) t/T=0.52, d) t/T=0.63, e) t/T=0.75, f) t/T=0.86, g) t/T=0.97, h) t/T=1.08, i) t/T=1.19, j) t/T=1.31, k) t/T=1.42, l) t/T=1.53. \( \omega = \partial u_x / \partial r - \partial u_r / \partial x \). PIV data is taken at 6250Hz. \( F_o = 700 \text{Hz} \). Vortex merging is observed in images (h)-(k).
The meshing of the negative and positive velocities in synthetic jets can also be examined by the development of the saddle point in the jet, which is shown using the streamline maps in Figure 4.3 taken from the phase-averaged data. A saddle point is defined as the stagnation point in the centerline of the jet. The images show formation of a saddle point that moves downstream and then recedes back towards the orifice as the suction cycle progress. This axial progression during the cycle is shown in Figure 4.4, which also plots the axial location of the left and right sides of the vortex ring. The saddle point reaches up to one diameter above the orifice around $t/T=0.8$ before it starts to recede back. Smith and Glezer [56] showed that the maximum axial location of the saddle point in a 2-D synthetic jet increases with the magnitude of the stroke length ($L_o/h$). For the circular synthetic jet, Di Cicca and Iuso [51] observed the saddle point moving up to two diameters above the orifice for a stroke length of $L_o/D=23.32$. The lower axial location and the lower stroke length of the current data (see Table 4.2) shows that the same conclusion probably holds for the circular case. Figure 4.4 also shows that the saddle point begins to develop immediately after the beginning of the suction cycle. At this phase, the vortex ring is located about 1.8 diameters above it, hence removed enough not to be affected by the entrained flow.
Figure 4.2: Mean axial velocity fields. a) Based on all velocity values (Eqn. 2.1), b) Based on positive velocity (Eqn. 3.1), c) Based on negative velocity (showing magnitude)
Figure 4.3: Phase averaged velocity fields with streamlines showing axial progression of the saddle point in the jet. a) $t/T=0.51$, b) $t/T=0.55$, c) $t/T=0.59$, d) $t/T=0.63$, e) $t/T=0.67$, f) $t/T=0.71$, g) $t/T=0.75$, h) $t/T=0.79$, i) $t/T=0.83$, j) $t/T=0.87$, k) $t/T=0.91$, l) $t/T=0.95$. 
The downstream decreasing magnitude of the negative velocity also suggests that the temporal span of the negative velocity in the flow decreases. This is shown in Figure 4.5 that tracks how the parameter $T^*$ in Eqn. 3.1, which indicates the span of the positive velocity, changes along the centerline of the jet. The variation in $T^*$ shows that it starts from about 60% of the cycle and increases downstream until the entire cycle has positive velocity at about $x/D=1.0$. At this axial location the entrainment flow is no longer affecting the centerline velocity, which is also seen in Figure 4.2c.

The lack of negative velocity also makes Eqns. 3.1 and 2.1 identical. This is shown in Figure 4.6a, which plots the positive, negative, and both components of the centerline velocity in the jet. The velocities values in Figure 4.6a are normalized by the same exit velocity, $U_o$, which is calculated from Eqn. 2.1. The figure shows how
Figure 4.5: Change in integration time, $T^*$, for the centerline velocity. $F_o = 700$Hz. $U_o = \frac{1}{T^*} \int_0^{T^*} u_o(t)dt$.

significant the drop in the forward momentum is, and how averaging the negative and positive velocities together hides this characteristic of the jet.

Figure 4.6a also shows that the negative velocity acts in contention to the convective velocity and hindering the vortex ring from advecting downstream. The diminishing negative velocity is matched by an increase in the convective velocity (up to $x/D=1.2$). The convective velocity starts to drop again at $x/D=2.5$ when the vortex ring begins to decay.

Comparison of the centerline velocity based on the current data and other studies on circular synthetic jets is shown in Figure 4.6b. The current data is shown using three methods: the first calculates $U_{cl}$ and $U_o$ based on Eqn. 2.1. The second method calculates $U_{cl}$ based on Eqn. 2.1 and $U_o$ based on Eqn. 2.2. The third method calculates $U_{cl}$ and $U_o$ based on Eqn. 3.1. The data from Mallinson et al. [52] was computed in the same manner as the first method and the difference with
The current data probably stems from the differences in measurement techniques; Mallinson [52] used hot-wire anemometry, which cannot give accurate differentiation between negative and positive velocities. The data from Di Cicca and Iuso [51] and Müller et al. [6] was computed in the same manner as the second method. Smith and Shuster [5] showed that the axial distribution of the centerline velocity varies based on the stroke length of the synthetic jet, which explains the difference between the current and the other studies.

The results from the current data are compared with the centerline velocity of continuous jets in Figure 4.6c. The centerline velocity computed by the first method suggests similarity with the centerline velocity of continuous jets. This conclusion should be taken with care because Eqn. 2.1 misrepresent the true dynamics of the centerline flow at and near the orifice. Using the second and the third methods to compute the centerline velocity shows that synthetic jets decay faster than continuous jet, which was shown by Smith and Glezer [3] for the 2-D jet and by Di Cicca and Iuso [51] and Shuster and Smith [5] for the circular jets.

The decay rate of the jet centerline velocity, $\frac{dU_{cl}}{dx}$ of some axisymmetric jets are compared in Figure 4.7 based on their Re and St$_D$ numbers. Figures 4.7a and 4.7b show that the decay rate of a synthetic jet is about tenfold higher than the decay rates of the forced and the continuous jets. The current data is comparable to the data of Smith et al. [4] and in both studies the decay rate is much higher than the data reported by Di Cicca and Iuso [5]. The medium in the latter was water while the formers were done in air. Consequently the exit velocities, $U_o$, of the current data and Smith’s data are much higher than the exit velocity of the jet in Di Cicca’s data (for similar Re numbers). Since the jets in these studies last for about the same axial
Figure 4.6: Centerline velocity of the jet. a) Negative, positive (Eqn. 3.1), and both (Eqn. 2.1) components. $U_o$ is computed from Eqn. 2.1. $U_{conv}$ is the convective velocity of the vortex ring. b) Comparison with other synthetic jet data: Di Cicca and Iuso [51], Mallinson et al. [52], and Müller et al. [6]. b) Comparison with forced jets: Crow and Champange [11], Hasan and Hussain [12]. Continuous jets: Hasan and Hussain [12], Zaman [66], and Quinn [67].
Figure 4.7: Comparison of the decay rate of the centerline velocity in different axisymmetric jets. Current data is compared with: Smith et al. [4], Di Cicca and Iuso [51], Hasan and Hussain [12], Crow and Champagne [11], Bremhorst and Hollis [16], Wygnanski and Fiedler [9], Obot et al. [68], Boguslawski et al. [69], and Quinn [70]. SJ- synthetic jet, FJ- forced jet, PJ- pulsed jet, CJ- continuous jet.

distance, it is expected that the decay rate in the air medium would be much higher.

The centerline exit velocity, $U_o$, for a single cycle in the current data is shown in Figure 4.8. The values shown are taken from the closest interrogation window to the center of the orifice. The figure shows that the magnitude of the peak negative velocity in the current data is about 40% of the magnitude of the peak positive velocity. Figure 4.8 also shows that the positive velocity spans about 60% of the cycle. Similar asymmetry of the centerline exit velocity was shown by Smith et al. [4], and Shuster and Smith [5]. The asymmetry of the cycles, which is used to compute the exit velocity in the jet, negates the zero-net-mass-flux characteristic that exists at the orifice. All the data for the circular cases in Figure 4.8 was taken using PIV, where each velocity vector that is computed represents the data for the center of its interrogation window. This means that the first interrogation window above the
orifice is actually showing the data at $x/D=0.1$. This value can vary based on the size of the interrogation window. Rizzetta et al. [71] showed similar asymmetric results for the centerline velocity at the exit in his computational model and attributed it to the difference between the boundary layer that is formed inside the orifice during the ejection part of the cycle, and the lack of a similar boundary layer during the inflow part of the cycle.

The asymmetry of centerline velocity at the exit observed in the circular synthetic jet is not observed in the 2-D jet. Smith and Glezer [3] used hot-wire anemometry to measure the exit velocity at $x/h=0$, and inverted the velocities measured during the suction phase. The method they suggested to compute $U_o$ (i.e. Eqn. 2.2) is adequate for computing the exit velocity for a slot orifice since the magnitude and duration of the velocity during the ejection and intake cycles are equal. The asymmetry in the magnitude and the temporal distributions of the negative and positive velocities at the exit in the case of the circular orifice suggests that Eqn. 2.2 is not adequate enough.

The different methods to compute the exit velocity (Eqns. 2.1, 2.2, and 3.1) also yield different Strouhal number values from the same jet: $St_D = F_o D / U_o$, where $F_o$ is the forcing frequency and $D$ is the orifice exit diameter. The variation in $St_D$ for the current data is shown in Table 4.2. Based on Eqn. 2.1, $St_D = 0.26$, which is within the range reported by Gutmark and Ho [15] for forced jets. Using Eqn. 3.1 gives a much lower value of $St_D = 0.12$. Table 4.2 also shows the Strouhal number data from other studies on circular synthetic jets. The data was either given or calculated based on the dimensionless stroke length, which was shown to be equivalent to the inverse of the Strouhal number (Holman et al. [50]). It shows that a substantial range for
Figure 4.8: Axial velocity at the center of the orifice during one cycle. x/D=0.1, F_o=700Hz. Exit velocity data for circular orifice is reproduce from Smith, Trautman, and Glezer [4] (PIV), and Shuster and Smith [5] (PIV), and slot orifice from Smith and Glezer [3] (hot-wire)

the values is reported in the literature (St_D varies from 0.007-1.22). The importance of how the St_D number of the jet is calculated is significant for synthetic jets because it was shown that their flow properties will vary with the St_D number of the jet ([3, 51, 5, 6]). If the St_D number, which is computed using U_o, is not calculated in the same manner, it can lead to erroneous comparisons between different jet studies. This might explain some of the differences that exist in the literature.

The cross-sectional velocity profiles of the synthetic jet at x/D=1.0 (Figure 4.9a) were computed using Eqn. 2.1 and Eqn. 3.1. Comparing these profiles shows that the entrainment is still affecting the flow towards the outer edge of the jet. At x/D=1.0 the negative velocity near the centerline is minimal and the two profiles almost overlap up to r/r_{1/2}=1.2. The velocity profile for synthetic jet at this axial location is different than the profile of continuous jets. The latter shows a more uniform velocity profile, which is a characteristic of flow emanating from a nozzle. Further downstream, where
the entrainment is no longer affecting the flow, the synthetic jet establishes the self-preserving behavior (Figure 4.9b). Continuous jets show the self-preserving behavior further downstream from the end of their potential core. Synthetic jets lack such a core, and if the effects from the entrainment flow are excluded (using Eqn. 3.1), then the synthetic jet attains self-preserving behavior at x/D=1.0.

The extraction of the turbulence quantities was done using the triple decomposition method suggested by Hussain and Reynolds [72]:

$$U = U_{ta} + \langle u \rangle = U_{ta} + \bar{u} + u'$$

(4.1)

Where $\langle u \rangle$, $\bar{u}$, and $u'$ are the total, deterministic, and the random fluctuations in the jet, respectively. $U_{ta}$ is the time-averaged velocity. To extract the random fluctuations in the flow, the time-average and the deterministic fluctuations were subtracted from each instantaneous velocity field: $u' = U - U_{ta} - \bar{u} = \langle u \rangle - \bar{u}$. The deterministic
fluctuations were extracted from the phase-averaged velocity data. Profiles of the axial and radial fluctuations are shown in Figure 4.10. At x/D=1.0 the deterministic component dominates the profiles of velocity components. The peak at the center of the axial velocity fluctuations (Figure 4.10a), the two peaks near the shear of the radial velocity fluctuations (Figure 4.10b), and the large magnitude of these fluctuations were also seen in the pulsed jet of Bremhorst and Hollis [16], who attribute this characteristic to the dominance of the periodic component in the flow. The maximum magnitude of the random fluctuations in the axial velocity is about 0.05U_{cl} and occurs near the shear. This magnitude is lower than the 0.1U_{cl} magnitude that is observed in continuous jets (Quinn [67]).

Further downstream the dominance of the deterministic component starts to lessen and the total fluctuations in the flow start to reduce correspondently, which was also observed in the pulsed jet [16]. At x/D=4.0 the maximum deterministic axial fluctuations are about 0.5U_{cl}, which match well with the profile measured by Shuster and Smith [5], and slightly below what was measured by Cater and Soria [39] (Figure 4.10c). The level of the random axial fluctuations increases to 0.2U_{cl}, which is slightly higher than the levels observed for continuous jets [67]. The deterministic fluctuations of the radial velocity at x/D=4.0 (Figure 4.10b) decrease from its upstream level. The maximum random fluctuations at the centerline of the radial velocity remained at the same level of 0.25U_{cl}, but the profile itself starts to expand indicating that more random fluctuations are now present in the radial velocity. The decrease of the deterministic component in the flow is correlated with the decrease in the magnitude of the vorticity of the vortex ring shown in Figure 4.1. The complement increase in the magnitude of the random fluctuations indicates that the vortex ring is decaying. The
decay of the vortex ring is also connected with the deceleration of the jet centerline velocity shown in Figure 4.6.

At x/D=7.0 (Figures 4.10e and 4.10f) the deterministic fluctuations are minimal in both velocity components. The total fluctuation is about 0.3U_{cl} in both velocity components, which is similar to the axial levels measured by Shuster and Smith [5]. The magnitude of the profile is also similar to what was measured by Wygnanski and Fiedler [34] for x/D>20 (about 0.27U_{cl}). At this axial location the flow is dominated by its random fluctuations. The magnitudes of the random and deterministic fluctuations suggest that the synthetic jet has nearly completely transitioned into a continuous jet.

The profiles of the Reynolds shear stresses in the synthetic jets are shown in Figure 4.11. The high magnitude of the total shear stresses ($\langle u'_x u'_r \rangle / U_o^2 = 4.0 \times 10^4$) was also seen in the pulsed jet of Bremhorst and Hollis [16] ($\langle u'_x u'_r \rangle / U_o^2 = 6.0 \times 10^4$), which they attribute to the contribution from the axial accelerations in the flow. The level of the random shear fluctuations at x/D=1.0 (Figure 4.11a) matches with the random fluctuation seen in the continuous jet of Wygnani and Fiedler [9], who observed a maximum level of $u'v'/U_o^2=1.7 \times 10^4$. Similarly to the continuous jets, the level of the total shear fluctuations does not changes with the axial location of the jet. This was also observed in the pulsed jet. In a similar manner to the axial and radial fluctuations (Figure 4.10), the distribution of the random and deterministic components in the shear stresses changes with the axial location. At x/D=4.0 (Figure 4.11b) the magnitude of the random shear stresses is higher than the magnitude of the deterministic shear stresses, which is different than what was shown for the axial
Figure 4.10: Turbulence profiles using triple decomposition. \( \langle u \rangle \) - Total fluctuations, \( \tilde{u} \) - Deterministic fluctuations, \( u \) - Random fluctuations. Comparison is made with continuous jet (Quinn [67]) and the total fluctuations measured in other synthetic jet data: Shuster and Smith [5] and Cater and Soria [39].
Figure 4.11: Reynolds stress for a) $x/D=1.0$, b) $x/D=4.0$, and c) $x/D=7.0$. Comparison with: pulse jet (Bremhorst and Hollis [16]), and continuous jet (Wygnanski and Fiedler [9]).

and radial velocity fluctuations (Figure 4.10c, and 4.10d). At $x/D=7.0$ (Figure 4.11c) the shear fluctuations are all coming from the random fluctuations.

The axial change in the fluctuating components in the flow is shown in Figure 4.12. The images in the figure show the fluctuations along the centerline (Figure 4.12a) and near the shear layer, where $U=0.5U_{cl}$ (Figure 4.12b). In both cases the decay in the deterministic component starts at the orifice ($x/D=0$). The random fluctuations of the jet are initially minimal for $x/D>0$ and start to increase around $x/D>0.5$ near the shear and $x/D>2.5$ at the centerline. The increase in the random fluctuations around
Figure 4.12: Turbulence fluctuation components of the axial velocity along the a) centerline and b) near the shear layer (where \( U = 0.5U_{cl} \)) of the jet.

\( x/D = 2.5 \) is correlated with the decrease in the centerline velocity, which was observed in Figure 4.6. The decrease in the magnitude of the deterministic component also corresponds to the decreased size of the vortex ring (compare Figures 4.1b and 4.1e). Combing these observations suggest that by \( x/D = 2.5 \) the decay of synthetic jet into a continuous jet is in progress. The random fluctuations along the centerline surpass the deterministic fluctuations around \( x/D = 5.5 \), but occur about two diameters upstream (around \( x/D = 3.5 \)) in the shear. Bremhorst and Hollis [16] observed the periodic component in the pulsed jet to be dominated up to \( x/D = 50 \). The deterministic component becomes minimal in the shear around \( x/D = 5.5 \) and vanishes on the centerline around \( x/D = 8.0 \). The magnitude of the fluctuations in the jet levels off to a magnitude of \( 0.3U_{cl} \) for both velocity components, which is higher than the level measured in continuous jets (e.g. \( 0.1U_{cl} \) in Crow and Champange [11]), but is the same level (\( 0.3U_{cl} \)) as measured in the pulsed jet [16].
Quantifying the spreading rate of synthetic jets is commonly done based on the half width of the jet, which is computed from the time-averaged velocity field. As was shown earlier for the centerline velocity, the spreading rate near the orifice of the synthetic jet can vary based on how the time-averaged data is calculated. Figure 4.13a shows the jet width based on its positive, negative, and both components of the velocity. The steep spreading rate of the negative velocity is because the majority of this component is coming from the entrainment (i.e., sides of the orifice), which is also seen in Figure 4.2c. Figure 4.13a also shows that for $0 < x/D < 1.2$ the spreading rate of the positive velocity is higher than the spreading rate calculated using both components, and similarly to the centerline velocity, the jet widths (based on the two methods) become identical for $x/D > 1.2$. Compared with other studies (Figure 4.13b) the current data does not show a region where the spreading rate is clearly changing; rather the jet width seems to increase monotonically for $x/D > 1.0$. Di Cicca and Iuso [51] showed that the spreading rate changes around $x/D = 3.0$, which is also seen to occur in the synthetic jet of Müller et al. [6]. Shuster and Smith [5] showed that the spreading rate of the circular synthetic jet will vary based on its slug length, which explains the difference between the current data and the other studies. Gutmark and Ho [15] showed that the spreading rate in a continuous jet can vary based on the initial (upstream) conditions that are facility dependent. The same principle is likely to hold for the synthetic jet.

The spreading rate, $db/dx$ of some axisymmetric jets are compared in Figure 4.14 based on their Re and $St_D$ numbers. The axial distance of the jet in the current data was scaled with the stroke length, $L_o$, and the comparison with the data of Shuster and Smith [5] is shown in Figures 4.14b and 4.14d. The images in Figure 4.14 show

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Figure 4.13: Jet width as a function of axial distance. a) Based on positive, negative and both components of the velocity. B) Comparison with synthetic (Di Cicca and Iuso [51], Müller et al. [6]) and continuous (Quinn [67], Gutmark and Schadow [73], and pulsed (Bremhorst and Hollis [16]) jets.

that the spreading rate of forced, pulsed, and synthetic jets is similar, regardless of the Re or the St$_D$ numbers of the jet. Shuster and Smith [5] showed that the spreading of synthetic jet is scaled with the dimensionless stroke length of the actuator, $L_o/D$. The dimensionless stroke length relates an amount of fluid to the orifice diameter. When the amount of fluid is increased, it will increase the spreading of the jet because the velocity of the jet at the orifice exit is higher. The customary way to calculate the Strouhal number relates the velocity of the jet to its diameter based on some time scale (i.e. $St_D = f \cdot D/U_o$). Although it was shown mathematically that the dimensionless stroke length is the inverse of the Strouhal number [50], physically these quantities are different. Figure 4.14 shows that the spreading rate of axisymmetric jets is independent of the Strouhal and the Reynolds numbers.
Figure 4.14: Comparison of the spreading rate in different axisymmetric jets. Current data is compared with: Shuster and Smith [5], Di Cicca and Iuso [51], Hasan and Hussain [12], Bremhorst and Hollis [16], Bremhorst and Harch [74], Wygnanski and Fiedler [9], Obot et al. [68], Quinn [70], and Mi et al. [75]. SJ- synthetic jet, FJ- forced jet, PJ- pulsed jet, CJ- continuous jet.
4.1.2 The instability process

Power spectra in the shear layer (near $U=0.5U_{cl}$) at two axial locations in the jet ($x/D=1.0$ and $x/D=7.5$) are shown in Figure 4.15. The frequency information was computed from the time resolved PIV random data by using the velocity measurements at each interrogation window. The data was filtered in Matlab® and the frequency information was resolved up to 3125Hz ($\lambda=3.2e^{-4}$) to avoid the affects from the Nyquist frequency. The micro-scales for the jet are estimated to be $\lambda=1.81e^{-4}$ and $\lambda=4.6e^{-4}$ (or 5.6kHz and 5.5kHz) at $x/D=1.0$ and $x/D=7.5$, respectively. The peaks of the forcing frequency and its harmonics are prominent near the orifice, but not downstream. At $x/D=1.0$ the majority of the energy is in the forcing and harmonic frequencies. Further downstream, at $x/D=7.5$, the fundamental and harmonics attenuate and a broadband peak is observed at the second subharmonic frequency. Smith and Glezer [3] noted that they did not observe broadband peaks at the subharmonics, but their data was shown for the jet centerline.

The peak frequencies along the jet’s centerline and the shear layer were identified and are plotted in Figure 4.16. The forcing frequency is present in the shear layer up to $x/D=5.0$ and up to $x/D=8.0$ in the centerline. Peaks of the first subharmonic were observed initially in the shear around $x/D=3.5$ and around $x/D=6.5$ on the centerline. The second subharmonic was observed around $x/D=5.5$ in the shear and around $x/D=9.5$ on the centerline. Figure 4.16 shows that subharmonic frequencies are formed in the shear layer much further upstream than their formation on the jet centerline.

The energy that is associated with the wavelengths in the flow was integrated according to: $E(f) = \int_{-\infty}^{\infty} u'(f)dr$ and the results for the forcing frequency, the first
Figure 4.15: Power spectrum for the axial (green line) and radial (blue dotted line) velocity components near the shear layer (where \( U=0.5U_c \)): a) \( x/D=1.0 \) and b) \( x/D=7.5 \). \( F_o=700\text{Hz} \). Note the break on the ordinate axis for the left image.

Figure 4.16: Peak frequencies along the jet. Peaks are extracted from spectrums similar to those in Figure 4.15.
harmonic, and the subharmonic are shown in Figure 4.17. The frequencies used for the computation of the subharmonic were based on the measurements in the shear. It shows that the initial energy level of the forcing frequency is an order of magnitude higher than the harmonic and five orders higher than the subharmonic. The energy in the subharmonic is shown on the right ordinate due to the sizeable difference in magnitude. There is a noticeable broadband peak in the energy of the subharmonics between 4.5<x/D<6.0. Such a peak in the subharmonic is required in order for vortex merging to occur (Crow and Champagne [11], Hasan and Hussain [12], Wygnanski and Fiedler [9], Ho and Huang [57], and Gutmark and Ho [15]).

The energy distribution of all the wavelengths along the jet is shown by a spectrogram in Figure 4.18. The energy of the subharmonics starts to increase around
Figure 4.18: Spectrogram of the energy distribution along the jet. Energy in the forcing frequency is observed up to $x/D=8.0$. Energy in the subharmonics is observed for $x/D>2.5$.

$x/D=2.5$ concurrent with the decrease in the energy of the harmonics. This corresponds to data shown in Figure 4.12, which showed the random centerline fluctuations start to increase around $x/D>2.5$ while the deterministic centerline fluctuations start to lessen. According to Figure 4.18, by $x/D=8.0$ the jet is completely continuous, and there is no more energy coming from the forcing frequency of the jet.

To further examine the transition from a train of vortices into a continuous jet, the dominant modes in the synthetic jet were extracted from 1,200 random instantaneous velocity fields using POD. The POD analysis was first applied for the entire velocity field and the first 8 modes are shown in Table 4.1 together with their spatial energy level and the power spectrum that is computed from their modal amplitudes. The first two modes are related to the forcing frequency and contain 46% of the total spatial energy (28% and 18%, respectively). The strong excitation (i.e. forcing) of the synthetic jet induced more energy into the largest structures of the jet, and the energy level is much higher than what is observed in forced jets. For comparison,
Kastner et al. [76] observed energy levels of 19% and 17% for the first and second modes in an axisymmetric jet with $St_D=0.36$. The third and fourth POD modes are related to the first harmonic. This is determined from the power spectrum and the observation that there are twice the structures compared with the first modes. The first four axial POD modes come from the periodicity that characterizes the synthetic jet. The concurrent radial modes come from the trajectory of the vortex pair. All these modes are concentrated near the orifice. The sixth, seventh, and eighth POD modes show a change in pattern compared with the first four modes, where the axial modes capture the vortex trajectory and the radial modes capture the periodicity in the flow. These modes are also concentrated further downstream. The power spectrum of these modes suggests that they are related to the subharmonics. The fifth mode seems to be a transitional mode as its structures cover the entire flow field.

The POD analysis on the 1,200 instantaneous velocity fields was repeated while applying a masking window sufficient in size to contain the largest structures in the first 8 modes. This window is illustrated as the dashed line in the first radial mode. The POD analysis was preformed only to the velocity field inside the window. The window was traversed downstream at $x/D=0.5$ steps and the analysis of the velocity field inside it was repeated. This technique enables to tract how the energy associated with each mode changes as a function of axial distance. Determining if the POD modes inside the window were related to the forcing, harmonic, or subharmonics frequencies was done by comparing their pattern visually with the modes obtained from analyzing the entire flow field, and using the power spectrum from the modal amplitudes of each mode. The process shows that the energy of the first subharmonic mode surpasses the energy of the first forcing mode around $x/D=6.0$ (Figure 4.19),
which is close to the axial location ($x/D=5.5$) where the random fluctuations on the jet centerline surpassed the deterministic ones.

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Table 4.1: The first 8 axial and radial POD modes and their corresponding power spectrum and spatial energy for the axisymmetric synthetic jet. The window used for the axial distribution of the POD energy is shown in radial mode 1.

4.1.3 Vortex merging

Smith and Glezer [3] used phase averaged Schlieren images to visualize the synthetic jet in their study. They showed only one vortex pair in the field of view, and concluded that the transition into a continuous turbulent jet begun around x/h=10. Other studies by Smith et al. [4] Amitay and Cannelle [7], and Béra et al. [54] used PIV and showed similar results based on phase averaged data (i.e. only one vortex pair/ring visible in the field of view). Béra et al. [54] showed the location for the center of each vortex pair during one cycle and noted that the vortex pair was still
Figure 4.19: Axial energy distribution of the first forcing and the subharmonic POD modes.

present further downstream (x/h=30), but was no longer in-phase with the forcing frequency of the jet, such that their spatial location varied. Figure 4.20 shows a series of five phase-locked images that illustrate the evolution of the vortex ring during the cycle. The bottom row shows the phase-averaged velocity field and the top two rows show samples of two instantaneous images corresponding to that phase. Near the orifice the vortex ring is still in phase with the forcing frequency of the actuator and its spatial location in the instantaneous images is the same for each realization. Further downstream the pair is no longer in phase with the actuator and appears at random axial locations during the same phase. The instantaneous images show that the vortex ring can stay symmetric (e.g. t/T=0.25 second sequence), lose its symmetry (e.g. t/T=0.05 first sequence or t/T=0.25 first sequence), or that another type of vortex can develop (e.g. t/T=0.45 first sequence). The difference in the spatial location of the second vortex ring creates an ensemble average that shows only one vortex ring in the field of view. The streamlines in the flow get bent around the average axial location that is observed for the second vortex ring in the field of view.
Although Smith and Glezer [3] suggested that the strong coherent structure of the vortex pair inhibits the mechanism for merging of successive pairs, it is shown to occur in the instantaneous velocity fields (Figures 4.1h to 4.1k). The merging process begins around \(x/D=4.5\) and is completed by \(x/D=6.0\). Examination of all the random instantaneous velocity fields showed that symmetric vortex merging (i.e. merging on both sides of the ring) occurred in 2% of the data, and asymmetric merging occurred in 9% of the data (6% on one side). Ho and Huang [57] observed a peak in the energy of the subharmonics, a constant spreading rate of the jet, and an alignment of the vortices when vortex merging occurred. The peak in the subharmonic energy is shown in Figure 4.17 and the constant spreading rate is shown in Figure 4.13. The instantaneous images in Figure 4.1 suggest that at some instances the vortices align with respect to each other and merging of successive vortex rings occurs.
Figure 4.20: Phase average flow fields (bottom row) and samples of two sequences of instantaneous images (top two rows).
Table 4.2: Flow parameters for some of the jets compared with the current axisymmetric jet data. SJ- synthetic jet, FJ- forced jet, CJ- continuous jet, PJ- pulsed jet

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<td>0.44-2.7</td>
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4.2 Non-circular synthetic jets

4.2.1 Slot orifice

The mean velocity fields of the positive, negative, and both components of the axial velocity are shown in Figure 4.21. All the velocity values are normalized with the maximum magnitude of the velocity in the field. The images show that near the orifice the jet is initially contracting along its major plane (Figure 4.21a), while expanding along its minor plane (Figure 4.21b). This trend shifts near \( x/D_e = 4.0 \) and the jet expands on its major axis, while contacts on its minor axis. Further downstream \( (x/D_e > 10.0) \) the jet shows a slow monotonic expand on both planes.

The mean axial positive profiles on both planes shows the same observation as in the case of the axisymmetric jet, where the highest velocity magnitude occurs right at the exit of the orifice (see Figure 4.2b).

The centerline and exit velocity of the jet were computed using Eqn. 2.1 and are shown in Figure 4.22. The data shows good comparison with the slot data (AR=28) that was used in NASA’s workshop on synthetic jets [8]. It shows minimal decay up to \( x/D_e = 5.0 \) and constant decay rate for \( x/D_e > 5.0 \). The decay rate for \( x/D_e > 5.0 \) matches the decay rate of the elliptic jet of Ho and Gutmark [20] and the jet of Quinn [22].

Mean axial velocity profiles along the jet are shown in Figure 4.23. The profiles on the major and minor planes were normalized by the half width of the jet (Figures 4.23a and 4.23c), and by the slot equivalent diameter (Figures 4.23b and 4.23d). The profiles show that near the orifice at \( x/D_e = 1.0 \) the entrainment affects both profiles, but its magnitude on the major axis plane is slightly greater. Figures 4.23a and 4.23c show that further downstream the jet has self-similarity behavior, and like in the case of
Figure 4.21: Mean axial velocity fields of the slot synthetic jet in the a) major and b) minor planes. The mean velocity fields based on positive velocity for c) major and d) minor planes. Mean velocity fields based on negative velocity for the e) major and f) minor planes. All fields are normalized with the maximum velocity magnitude in the field.
Figure 4.22: Centerline velocity in the slot synthetic jet. Comparison is shown with the data from NASAs workshop on synthetic jets [8], and continuous jet: Ho and Gutmark [20] and Quinn [22].

the axisymmetric jet, when negative velocities are neglected, the self-similarity is also observed at $x/D_e=1.0$. The latter is due to the lack of a potential core in the jet.

Figure 4.23b shows that along the major plane the jet initially contracts and then begins to spread out. On the minor plane (Figure 4.23d), the jet initially spreads out and then begins to contract. This behavior of the flow stems from the axis switching that occurs. Similar behavior was observed in the elliptic jet of Gutmark and Schadow [73] (AR=3), who observed one axis switching within their measurement planes.

The development of the jet width along its major and minor planes (Figure 4.24) shows two locations of axis switching in the measurement plane. Figure 4.24a compares the jet width that is obtained when the mean velocity field is calculated with and without the negative velocities. Near the orifice, the affect of the negative velocity is more substantial on the major axis compared with the minor. When only the
Figure 4.23: Mean axial velocity profiles for the slot synthetic jet. a) Major axis normalized by the half width of the jet, b) Major axis normalized by the exit diameter of the jet, c) Minor axis normalized by the half width of the jet axis, and d) Minor axis normalized by the exit diameter of the jet.
positive velocity is being considered, the initial width of the jet is three times greater than the width of the minor axis, which is not shown when both velocity components are considered (the orifice slot has AR=3). The image shows that the excluding the negative velocities from the mean flow field does not change much the location of the axis switching in the jet (x/D_e=1.3 vs. x/D_e=1.4). The growth of the jet on its minor plane is monotonic and is not affected by the negative velocity.

Hussain and Husain [23] noted that increasing the excitation level of the jet shifted the switching location upstream. The current data is compared with their data in Figure 4.24b. Their data shows that when the excitation of the jet (at u'/U_o=0.15 level) shifted the location of the first axis switching about four diameters lengths upstream compared with the location in the unexcited jet. The current data shows that the first switch occurs further upstream, near x/D_e=1.3 (compared with Hussains data, x/D_e=2.3). Hussain and Husain [23] explained that (the first) axis switching in the jet occurs following the formation and subsequent deformation of the vortex. The excitation of the jet induces these processes to occur closer to the orifice. Due to the stronger excitation level of the synthetic jet the switching now occurs even closer to the orifice.

The jet characteristics were also assessed using cross-sectional measurements from PIV (Figure 4.25). The images show phase averaged velocity fields taken two axial stations along the jet. The counter rotating vortices at each corner of the jet that are observed at x/D_e=0.5 (Figure 4.25b) stem from the bending of the rectangular vortex ring. The azimuthal velocity of the flow is oriented in the same direction as the orifice. The second measurement station at x/D_e=3.0 shows that the orientation
Figure 4.24: Jet width in slot synthetic jet. a) Jet widths based on the mean velocity field being calculated with and without negative velocity. b) Comparison with excited and unexcited jets (Hussain and Husain [23], elliptical jet, AR=2). Solid and dash arrows indicate the crossing over location in the excited and unexcited jets, respectively.

of the jet has changes and that the counter rotating vortices are positioned along the major axis.

The velocity fields that were taken on the major, minor and diagonal axes of the jet were used to reconstruct cross-sectional profiles. These profiles are shown for different streamwise stations using constant velocity contours (Figure 4.26). The first station (Figure 4.26a) is shown for $x/D_e=0.5$ and the jet is still oriented at the slot orifice. The next station (Figure 4.26b) shows the cross-section profile at $x/D_e=1.3$, which is the axial location where the first cross-over occurs (See Figure 4.24). The minor axis has increased while the major axis has decreased, and the cross-section resembles a diamond shape. Further downstream at $x/D_e=3.0$ (Figure 4.26c) the jet is now wider on its minor axis. The second cross over of the axis switching occurs at $x/D_e=4.2$ and the jet assumed its diamond shape again (Figure 4.26d). The jet then becomes wider on its major axis again (Figures 4.26e to 4.26g), but the spreading
occurs on both axes. In the last station at $x/D_e=12.0$ the jet is still wider on its major axes, but it seems that the cross-sectional profile is moving towards an axisymmetric shape (Figure 4.26h).

The cross-section profiles of the synthetic jet were used to study the mass flow rate of the synthetic jet. The entrainment of the jet is shown as the difference between the flow rate at the exit of the orifice and the downstream station. The flow rate at the exit, $Q_o$ was calculated based on the area of the orifice and the centerline velocity calculated from the positive velocity of the flow (Eqn. 3.1). The entrainment flow that is calculated for the jet in the current study is comparable to the elliptic jet ($AR=2$) of Ho and Gutmark [20] and the rectangular jet ($AR=3$) of Grinstein [24]. The minimal difference with the flow rate of the forced jets is the same observation made by Cater and Soria [39] for the axisymmetric jet. The current data is also compared with the flow rate of the axisymmetric synthetic jet and show that more
Figure 4.26: Cross-sectional profiles of the synthetic jet at different axial stations. Contours levels show constant velocity and are the same in all images.
Figure 4.27: The mass flow rate for the synthetic jet flow. Data is compared with other slot (elliptic and rectangular) jets: Ho and Gutmark [20], Bridges et al. [77], Quinn [22], and Grinstein [24]. $Q = \bar{U} \cdot A$

Entrainment is induced into the flow, which is one of the prime characteristics of non-circular jets.

The turbulence characteristics were analyzed using triple decomposition of the flow (Eqn. 4.1). The results of the velocity fluctuations along the centerline of the jet (normalized by the exit velocity, $U_o$, calculated from Eqn. 2.1) are shown in Figure 4.28. The results are markedly similar to the fluctuations in the axisymmetric jet (Figure 4.12). The coherent structures dominate the flow near the orifice, which yields the highest level of deterministic fluctuations. The deterministic fluctuations begin to decay immediately downstream of the orifice and the random fluctuations begin to increase. Similar to the axisymmetric synthetic jet, the cross over occurs near $x/D_e=5.5$. At $x/D_e=8.0$ all the fluctuations in the jet are random and converge to a $0.3U_{cl}$ level, which is higher than what was observed in the excited elliptic jet of
Figure 4.28: Centerline axial velocity fluctuations in the slot jet. \( \langle u \rangle \)- total fluctuations, \( \bar{u} \)- deterministic fluctuations, \( u' \)- random fluctuations.

Hussain and Husain [23] (0.1\( U_{cl} \)) but is similar to the level observed in the pulsed jet of Bremhorst and Hollis [16] (0.3\( U_{cl} \)) and the axisymmetric synthetic jet.

The distribution of the streamwise velocity fluctuations at different axial stations in the synthetic jet are shown in Figure 4.29. The profiles on both major and minor axes agree with the characteristics described earlier; At \( x/D_e=1.0 \) (Figures 4.29a and 4.29b) the deterministic fluctuations are dominating the flow. Their large magnitude at the center stems from the pulsatile nature of the flow. The axis switching in the jet explains why the peaks in the random fluctuation at \( x/D_e=3.0 \) are spread out more in the minor axis (\( z/b=1.1 \), Figure 4.29d) compared with the major axis (\( y/b=0.9 \), Figure 4.29c). At \( x/D_e=6.0 \) the random fluctuations are higher than the deterministic ones on both axes. The random peaks in the major axis are more spread out than the minor axis, which correspond to the second axis switching that occurs in the jet.
Figure 4.29: Streamwise velocity fluctuations profiles in the major and minor axes of the jet.
The transverse velocity fluctuations at the same axial locations are shown in Figure 4.30. The transverse fluctuations also exhibit how the coherent structures diminish downstream in the jet. At \( x/D_e = 12.0 \) the streamwise and the transverse fluctuations converge for the same level of axial velocity fluctuation: \( \langle u \rangle / U_{cl} = 0.25 \), which is higher than the level observed in the elliptic jet of Ho and Gutmark [20] (continuous jet) and Hussain and Husain [23] (excited jet), but are similar to the level observed in the pulsed jet [16].

The POD modes of the jet were extracted using 2,000 images, and the first 8 modes, their spatial energy, and their power spectrum (computed from the modal amplitudes) are shown in Table 4.3 for the major plane and Table 4.4 for the minor plane. Just like in the case of the axisymmetric synthetic jet, the first and second modes are associated with the forcing of the jet, and contained nearly half of the total spatial energy in the jet (46.1\% on the major and 47.5\% on the minor). The third and fourth modes are associated with the harmonics and contain 5.7\% and 8.4\% of the total spatial energy in the major and minor planes, respectively. The contraction of the jet in the major plane near the orifice and the corresponding expansion in the minor plane can also be seen in these modes (i.e. see 2\textsuperscript{nd} and 3\textsuperscript{rd} transverse modes). The first four streamwise modes capture the pulsatile characteristics of the jet, while the transverse modes capture the vortex trajectory. A noticeable change occurs in the fifth mode in both planes where larger structures appear further downstream from the orifice. The pattern of the streamwise and transverse modes is also switched. The power spectrum shown for these modes indicates that they are related to the subharmonic structures that occur in the flow. The fifth mode on the minor axis shows that smaller structures exist near the orifice, and its power spectrum suggests
Figure 4.30: Transverse velocity fluctuations profiles in the major and minor axes of the jet. Symbols are the same as in Figure 4.29.
that these are related to the harmonics of the flow. Similar observations are made for modes six through eight where the smaller structures that exist near the orifice are related to the harmonic frequency while the larger structures that exist downstream are related to the subharmonic frequencies of the flow.

The power spectrums from the modal amplitude show a peak in the forcing frequency of the jet in modes 1-4. Modes 5-8 show a broadband peak that covers the forcing frequency and its subharmonics and also show peaks in the harmonic frequencies. These modes probably capture the transition process that occurs in the jet. The lack of structures that are related to the forcing or harmonic frequencies for \( x/D_e > 8.0 \) suggest that the jet is mostly continuous at this axial location.
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Table 4.3: The first 8 axial and radial POD modes and their corresponding power spectrum and energy for the slot synthetic jet along its major plane.
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Table 4.4: The first 8 axial and radial POD modes and their corresponding power spectrum and energy for the slot synthetic jet along its minor plane.

4.2.2 Triangular orifice

The flow characteristics in a synthetic jet that is emanating from an equilateral triangle orifice are governed by the different dynamics that exist on the two sides of the jet. The difference in the formation of the jet on its vertex side compared with the flat side is shown in Figure 4.31. The figure shows a series of phase averaged velocity fields taken during the ejection phase of the cycle. They show that the triangular vortex ring forms faster on its vertex side with slightly higher vorticity magnitude (Figures 4.31a and 4.31b). The faster formation is due to the thicker shear layer that develops in the (sharp) corner of the jet. As the ejection cycle progresses, the vorticity of the triangular vortex ring grows stronger on its flat side (Figures 4.31c and 4.31d). The magnitude of vorticity is proportional to the coherent magnitude of the jet. Schadow et al. [25] showed that coherent structures are dominant on the flat side of the jet, while the vertex is characterized with turbulent flow. The strong forcing of
the synthetic jet significantly reduces the initial turbulent characteristics of the jet and significantly increases its coherent (Amitay and Cannelle [7]). The triangular orifice then produce stronger coherent of the jet on its flat side. The strong forcing suppress the magnitude of the higher modes that gets amplified on the vertex side of the jet. Figures 4.31e to 4.31h show that the vorticity of the vertex side is higher again, which stems from the axis switching that occurs near the orifice.
Figure 4.31: Phase averaged velocity fields for triangular synthetic jet a) $t/T=0.10$, b) $t/T=0.12$, c) $t/T=0.14$, d) $t/T=0.16$, e) $t/T=0.18$, f) $t/T=0.20$, g) $t/T=0.22$, h) $t/T=0.24$. $F_0 = 700$ Hz.
The mean axial velocity field (Figure 4.32) was decomposed into its positive and negative components. The mean flow field shows that the jet spreads out more on its flat side (Figure 4.32a). The mean flow field of the positive velocity shows that the velocity of the jet is constantly decreasing immediately downstream of the orifice (Figure 4.32b), which is akin to the observations in the axisymmetric and the slot jets. The mean flow field of the negative velocity (Figure 4.32c) shows that more entrainment enters the flow in its vertex side. This is complementary to the observation that the jet spreads out more on its flat side. The higher magnitude of the negative velocity that is observed near the orifice comes from the inverse affect that the corner of the orifice has; during suction the thicker shear layer in the corner of the orifice prompts faster (negative) velocity to form.

Figure 4.33 compares the decay of the centerline velocity of all the synthetic jets from the current study. The velocities were computed according to Eqn. 3.1. The figure shows that the same rapid decay of the (positive) velocity occurs near the orifice (x/D_e <1.0) for all the jets. Further downstream, the most rapid decay of the velocity occurs in the axisymmetric jet, while the most measurable decay occurs in the slot. Similar results were shown computationally by Miller et al. [17] and by Hussain and Husain [23] who attribute the differences to the higher entrainment rate in the slot orifice.

Axial velocity profiles of the jet are shown in Figure 4.34. The profile at x/D_e=0.5 shows that near the orifice the negative velocity is nearly three times higher on the side vertex compare with the flat side of the jet (-0.13U_cl vs. -0.05U_cl) and spans about 30% of the width compared with 25% (Figure 4.34a). The profiles at stations x/D_e=0.5, 1.0, and 2.0 show that the jet is spreads out more on its flat side (Figure
Figure 4.32: Mean axial velocity field in the triangular synthetic jet. a) computed by both velocity components. b) computed by positive velocities. c) computed by negative velocities. Velocities are normalized by the maximum velocity magnitude in the flow field.
Figure 4.33: Comparison of the centerline velocity between the different synthetic jets. Velocity were computed according to Eqn. 3.1. Axisymmetric, $St_D = 0.12$, Slot, $St_D = 0.13$, Triangular, $St_D = 0.12$.

4.34b). At $x/D_e=4.0$ the axial velocity profile shows the jet is spreading more on its vertex side. This change is due to the axis switching that occurs. Further downstream at $x/D_e=6.0$ and $8.0$ the jet spreads out uniformly on both its sides.

Axis switching in the current data was observed only near $x/D_e=6.0$ (Figure 4.35). The computational model of Miller et al. [17] showed two locations for axis switching in equilateral triangle jet (near $x/D_e=1.5$ and near $x/D_e=4.6$). Koshigoe et al. [26] showed existence of one axis switching around $x/D_e=0.7$. The data that is shown does not support the existence of additional location of axis switching close to the orifice, but this could stem from the method that the mean velocity field was calculated (which includes the negative velocity). The changes in the maximum vorticity location shown in Figure 4.31 suggest that such switch does exist near the orifice. Further downstream the spreading rate on the flat side of the jet is greater than the vertex...
Figure 4.34: Axial velocity profiles. a) Profiles near the orifice showing more entrainment on the vertex side. b) Profiles further downstream showing axis switching.

side, which can be also observed in Figure 4.32. Higher spreading rate on the vertex side of the jet was also observed by Schadow et al. [25].

The axial velocity fluctuations in the centerline of the jet are shown in Figure 4.36. The fluctuations in the jet are initially dominated by the deterministic fluctuations, which is parallel to the observations in the axisymmetric and the slot jets (see Figure 4.12 and Figure 4.28). The cross over location between the deterministic and the random fluctuations occurs near $x/D_e=6.0$. This location is half a diameter further downstream compare with the axisymmetric and slot jets. The circular, the slot, and the triangular jets have (about) the same $StD$ number (Table 3.1) hence the difference probably stems from the different dynamic of the flows. By $x/D_e=8.0$ all the centerline fluctuations are random and their magnitude, $0.3U_{cl}$, is the same magnitude that was observed in the circular and the slot jets as well as the pulsed jet [16].
Figure 4.35: Variation of the jet width for the flat and vertex sides in the triangular synthetic jet. Comparison data is taken from Miller et al. [17]

Figure 4.36: Axial velocity fluctuations in the centerline of the triangular synthetic jet. Turbulence data was decompose according to Eqn. 4.1.
Spectral analysis of the flow at different axial stations is shown in Figure 4.37. At \( x/D_e = 0.1 \) (Figure 4.37a) the spectrum shows that the forcing frequency is highest at the centerline of the jet, and is about 1dB higher in the flat side compare with the vertex. As seen in Figure 4.31 the strong forcing of the jet increases its coherent in the vertex side, hence the higher magnitude. For comparison, Schadow et al. [25] observed peak magnitude that was 100 dB higher in the flat side compare with the vertex.

Further downstream at \( x/D_e = 1.0, 2.0, \) and \( 4.0 \) the fashion of the energy distribution in the jet is kept (i.e. forcing frequency is highest in the centerline, but its magnitudes lessens). At \( x/D_e = 6.0 \) (Figure 4.37e) the forcing frequency of the jet is observed only at its centerline. At \( x/D_e = 8.0 \) (Figure 4.37f) there is no clear frequency peak in the, rather a broadband peak around the subharmonics of the jet. This is complement to Figure 4.36, which showed that at this axial location all the fluctuations in the flow are random. The lack of forcing frequency in the jet suggests that the transition process of the synthetic jet into continuous turbulent jet has completed.

POD analysis of the triangular jet showed similar characteristics of the modes and the spatial energy to the ones observed in circular and the slot jets. The first 8 axial and transverse POD modes, their spatial energy, and the power spectrum computed form the modal amplitudes are shown in Table 4.5. The first two modes are associated with the forcing frequency, contain about 48% of the total spatial energy, and show that the biggest structures in the flow exist near the orifice. The third and fourth modes are associated with the harmonics in the flow and contain about 8% of the total spatial energy. The fifth and sixth modes come from the subharmonics and contain about 3% of the total spatial energy. The structures in the fifth and sixth
Figure 4.37: Spectral distributions at the centerline, flat, and vertex sides in the triangular synthetic jet.
modes appear further downstream, which signifies that the subharmonics appear in the flow further downstream. Modes seven and eight contain about 2% of the total spatial energy, and appear to capture the transition between the forcing, harmonics, and subharmonics modes, which is similar to the slot jet. In these modes the coherent structures appear near the orifice while the structures further downstream are more indistinct.

<table>
<thead>
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<th>Axial Mode</th>
<th>Transverse Mode</th>
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Table 4.5: The first 8 axial and transverse POD modes in the triangular synthetic jet.

### 4.3 Variation of the jet forcing frequency

Gallas et al. [43] showed that the optimal performance of synthetic actuator (i.e. highest velocity of the jet) occurs when the mechanical resonance of the vibrating element is close to the acoustic resonance of the actuator such that coupling occurs. The mechanical resonance of the vibrating element in the actuator depends on its
material properties, hence customizing this frequency for a given element can be very costly. On the other hand, the geometry of the actuator is more easy to change in order to achieve a desired frequency for the acoustic resonance of the actuator (Gallas et al. [43] and Gomes et al. [46]). Figure 4.38a shows hot-wire measurements of peak velocities at different frequencies one diameter above the circular orifice. Each case represents measurements taken with different clamping force, which was changed by tightening (or loosening) the screws that are used to attach the back plate with the orifice plate of the actuator. The actual force was not quantified, but it was noted that tightening of the screws increased in the forcing frequency of the synthetic jet. The forcing frequencies (i.e. The frequency where \( U_{\text{peak}} \) is at max) for the jets in cases I-IV that are shown are 640Hz, 660Hz, 560Hz, and 740Hz, respectively. The peak velocity for each case was calculated by averaging the maximum velocity in each cycle. These four cases in Figure 4.38a span about 200Hz and the average peak velocity that is measured from all these cases is 33.9m/s with SD= ±0.8m/s (about 2.3% difference).

The secondary peaks around 300Hz in Figure 4.38a corresponds to the mechanical resonance of the piezoelectric diaphragm. The lowest clamping force (Case I) yields the highest peak velocity at the mechanical resonance. Complement to that, the highest clamping force (Case IV) yields the lowest peak velocity that is measured around 300Hz. The proportionality of the peak velocity to the clamping force at the mechanical resonance is expected, but it is unclear why the small shifts in the resonance frequency are also observed.

A final observation about varying the clamping force, is that too much tightening or too much loosening of the screws that connect the actuator plates greatly affected
the performance (i.e. magnitude of the peak velocity) of the jet. The clamping force needed to be within a certain range, because too much or too little force did not produce any jet. This probably occurs because the clamping force affects the performance (i.e. vibration characteristics) of the vibrating element.

Figure 4.38b shows peak velocities measurements at different frequencies one diameter above the circular orifice when the clamping method of the actuator is varied. The first clamping method (shown by Case II) the piezoelectric diaphragm was clamped between the orifice and the back plates directly (i.e. metal to metal contact on both sides of the diaphragm). In the second clamping method, the piezoelectric diaphragm was attached to the orifice plate on one side (i.e. metal on metal contact), but was held by a rigid O-ring (50mm OD, 48mm ID, and 80 shore durameter) on its backside. The O-ring served as a buffer between the piezoelectric diaphragm and the back plate and placing it solely on the backside of the diaphragm was intended to keep the same the acoustic resonance properties of the actuator. This clamping method follows the guidelines for the actuator that was build for NASA (Chen et al. [45]) and was used to generate the experimental data for the CFD Validation of Synthetic Jets and Turbulent Separation Control workshop at NASA Langley Research Center in 2004 (Rumsey et al. [8]).

The clamping force on the piezoelectric diaphragm in the second method was adjusted to so that the forcing frequency of the jet will occur at the same resonance frequency as in Case II (660Hz). The figure shows that when an O-ring is used for clamping of the diaphragm, with all other driving conditions of the actuator being equal, it reduces the peak velocity of the synthetic jet. The peak velocity in the two cases that are compared in Figure 4.38b is reduced from 35m/s to 26m/s (about
26% difference). The reduction in the performance of the actuator when using an O-ring for clamping probably stems from the dampening that occurs in the vibrations magnitude of the diaphragm. Less magnitude of the vibrations means that less fluid volume is displaced in and out of the actuators cavity. The magnitude of the latter directly affects the velocity of the jet (Gomes et al. [46], Smith et al. [4], and Shuster and Smith [5]).

These results show that changing the clamping force or that changing the clamping method on the vibrating element can affect the performance of the synthetic jet actuator and allow it to operate at a wider frequency range. The latter is important for flow control applications that might require operating in a range of Strouhal numbers (rather than a specific one).
Chapter 5: Summary - synthetic jets

The aforementioned work details the flow characteristics of axisymmetric and non-circular synthetic jets. The marked finding from this work is that the transition mechanism of a synthetic jet into a continuous turbulent jet can include the merging of successive vortex pairs. It is well established that this merging process increases the mixing properties in the flow and observing it in synthetic jets further substantiates their potential in active flow control.

The characteristics of synthetic jets were investigated using different analysis techniques. A new method that computes the mean velocity based on the forward momentum (i.e. positive velocity) in the jet was suggested. The flow was also analyzed using the triple decomposition and the POD techniques. The analyses suggested the existence of four regions of interest:

The first region occurs for \( x/D < 1.0 \), where the entrainment that flows into the orifice affects the time-averaged characteristics of the flow. The main effect is observed on the centerline velocity where it was shown that the magnitude starts to decay immediately downstream of the orifice when only the positive velocity is considered. This is different than the centerline velocity characteristic that is observed when the negative velocities are included, which shows that the magnitude is increasing in this region.
In the non-circular cases, the higher forcing level of the synthetic jet shifted the location of the axis switching further upstream in the case of the slot jet and contributed to the formation of a vortex in the vertex of the triangular jet orifice.

The second region occurs at \( x/D > 2.5 \) where the decay of the vortex ring is at its beginning stage. This axial location is marked by the beginning of an increase in the random fluctuations in the flow and also corresponds to a decrease in the centerline velocity and the convective velocity of the vortex. The third region occurs between \( 5.0 < x/D < 6.0 \) where the random fluctuating component in the synthetic jet surpasses the deterministic one. The last region occurs at \( x/D > 8.0 \) where the transition process is complete. The deterministic component in the flow is minimal and the random fluctuating levels converge to the levels observed in continuous turbulent jets. The forcing frequency is no longer present and all the energy in the jet is associated with sub-forcing frequencies.

Other studies have shown that the dimensionless actuator stroke length, which is mathematically the inverse of the Strouhal number, can scale the jet width characteristics of synthetic jets. Comparison of the current data with others showed that the spreading rate is actually independent of the \( \text{St}_D \) when the latter is calculated in the normal way.

The current work also showed that in the axisymmetric case, the method of computing the \( \text{St}_D \) number lacks some certainty because of the asymmetry in the cycle of the positive and negative velocities that occur on the centerline of the jet. This can lead to a \( \text{St}_D \) number that misrepresents the synthetic jet.
Comparison of the flow characteristics of synthetic jets with continuous jets showed that the main differences near the orifice occur due to the dominance of the pulsatile nature of the jet, the lack of potential core, and the reversal of the flow.
Chapter 6: Introduction - vortical structures during phonation

The pulsatile nature of synthetic jets can be related to the pulsatile nature of the airflow that passes through the vibrating vocal folds. The flow in a synthetic jet is characterized by the dominance of vortical structures that are formed by acoustical means. The vibrations of the vocal folds modulate the airflow that passes between them and create the human voice. The airflow that passes between the vibrating folds is also characterized by vortical structures that are formed by aeroelastic means. Hence the previous work on the vortex dynamics in synthetic jets gives deeper understanding to the fluid dynamics that occur in the voice.

According to the myoelastic-aerodynamic theory of phonation, the vibrations of the vocal folds result from the airflow between the folds and the elastic properties of the vocal folds tissue [78]. The myoelastic-aerodynamic theory states that the pressure of the airflow abducts the folds laterally until the strain in the tissue prevails and adducts the folds together again. The opening and closing process repeats itself and produces self-sustained oscillations. The opening and closing velocity of the folds is not symmetric, and it known that the closing velocity is more clinically significant because it is correlated with the intensity of the voice [79].
The underlying mechanism of the vocal folds vibration process is not completely understood and new hypotheses regarding the underlying mechanisms are constantly being suggested and challenged. One reason for the discrepancies of the theories is the manner in which the folds close together during the vibration cycle. According to the myoelastic-aerodynamic theory, this occurs due to the recoil forces in the tissue, which implies that highest closing speed of the folds will occur during the beginning of the closing phase. This presumption negates evidence that shows that the maximum closing speed actually occurs towards the latter part of closing phase [80, 81, 82].

Another theory for the mechanism of vocal fold vibration suggests that the vortical structures that are formed during the cycle have a significant contribution to the acoustic characteristics of the human voice. The actual role of these vortical structures in the process is yet to be determined.

The majority of previous studies that were aimed to better understand the vibration mechanism of the vocal folds were done in mechanical or animal models. Studies based on the former typically lack the dynamic conditions of the vibrations, or they do not mimic the complexion of the flow or the manner in which the fold vibrate. Flow measurements in animal models were taken above or below the vibrating folds, while flow measurements along the fold were taken in a hemilarynx model. In the latter, half of the larynx is removed (along its sagittal plane) and is replaced by a wall, hence assuming symmetry of the flow that passes between the vibrating folds. This assumption is yet to be proven experimentally.

The work in this part of the dissertation is intended to measure the velocity field between the folds in a full vibrating larynx. These velocity measurements are then used to compute the pressure distribution between the folds that occur during the
closing phase. The pressure from the flow that is acting on the walls of the folds can produce an additional force that contributes to the closing mechanism of the folds.

This work lays the foundation for determining how vortices affect the vibration mechanism of the vocal folds. Better understanding of the mechanism that produces the human voice is crucial for the further refinement of treatments and improving the outcomes for patients afflicted with voice disorders.
Chapter 7: Background - vortical structures during phonation

The cardinal point of this work is that flow measurements are taken between the folds in a full vibrating larynx. There are no preceding studies that interpolate such measurements. The literature being reviewed in this chapter targets studies that rest on measurements taken above or below the vibrating folds, and studies that were based on models intended to mimic or emulate the vibrations of the folds.

A brief review of the relevant anatomy and the process of phonation are given. They are follow by summarization of the most relevant findings with regards to the current work from analytical, computational, and mechanical models. The flow characteristics above and below the folds are then reviewed. This chapter concludes with a review of some of the elasticity measurements in the vocal folds.

7.1 Review of relevant anatomy and the process of phonation

The vocal folds (or vocal cords) are located in the larynx, which is positioned in the area often called as Adam’s apple (Figure 7.1a). Inferiorly, the larynx is connected with the trachea that connects to the lungs. Superiorly, the larynx is connected with the pharynx, which is considered to be the beginning of the vocal tract (i.e. nasal and oral cavities, cheeks, tongue, etc.). The vocal folds average 16mm in length in males
and 10mm in females (Titze [83]). The dimensions for the average glottal width and height in humans are not currently available because there are no clear definitions for what are the boundaries that constitute them (Titze [78]). The space between the folds is called the glottis, and subsequently the airflow that passes through the vocal folds is referred to as the glottal flow or intraglottal flow. The flow above/below the vocal folds is referred to as the supraglottal/subglottal flow.

The vocal folds are normally open to allow free motion of the airflow in and out of the lungs. The phonation process, which is a term used to describe the process in which sound is produced by the vibration of the vocal folds, begins by stimulating the laryngeal muscles to adduct the folds together (Figure 7.1b). The pressure caused by the airflow from the lungs causes the folds to abduct. According to the myoelastic-aerodynamic theory (Titze [78]), at certain point the strain is the tissue is high enough to cause the folds to adduct again (i.e. recoil due to the elastic forces in the tissue). The process then repeats itself and produces self-sustained oscillations.

The glottis changes its shape during opening and closing due to a mucosal wave that travels along the surface of the vocal folds. During the opening phase, when the folds are abducted from each other, the glottis takes on the shape of a converging nozzle and the airflow coming from the lung is attached to the surface of the vocal folds. During closing, the glottis takes on the shape of a diverging nozzle. When the diverging angle of the duct exceeds a certain value, the flow cannot follow the glottal walls and separates. The result of this intraglottal flow separation can produce a rotational motion that develops into vortices. These vortices are termed flow separation vortices (FSV). Several studies has shown or predicted intraglottal flow separation from analytical, mechanical or computational models of vocal fold vibration (Pelorson
Figure 7.1: Anatomy related to the vocal folds. a) The folds are located in the larynx, just below the protrusion of the thyroid cartilage (also known as Adam’s apple). Diagram is adopted from nlm.nih.gov. b) The vocal folds are normally abducted to allow clear passage for the airflow during breathing. During phonation the folds are adducted by the laryngeal muscles and vibrations ensue. Diagram is adopted from the Mayo Foundation.

et al. [84], Zhao et al. [85], Alipour and Titze [86], Shinwari et al. [87], Liljencrants [88], Shadle et al. [89], Kucinschi et al. [90], Erath and Plesniak [91], Krane and Wei [92], Krane et al. [93], and Howe and McGowan [94]).

The vibrations of the vocal folds modulate the airflow that passes through it. The change in the flow rate that ensues, $\partial Q/dt$, is the source of sound in the phonation process. The intensity of the sound produced by the vocal folds is highly correlated with the (rapid) closing of the folds during the vibration cycle (Sundberg and Gauffin [95], Holmberg et al. [96], Granqvist et al. [97], and Scherer et al [98]).

One of the fundamental assumptions in the myoelastic theory is that increasing the maximum lateral displacement of the folds increases the rapid closing of the folds due to the higher strain in the tissue (Titze [78]). The higher strain increases the
elastic recoil forces in the tissue. It is therefore expected that the intensity of the voice will increase with the lateral displacement of the folds. However, Woo [79] analyzed stroboscopic images from patients under different phonatory conditions and showed that the vocal intensity was highly correlated with maximum vocal fold closing speed but not with the maximum lateral displacement. Woo’s list of possible reasons for the latter finding include limitations of videostroboscopy and increased muscular tension limiting lateral excursion during loud conditions.

7.2 Analytical and computational models

The analytical and computational models vary in their assumptions about the mechanism for and the location where the flow separates in the glottis during closing. Based on the assumptions being made, the values of the intraglottal pressures changes dramatically. These models can be broadly classified into three types: The first assumes that the glottal flow does not separate from the glottal wall and thus flow separation occurs at the glottal exit (Ishizaka and Matsudaira [99]). This assumption implies that Bernoulli’s law is valid in the entire glottis and that intraglottal pressures are more negative in the inferior glottis than in the superior glottis during closing. Negative pressure refers to the gauge pressure, or the pressure relative to the ambient pressure. The second type of model assumes that during closing, flow can separate from the divergent vocal folds well upstream of the glottal exit, and that the separation point can move. In order to limit the complexity of this model, approximation is made that pressures within and above the glottis are uniform and equal to the atmospheric pressure downstream of the point of flow separation (Pelorson et al. [84]). This model predicts that intraglottal vortices will occur but that they do not
produce significant negative pressure. As with the first model, this model predicts that intraglottal pressure are most negative in the inferior aspect of the glottis (or glottal entrance). The third type assumes that intraglottal vortices occur and are associated with negative pressures (Khosla et al. [80]). This model assumes that flow separation vortices represent areas of low pressure relative to the essentially uniform ambient pressure downstream of the separation point.

The effect of negative pressures produced by vortices has been extensively studied in many engineering applications. Vortices generate negative pressures, and the magnitude of these pressures depends on the strength of the rotational motion, which is dependent upon the magnitudes and directions of the velocity field. One such biological example is a study of the mechanism that accounts for lift experienced by slow-flying bats. Calculations from experimentally measured velocity fields show that the flow separation vortices occurred directly above bat wings and calculations found that the vortices produced 40% of the lift force that is required for the bats to fly (Muijres et al. [100]). The FSV produce negative pressures on the upper surface of the bat’s wing, which generate a lift force by sucking the wing upwards.

Zhao et al. [85] (using DNS) and Suh and Frankel [101] (using LES) predicted computationally that lower pressure will occur at the inferior edge of the folds. Both studies were done on static model (i.e. not vibrating) of the larynx and showed time-averaged results, not instantaneous results. The time-averaged results may not accurately reflect the dynamics of the vortices as they form and travel downstream in a pulsatile flow, even if the input flow is steady. Mihaescu et al. [102] used LES in a static model of the larynx and predicted based on the instantaneous data that more negative pressure will occur in the superior aspect of the divergent glottis.
7.3 Mechanical models

To study the vibration mechanism of the vocal folds, several mechanical models were developed. Scherer et al. [103], Scherer et al. [104], and Shinwari et al. [87] used a 7.5 scaled model of a normal male larynx. The static model intended to investigate the pressure distribution along the glottal wall during closing (using a divergent angle of $10^\circ$). Pressure measurements were made using an array of pressure ports along the wall of the model, and the flow was visualized for qualitative analysis. These studies observed that the flow separated from the glottal wall, but lower pressure was measured in the inferior aspect of the model. Similar results for lower pressure towards the inferior aspect were shown by Li et al. [105] who used a 1.732 scaled model, and Fulcher et al. [106] who used a 7.5 scaled hemilarynx model. These studies also showed that the magnitude of the pressure changes as the divergence angle of the fold in the model is changed.

The hemilarynx mechanical model of Alipour and Scherer [107] looked at the effect of the glottal gap on the intraglottal pressure distribution. Their model had about a 2:1 scale and their measurements showed that lower negative pressure occurred toward the superior aspect of the fold. Unlike the pressure measurements taken in the full larynx model (which were taken by connecting a silicon tube from the pressure port to the pressure transducer), these pressure measurements were taken by placing the pressure transducers flush against the model wall. Such a configuration has optimized frequency response for the pressure measurement (Tavoularis [108] and Shaw [109]).

Several dynamic models were developed to mimic the vibrations of the vocal folds (Triep and Brücker [110], Drechsel and Thomson [111], and Neubauer et al. [112]). The mechanisms for the self-sustained oscillations varies in these models, but flow

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measurements show characteristics such as formation of vortices, axis switching, and jet skewing (but not when a secondary constriction such as false folds was introduced).

7.4 Subglottal flow characteristics

Glottal airflow produced during phonation is unsteady and can be separated into mean, coherent and random components. The mean component represents the non-time varying (steady) flow, and may be seen in conditions such as a persistent posterior gap. The coherent component usually refers to organized flow structures (vortices) that are well defined, both in time and in space. The random component refers to disorganized, irregular patterns of airflow, or turbulence. The amount of random (or turbulent) airflow generated in the glottis is not yet clear, even when tracheal airflow is laminar. The coherent component can produce acoustic energy in narrow frequency bands such as the harmonics and formants. On the other hand, random flow produces sound over a broad range of frequencies; in acoustics and other engineering fields, this broadband sound is often referred to as noise.

This broadband noise, for example, is responsible for the static heard on a radio; although usually undesirable in a radio, this noise can be desirable in speech. For example, broadband sound produced by turbulence is the predominant source of sound produced in fricatives and many unvoiced consonants (Krane et al [113]). Broadband noise is probably much less important in vowels and other voiced sounds that have a relatively wide open vocal tract (Stevens [114]). While a certain amount of broadband noise may be important for normal phonation, a high degree of random airflow is associated with reduced voice quality. Increasing the random component increases the noise, and thus reduces the harmonics-to-noise ratio (HNR); such reduction is
strongly correlated with an abnormal voice (de Krom [115]). The random component has been also correlated with breathiness (Hanson [116]). Irregular glottal airflow may also influence glottal vibrations; using a two mass model, Jiang et al. [117] showed that as turbulence in the glottis increases, airflow can produce irregular or chaotic vocal fold vibrations.

Random flow is characterized by a parameter known as turbulence intensity (TI) (Hinze [118]). The TI is not affected by the coherent component, but increases with the random component. Turbulent airflow may be generated in the glottis, but it may also be introduced in the lungs or trachea. As mentioned above, during soft and moderate phonation, turbulence in the trachea can be low, but can become predominant in louder speech and in patients with lung or tracheal disease (Ultman [119]). Khosla et al. [80, 120] have found that airflow directly above the glottis has a low random component even when airflow in the trachea in the excised canine larynx model has a high TI. The mechanism of this turbulence reduction is not known.

7.5 Flow characteristics above the folds

Velocity measurements of the flow that passes between the vibrating folds are difficult to perform due to the dimensions and dynamics of the measurement plane. While there have been no published reports of intraglottal velocities in an excised larynx, velocity measurements have been made above the vocal folds.

7.5.1 Hot-wire measurements

Previous studies that measured the airflow above the glottis suggested that the flow is highly random with minimal coherent flow structures. Alipour and Scherer [121] measured the supra and infra glottal flow distribution 10mm above/below the
glottis (to avoid damaging the hot-wire probe). They observed that the flow above the glottis was highly turbulent during the vibratory cycle, while the subglottal flow did not show any turbulence. They also observed that the highest velocity occurred toward the anterior section of the folds. Similar results were observed by Berke et al. [122] and Verneuil et al. [123]. Verneuil et al. [123] also measured the change in glottal area using videostroboscopy and found poor correlation of the glottal area with the glottal flow.

The results about the anterior-posterior velocity gradient varied between these studies, with no clear conclusion about the gradient of the flow in this measurement plane. One possible reason for this is that these velocity measurements were extracted using a single component hot-wire probe, which is incapable of measuring multidirectional flow. Single component hot-wire assumes that the flow is unidirectional and it cannot measure rotational motion or vortical structure.

7.5.2 PIV measurements

Using a two-dimensional particle imaging velocimetry (PIV) technique, Khosla et al. [80] showed a variety of coherent vortices within the first 10mm above the glottal exit. Khosla et al. [120] also identified three dimensional vortices that were much more repeatable, complex, and coherent than has been previously shown in mechanical or animal models. During opening they observed formation of starting vortices, which known to occur in pulsed jets. They also observed formation of Kelvin-Helmholtz vortices in the mid-cycle, and vortices that form during closing. They suggested that the latter are created inside the glottis due to the flow being separated from the glottal
wall. Khosla et al. [80] also calculated the pressure associated with the vortices they observed and showed that they produce negative pressure above the vibrating folds.

Khosla et al. [120] measured the supraglottal flow along its anterior-posterior plane and shows that the highest velocity gradient occurs towards the anterior and posterior aspects of the folds, but no gradient was observed on the mid-membranous plane. The last finding was important since it shows that for the 2-D PIV measurements that are taken along the mid-membranous plane of the fold there is no out-of-plane component of the flow.

7.6 Intraglottal pressure measurements

Intraglottal pressure measurements were done in a vibrating excised hemilarynx model (Alipour and Scherer [124]). Their measurements showed significant negative pressures, during closing, that were greater in the superior aspect of the glottis than in the inferior aspect. A vocal tract was not used in their experiment, ruling out inertia forces of a vocal tract being responsible for generating the measured negative pressures. The spatial resolution of their pressure data was limited due to of the size of the pressure transducers and the fact that the transducers were only placed in the plexiglass wall. Velocity measurements were taken 10mm above the vibration fold (using hot-wire).

Khosla et al. [80] and Murugappan et al. [81] published estimates of the (negative) pressures associated with vortices they observed. They computed the pressure associated with the measured velocity fields above the vibrating folds using Bernoulli’s equation and extrapolated their results into the flow field inside the glottis. The
magnitude of their values were comparable to those found by Alipour and Scherer [124] in the hemilarynx model and Mihaescu et al. [102] in the LES model.

7.7 Elasticity measurements of the vocal folds

Elastic measurements of the vocal fold are challenging because of the geometry, size, and complex structure of the tissue. The composition of the vocal fold tissue is beyond the scope of this thesis. To transcend this difficulty, studies have subdivided the folds into different regions and ascribe different elasticity values for each region. The results in the literature vary greatly in the data being reported (Table 7.1).

Perlman et al. [125] and Alipour and Titze [126] excised the folds from a canine larynx and used force-elongation test to evaluated the elastic properties of the tissue. Perlman et al. [125] evaluated the properties for the gross fold, while Alipour and Titze [126] separated the elasticity of the body and the cover of the fold. Both studies showed that the stress-strain curve/s of the folds is/are non-linear. They used curve-fitting functions in order to evaluate the Young’s modulus, which varied as a function of tissue strain. For low strain (10%) Perlman et al. [125] calculated mean Young’s modulus of 226kPa with $C_v=0.18$. For the same low strain, Alipour and Titze [126] calculated Young’s moduli of $\sim21$kPa ($C_v=0.18$) and $\sim42$kPa ($C_v=0.17$) for the body and cover parts, respectively.

In a more recent study Chhetri et al. [127] used cadaveric human folds to measure its Young’s modulus at the superior, medial, and inferior parts of the fold cover together with the body. Following the body (2.0kPa), they observed that the superior part of the cover was the softest (2.9kPa) and the inferior cover was the stiffest (7.5kPa). Their measurements were taken from 1mm indentation of the tissue.
The major complication of the tissue elasticity data available to-date is that it was taken \textit{in-vitro} from a non-vibrating folds. There is no indication how such measurements would be translated in an \textit{in-situ} and \textit{in-vivo} vibrating model of the vocal folds.
Table 7.1: Summary of studies measuring vocal fold tissue elasticity

<table>
<thead>
<tr>
<th>Study</th>
<th>Testing subject, quantity</th>
<th>Method and stress direction</th>
<th>Young’s Modulus</th>
</tr>
</thead>
</table>
| Alipour and Titze [126]       | Canine, 10                | Elongation along the fold’s length | 0%-15% strain:  
  - body: 20.7 kPa ± 2.4 kPa  
  - cover: 41.9 kPa ± 7.1 kPa |
| Chan et al. [128]             | Human, 20 (12 male, 8 female) | Elongation along the fold’s length | 10% strain:  
  - 40 kPa  
  30% strain:  
  - 420 kPa (male)  
  - 185 kPa (female)  
  40% strain:  
  - 1750 kPa ligament (male)  
  - 1000 kPa cover (male)  
  - 480 kPa cover (female)  
  - 350 kPa (female) ligament |
| Goodyer et al. [129]          | Human, 20                 | Linear Skin Rheometer       | Shear modulus:  
  - 1,008 Pa ± 380 Pa (male)  
  - 1,237 Pa ± 768 Pa (female) |
| Perlman et al. [125]          | Canine, 7                 | Elongation along the fold’s length | 10% strain:  
  - 3.47e5 kPa ± 2.45e5 kPa  
  30% strain:  
  - 2.8e5 kPa ± 9.27e4 kPa  
  50% strain:  
  - 4.12e5 kPa ± 1.51e5 kPa |
| Chhetri et al. [127]          | Human, 3                  | Indentation in hemilarynx    | -superior: 2.9 kPa  
  - medial cover: 4.8 kPa  
  - inferior: 7.5 kPa  
  - body: 2.0 kPa |
<table>
<thead>
<tr>
<th>Study</th>
<th>Testing subject, quantity</th>
<th>Method and stress direction</th>
<th>Young's Modulus</th>
</tr>
</thead>
<tbody>
<tr>
<td>Smith and Thomson, [130]</td>
<td>NA</td>
<td>Computation</td>
<td>5% strain:</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>· cover: 0.4 kPa</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>· ligament: 2 kPa</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>· body: 14.9 kPa</td>
</tr>
<tr>
<td>Berke and Smith [131]</td>
<td>Human, 3</td>
<td>Intraoperative, indentation on adduct folds</td>
<td>Patient 1, 75% strain:</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>· 10 kPa</td>
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<td></td>
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<td></td>
<td>Patient 2, 50% strain:</td>
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<td></td>
<td></td>
<td></td>
<td>· 10 kPa</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>Patient 3, 75% strain:</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>· 14 kPa</td>
</tr>
<tr>
<td>Min et al. [132]</td>
<td>Human, 3</td>
<td>Elongation along the fold’s length</td>
<td>Human, low strain:</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>· 33.1 kPa ±10.4 kPa</td>
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<td></td>
<td></td>
<td></td>
<td>Human, high strain:</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>· 600 kPa</td>
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<tr>
<td></td>
<td>Canines, (not specified)</td>
<td></td>
<td>Canine, 25% strain:</td>
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<td></td>
<td></td>
<td></td>
<td>· 100 kPa</td>
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<td></td>
<td></td>
<td></td>
<td>Canine, 40% strain:</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>· 300 kPa</td>
</tr>
<tr>
<td>Tran et al. [133]</td>
<td>Human, 5</td>
<td>Intraoperative, indentation on adduct and at rest fold</td>
<td>Rest:</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>· 12.6 kPa ±7.6 kPa</td>
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<td></td>
<td></td>
<td></td>
<td>Low stimulation:</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>· 19.1 kPa ±11.1 kPa</td>
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<td></td>
<td></td>
<td>High stimulation:</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>· 21.5 kPa ±1.1 kPa</td>
</tr>
<tr>
<td>Ishizaka and Kaneko</td>
<td>Human, 5</td>
<td>Lateral elongation</td>
<td>Stiffness constant:</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>· 3.7 kPa</td>
</tr>
<tr>
<td>Perlman and Durham [135]</td>
<td>Human, 5</td>
<td>Lateral elongation</td>
<td>10% Strain:</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>· 100 kPa</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>50% Strain:</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>· 400 kPa</td>
</tr>
<tr>
<td>Stevens [114]</td>
<td>NA</td>
<td>Computation</td>
<td>50% Strain:</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>· 3.3 kPa</td>
</tr>
<tr>
<td>Berke [136]</td>
<td>Canine, 5</td>
<td>Indentation on adduct folds</td>
<td>50% Strain:</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>· 12.3 kPa</td>
</tr>
</tbody>
</table>
Chapter 8: Methodology - vortical structures during phonation

8.1 Experimental facility

8.1.1 Airflow control in laryngeal experiments

The conditioning of the airflow that entered the glottis was done using an aerodynamic nozzle that was connected to a cylindrical settling chamber (101mm ID, 250mm long). The settling chamber and the nozzle were designed according to guidelines given by Morel [137] and Mehta [138]. The chamber included a perforated wedge, honeycomb, and screens (Figure 8.1a). The main airflow and the seeded airflow were injected at the bottom of the plenum, upstream of the flow conditioners. The (static) pressure inside the chamber was measured using a pressure transducer (Honeywell, FPG) via pressure ports located downstream of the conditioning elements. The airflow transitioned from the chamber into the trachea via a nozzle having a contraction ratio of 1:35 with a fifth order polynomial profile. The exit section of the nozzle that was connected to the trachea was 25.4mm long, with an ID of 12.7mm at its inlet and 17.0mm at the exit. Before entering the settling chamber, the airflow was heated (37°C) and humidified (Hudson RCI, ConchaTherm III®).
The flow rate upstream was measured and controlled using a coriolis flow meter (Micro Motion, CMF025), a pressure regulator (ControlAir Inc., Model 700), and a mass flow controller (Parker, MPC 251). The control of the flow rate and the data acquisition for the pressure measurements were done in Labview®. The schematics for the overall setup in the laryngeal experiments is shown in Figure 8.1b.

8.1.2 Apparatus for producing high-intensity turbulent flow

To enhance the turbulence in the flow that entered the subglottis, a special apparatus was made where the source air (917 cm³/sec) was injected into a sealed cylindrical chamber via four ports symmetrically placed around its curved surface. The chamber was made of a PVC threaded nipple (5.7 cm ID) enclosed by two cups. An aluminum pipe was then axially inserted into the chamber via openings drilled into the cups, perpendicular to the ports and ensuring proper sealing. At approximately 6 cm below the pipe’s exit, four holes (2 mm diameter) were drilled such that the air entering the pipe from the chamber would create co- and counter-swirls. A swirl in the flow can be described as steady rotational flow around an axis where its level and direction has a direct impact on the TI in the jet (Gutmark et al. [139]). Injecting co- and counter-swirls can consistently generate high TI within the pipe without generating mean swirl motion. Since significant instability can be produced when the co- and counter-swirls are directly impinging on each other, the co-swirling holes were shifted axially by 2 mm relative to the counter-swirling holes. Additionally, steady low flow rate (167 cm³/sec) was introduced into the pipe, upstream of the chamber to improve the symmetry of the mean velocity and TI profiles; without this additional steady flow, profiles for both TI and mean velocity were significantly asymmetric.
(a) Schematics of the nozzle and settling chamber used to condition the airflow in the laryngeal experiment. Engineering drawings of the different components are shown in Appendix A.

(b) Schematics of the air flow control and the setup for the laryngeal experiments.

Figure 8.1: Airflow control in laryngeal experiments

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This design also produced unidirectional flow. The experimental apparatus is shown in Figure 8.2 including schematic drawings for the pipe and the chamber.

8.2 Instrumentation

8.2.1 Flow measurements in the larynx

Flow measurements in the larynx were taken using hot-wire and PIV. The details of these techniques were reviewed in Methodology section of the synthetic jets
experiments (sections 3.2.1 and 3.2.2). The following sections review how the flow measurements were taken.

8.2.1.1 Flow measurements above the vocal folds using Hot-wire anemometry

The supraglottal flow was measured using a single component hot-wire connected to an anemometer to evaluate the turbulence intensity (TI) in the flow above the glottis. The calibration of the hot-wire probe was done for 0-60m/s and was performed by correlating the hot-wire voltage output with pressure measurements in a controlled, very low turbulence calibration jet. This range was sufficient to cover all expected velocities in the tests. A fifth order polynomial was fitted to the calibration curve and was used to convert the hot-wire voltage output into velocities. The signal from the hot-wire was digitized using LabVIEW®. During the supraglottal flow measurements, the hot-wire probe was checked periodically for contamination that could affect the accuracy of the calibration and corresponding data was discarded.

Baseline measurements, without the larynx, were taken 2.5 mm above the exit of the pipe before and after each trial to check for consistency of the measurements. A change of more than 5% in the baseline usually indicated that dirt was present on the hot-wire probe. In this case the probe was cleaned (using alcohol), the hot-wire system was recalibrated, and the testing was repeated.

Mean and turbulent velocity profiles were obtained by traversing the hot-wire 2-3mm above the posterior, medial, and anterior planes of the glottal exit. The medial plane was taken to be midway between the vocal process and the anterior commissure, and the distance between the medial plane and the anterior and posterior planes was approximately 5mm (Figure 8.3). Fine step measurements were taken at 0.13mm
Figure 8.3: Measurement planes above the larynx. The top view of the larynx shows the location of the posterior, medial and anterior hot-wire measurement planes.

Intervals using a motorized traverse system (Velmex Inc., BiSlide® and VXM motor). Special care was given to ensure that the measurements at each trial were done along the same axes and at the same height. A total of 100k data points at a sample rate of 25kHz were taken for each point. To determine how many points were required in one plane, the mean velocity value for each data point was immediately calculated and plotted in LabVIEW® after it was collected.

To avoid damaging the hot-wire probe, the injected air was not humidified. If phonation was observed, the measurements were delayed until the vocal folds had stopped vibrating (confirmed by the high-speed video camera). Each trial measured the velocity profiles along the three planes and lasted no more than 10min. The larynges were placed back in the saline bath for minimum of 60min between each trial, which was found to be enough time to get repeatable results.
All statistical calculations for the hot-wire measurements were done in MATLAB®. The data was imported into MATLAB® and processed to find the mean and RMS for each measurement point. TI was defined as velocity fluctuations (RMS) divided by mean velocity in percentage: $\text{TI} = \frac{u'}{\bar{U}} \times 100$.

### 8.2.1.2 Flow measurements in the glottis using PIV

Five excised larynges were harvested from shared research mongrel canines immediately after the animals were euthanized. The animals’ gender and weight were: male-15.0kg, female-17.2kg, female-19.1kg, male-17.2kg, and male-19.5kg. The membranous lengths of their vocal folds were 14.0, 14.2, 14.5, 14.0, and 17.0mm, respectively. The heights (measured along the medial aspect) of their folds were 2.5, 3.0, 3.0, 3.0, and 3.5mm, respectively. The tracheas were kept about 3 to 5cm long. These measurements were estimated using a hand-held caliper (Mitutoyo, 500-196-20 Absolute Digimatic Caliper). All cartilage and soft tissue above the vocal folds were removed in order to produce an unobstructed view of the folds. PIV measurements were performed 24hrs postmortem, and the larynges were kept in saline when not used. In order to get the vocal folds to vibrate, the folds were adducted together by placing a suture through both vocal processes at the same level. The stitch was tied with the minimal tension needed to have a pre-phonatory width of 0mm between the vocal processes. Special care was taken to position the suture symmetrically in both the anterior-posterior and inferior-superior directions. The posterior (cartilaginous) glottis was also closed with suture.

The larynx was placed inside a 50x50x50cm plexiglass chamber to enable seeding of the surrounding air, and was fixed in space using a four prong support attached to the cricoid. Both the chamber and the glottal flow were seeded using DEHS oil.
generated by an atomizer. The PIV measurements were performed by illuminating the flow using a high repetition rate, dual cavity, Nd:YLF laser system synchronized with a high speed video camera. Fluorescent red dye (Cole-Parmer, Rhodamine WT Dye) was applied to the tissue to reduce reflections from the laser. The high-speed camera was fitted with a Nikon 85mm F/1.4 lens, 72mm extension tubes, and x1.4 teleconverter. A 527nm band-pass filter was used to reduce the laser reflections from the tissue. An area of 11.4x8.6mm in the physical space was captured for each image, corresponding to a pixel resolution of 922x698. Each image pair was taken at a time interval of 3.0µsec. A total of 2,000 PIV images were taken at 5kHz and the camera TTL signal was captured for reference. Post processing of the PIV data was done using DAVIS® 8.1 software with a multi-pass decreasing window size (64x64 to 32x32) and adaptive interrogation window with 75% overlap.

The laser was focused and spread to produce a 1mm thick light sheet in the coronal plane, halfway between the vocal process and the anterior commissure (referred to as the mid-membranous plane). In order to perform intraglottal velocity measurements, the laser sheet illuminated the mid-membranous plane (x-y) from above and the camera was placed in the x-z plane above the vocal folds at an oblique angle of 40º relative to the x-y plane, directed towards the glottis (Figure 8.4). A Scheimpflug optical adaptor was connected between the camera and the teleconverter to correct the image distortion due to the oblique viewing angle.

8.2.2 Static pressure measurements

Pressure measurements were done using a transducer that converts pressure values into an electrical signal. The transducer contains a piezoelectric diaphragm that
Figure 8.4: Schematic of the PIV measurement at the mid-membranous plane. The z-axis is pointing out of the page. The PIV camera is located on the x-z plane, anterior and superior to the larynx. The laser is projected superiorly to the larynx.
displace (or deform) in response to the pressure in the flow. The magnitude of the current (i.e. voltage) that is output by the piezoelectric diaphragm is proportional to the absolute pressure. The greatest advantage of such electrical pressure transducers (compared with manometers or mechanical gauges) is their fast frequency response (up to 2kHz). The range of the transducer used to measure the pressure inside the plenum was 0-50inchH\textsubscript{2}O (0-127cmH\textsubscript{2}O). Calibration of the pressure transducer was made before and after each experiment.

8.2.3 Acoustic measurements

Acoustic measurements were done using a microphone. The microphone operates in a similar manner to the pressure transducer where deformation of a piezoelectric diaphragm produces measurable voltage output. The microphone measures the pressure fluctuations in the flow (as opposed to the absolute pressure) and thus holds a very high frequency response, which is needed for measuring unsteady and turbulent flows.

The acoustic measurements in the laryngeal experiment were taken with a 0.5inch free-field microphone (Brüel & Kjær, Model 4950). The microphone was placed about 5cm laterally and superiorly to the glottis where it did not interfere with the airflow. The accuracy of the microphone was ±0.2dB. In addition, a sound level meter (Larson Davis, Model 831) was placed opposite to the microphone to record the sound pressure level (SPL) data using a C-weighted function. The microphone gives instantaneous data based on the pressure fluctuation (limited up to its frequency response) while the SPL meter gives a mean quantity for the duration of the measurement.
The voltage output is converted into Pascals (Pa) based on the calibration (i.e.
sensitivity) of the microphone. The SPL is determined in dB using the formula:

\[ L_p = 20 \log \frac{p}{p_o} \]  

(8.1)

Here \( p_o \) is a standard reference pressure that is equal to \( 20 \mu \text{Pa} \), which is the threshold of human hearing.

### 8.2.4 Glottal opening area measurements

The glottal opening area was recorded using a high-speed video camera (Photron,
Fastcam SA4) that was placed approximately 80cm superiorly to the glottis. The
camera was fitted with a Nikon 105mm lens, 12mm extension tubes, and a x4 tele-
converter. The lens was equipped with a 555nm long-pass filter to abate the laser
light reflection from the folds. Each image captured 20x14mm in the physical space
Corresponding to 512x356 pixel resolution. A total of 14,000 images were taken for
each run at a sampling rate of 20kHz, and the camera TTL signal was recorded for
reference.

The opening and closing of the folds was also monitored by connecting an elec-
roglottograph (EGG) to the cricoid. The EGG measures the contact between the
folds by monitoring the change in current/resistance between its electrodes.

The glottal opening area was identified based on the difference in pixel intensity
of the membranous folds and the glottal opening, thus measuring the minimum glot-
tal area. Each frame from the camera was converted into Tagged Image File format
(TIFF) and the image processing was done in MATLAB®. The images were first
converted into a greyscale and then into binary image based on a specified threshold.
The area for the glottal opening was determined by adding all the pixels that corresponded to the glottal opening (having a value of one in the binary image). The size of each pixel in the physical space was determined by comparing the image to a previously recorded grid. During opening, the minimum glottal area occurs at the superior edge due to the converging shape of the folds. Likewise, during closing, the folds assume a divergent shape and the minimum glottal area occurs at the inferior edge.

8.2.5 Tissue elasticity measurements

The elastic properties of the tissue were evaluated using a custom load cell (Sensing Systems Corporation). A full Wheatstone bridge configuration of four strain gages was bonded to the load cell sensing element. The strain gage bridge provides a very sensitive electrical output signal as loads are applied to the load cell contact tip. The output signal was calibrated using dead weights suspended on the load cell contact point.

A schematic of the customized load cell used in the study is shown in Figure 8.5. The distal tip diameter, which contacted the tissue, was 1mm. The load cell was set to measure 0-10gram-force (0-100millinewton). Traversing the load cell at fine step increments was done using a motorized traverse system (Velmex Inc, BiSlide® and VXM motor).

Force measurements in the vocal tissue were taken in a full larynx mounted in the same manner described in section 8.2.1.2. The folds were adducted in order to draw the same pre-phonatory tension in the tissue that occurred during phonation. One fold was receded back using a vein retractor (Grieshaber, SS Cushing Design Vein...
Figure 8.5: Schematic of the customized load cell used to measure the elasticity of the vocal fold tissue. Measurements were taken in a full larynx with the folds adduct. The load cell was positioned by retracting one of the folds. Tip diameter is 1mm. Engineering drawing of the load cell is shown in Appendix A.

Retractor 8-1/2”) in order to clear space to insert the load cell. Force measurements were taken by displacing the tissue at Δy=0.1mm increments. A total of 1,000 data points were recorded at 1kHz for each point. Measurements were done following each PIV measurement at the three subglottal pressures. The total displacement for each trial was determined based on the maximum lateral displacement of the folds, which was determined from the glottal area measurements. The loading and unloading measurements were taken at the mid-membranous plane (the same plane as the PIV measurements) at the superior and inferior aspects of the fold. The superior edge measurements were taken first and the load cell was then traversed inferiorly based on the measurements for the glottal height.
The strain in the tissue was estimated as the ratio of the tissue displacement to the tissue initial width: $\varepsilon = \frac{l}{l_o}$. The Young’s modulus was estimated using the formula suggested by Chhetri et al. [127]:

$$E = \frac{1 - \nu^2}{D} \left( \frac{dF}{dl} \right)$$

(8.2)

where $\nu$ is the Poisson’s ratio for the tissue (estimated to be 0.47) and $dF/dl$ is the initial slope of the force measurement unloading curve. $D$ is the tip diameter of the load cell probe.

8.3 Mechanical and computational models of the fold

To validate the velocity measurements and the pressure calculations, a mechanical model that was intended to simulate the general shape of a divergent glottis was used (Figure 8.6). The model was made to be connected to the end of the nozzle described above. It was constructed of a straight wall on one side and a second wall having a straight section (5mm) and an inclined section at 20° from the vertical (5mm). The minimal gap, $y_{min}$, between the two straight sections was 1.5mm. To validate the new technique to measure the velocity one set of measurements was taken with the camera perpendicular to the x-y plane, and another set was taken by tilting the camera at the same oblique angle configuration of 40° that was used for the full larynx measurements. The chamber and the flow were seeded as described in section 3.2.2.1. A total of 2,000 PIV images were collected at 5kHz for each case. In addition, pressure measurements were taken at two ports on the inclined wall (located at $x/y_{min} = -0.7, -1.5$) and were used for comparison with the pressure
values computed from the flow field data. The pressure ports had 0.5mm diameter and were connected to the pressure transducers via a 3cm plastic tubing.

The results from the mechanical model were compared with computational results using Large Eddy Simulation (LES). The model used for the LES was the same static larynx model used by Mihaescu et al. [102] (Figure 8.7). The glottal wall in the LES model had a 20° divergence angle and it assumed symmetry relative to the mid-sagittal plane. The input flow conditions in the LES computations were adjusted to match the magnitude of the centerline velocity of the experimental data.
Figure 8.7: Schematics of the LES model used to compare with the mechanical model. The geometry for the LES model is based on the study of Mihaescu et al. [102]
8.4 Data processing

8.4.1 Phase estimation

The recording of the PIV and the glottal area images could not be made at specific periods of the vibration cycle (i.e. phase-locked). This known limitation of the high-speed image acquisition technique required that the phase of each image be determined based on a reference signal. The EGG signal was selected to be the reference signal because its cycle-to-cycle variation was lower (based on the coefficient of variation for the signal) compared to the microphone signal. In order to determine the phase of each image, the TTL signal from each camera was matched with the phase of the EGG signal, which was taken at a much higher sampling rate. The phase of each data point from the EGG signal was determined by identifying a specific reference point in the cycle, and setting the phases of all other points within the cycle with respect to that point. The phase difference between two consecutive reference points was set to 360°. The reference points for the EGG signal were taken at the tip of the sharp peaks in the time derivative of the signal (Figure 8.8). Golla et al. [140] showed that using the time derivative of the EGG signal provided the most distinctive and repeatable reference points, hence minimizing the cycle-to-cycle variations in the signal. When the TTL signal goes 'high', it marks the beginning of the camera image frame acquisition and the phase of this point is determined by matching it with the phase of the concurrent EGG point. In the final step, all the phases were shifted so that $\theta = 0^\circ$ was defined as the beginning of opening at the superior edge, which was determined visually from the high-speed images of the glottal area.
8.4.2 Pressure calculations from PIV

The pressure distribution of the flow field was calculated using the pressure Poisson equation for incompressible flow. This method of calculating pressure values from PIV data has shown to have good agreement with direct measurements (de Kat and van Oudheusden [141]). The pressure Poisson equation is derived from the Navier-Stokes equations by applying the divergence operator and simplifying using the continuity equation for steady flow (Anderson [142]):

$$\nabla^2 P = -\rho \nabla \cdot (V \cdot \nabla V)$$ \hspace{1cm} (8.3)

The right hand side of the equation can be solved using the velocity data obtained by PIV.
The Bernoulli equation gives very limited information about the pressure distribution in the flow field. It can only be used along streamlines and where no flow separation occurs. Like the Bernoulli equation the pressure Poisson equation neglects the viscosity in the flow, but it can be applied if flow separation occurs.

de Kat and van Oudheusden [141] suggested that other numerical schemes that are based on Eulerian forms can be used to compute pressure from PIV measurements, but these numerical schemes require knowledge of the flow acceleration, $dU/dt$. In the current study, the 5kHz acquisition rate of the PIV is far too low to accurately extract this parameter of the velocity. Using the pressure Poisson equation is preferable because it assumes that the flow is steady.

Mongeau et al. [143] showed that the glottal flow can be approximated as quasi-steady flow, except during the beginning of the opening cycle. Later Zhang et al. [144] and Krane and Wei [92] added that the quasi-steady assumption is also invalid at the end of closing, which they attribute to the dominance of unsteady acceleration in the flow. The quasi-steady approximation describes the unsteady flow as a series of steady flows with time varied wall geometry (i.e. boundary conditions) and assumes that the acceleration effects in the flow can be neglected. The pressure calculations in the current study were made from the beginning of closing, which was determined from the high-speed images of the glottal area, until no more intraglottal negative pressure was observed. The latter always occurred prior to the end of closing.

The Poisson equation is an elliptic equation and knowledge of the boundary conditions is required so that the equation can be solved. The lower boundary was taken as the subglottal pressure ($P_2$), which was computed from the pressure measured inside
the chamber \( (P_1) \), using Bernoulli’s equation:

\[
P_2 = P_1 - \frac{1}{2} \rho \left[ \left( \frac{Q}{A_2} \right)^2 - \left( \frac{Q}{A_1} \right)^2 \right]
\]  
(8.4)

where \( Q \) is the measured flow rate and \( A_1 \) and \( A_2 \) are the areas inside the chamber and the minimum subglottal opening area (measured at the inferior aspect of the folds during closing), respectively. In the mechanical model, \( A_2 \) was taken as the area inside the nozzle between the two walls. The upper boundary was assumed to be atmospheric and was set at the highest axial location of the PIV measurement plane. This was typically 3-4mm above the folds in the excised larynx, and 1mm above the exit of the mechanical model. No pressure gradient in the transverse direction (i.e. \( dP/dy = 0 \)) was assumed on the glottal walls or the walls in the mechanical model. This assumption is based on the simplifications to the Navier-Stokes equations in the boundary layer theory. Figure 8.4 shows the location of the lower and upper boundaries in a typical PIV image.

de Kat and van Oudheusden [141] also reported that in order to obtain optimal pressure calculations from PIV, the spatial resolution of the flow field should be five times smaller than the dominant structures in the turbulent flow. In the laryngeal experiments 1mm in the PIV image plane was covered by approximately 81 pixels. Analyzing the PIV images was done such that the final step was made with 32x32 interrogation window size and 75% overlap, which produced minimum of 7 velocity vectors in each 1mm. The most minimal gap that was observed in the mid-membranous plane (when pressure computations were made) was always greater than 1mm.
8.5 Experimental uncertainty estimation

The methods for computing the errors and the experimental uncertainty were discussed in the uncertainty section in the synthetic jets experiments (section 3.4). Based on those computation it was found that the upper bounds in the experiment was $S = 0.002$, which set the estimated errors due to the Stoke number effect at less than 2%.

The maximum velocity of the intraglottal jet varied corresponding to the changes in the subglottal pressures. In the course of each run, the velocity of the jet did not varied during closing (except during the end of closing, which was not considered as a phase of interest in the current work). The time interval between each image pair was set at 3µsec, which at the maximum jet velocity (i.e. at the highest subglottal pressure) corresponded to 13.3 pixel displacement. This yields 0.7% uncertainty of the measurement according to Eqn. 3.2. When flow separation occurred in the glottis, the velocity of the entrainment was significantly less than the velocity of the glottal jet. Based on the maximum velocity magnitude of the entrainment the uncertainty of the velocity measurements near the wall was estimated to be 4.2%.

The pressure computations from PIV were done using the pressure Poisson equation. The central difference numerical scheme was used to solve the equation using the measured velocity. This numerical scheme has second order accuracy [142].

According to manufacturer specifications the accuracies of the microphone and the pressure transducer were ±0.2dB and 0.1%, respectively. The accuracy of the customized load cell was 0.285%.
Chapter 9: Results - flow measurements in canine larynx

9.1 The role of subglottal shape in turbulence reduction

In order to account for the different larynx anatomy and different glottal openings of different animals, the velocities and length scales were normalized. Length scales were normalized by dividing the distance of each measurement point from the origin by the distance from the jet center to the point at which the mean velocity dropped to half of its value at the center velocity ($r_{1/2}$). Such normalization is used routinely in fluid mechanics to describe the growth of a jet and to define its lateral spread. The axial component of the mean velocity ($U$) was normalized by the centerline axial velocity ($U_{cl}$).

Figure 9.1 shows flow profiles taken 2.5mm above the exit of the pipe without the larynx. These flow profiles were assumed to be the same as the flow profiles upstream of the subglottis. Figure 9.1a is the baseline flow profile at the pipe’s exit when air enters the pipe axially (no air was injected via the chamber). The flow profile is typical of a low level turbulent pipe flow. The turbulence level in the flow (Figure 9.1b) is highest (~7%) in the shear layer. This turbulence level was determined to be too low for studying the turbulence reduction effect of the larynx. Hence a combination of axial and tangential co and counter swirling jets was used to enhance
the turbulence level. Figure 9.1c shows mean velocity profiles when the TI level was enhanced by injecting most of the air tangentially through the chambers ports and the rest axially (see methodology section). The mean velocity profiles and the corresponding enhanced TI profiles (Figure 9.1d) were used as the inlet conditions to the larynx. As a result of the lateral mixing induced by the high turbulence level the jet has a top-hat profile with uniform flow across the pipe’s cross section and steep gradients at the edges. The TI profiles varied between the different animals tested, but always had the highest TI level in the shear layer near the jet edges and somewhat lower TI level in the center of the flow. Using a Gaussian fit we found that the averaged profile had a maximum of 21% TI level in the shear layer and an average 15% TI level in the center.

A total of 17 cases were measured. Each case included measurements of velocity profiles in the anterior, medial, and posterior planes. Two cases were obtained from canine1, nine from canine2, and six from canine3. Figure 9.2 shows mean velocity profiles taken at the anterior, medial, and posterior planes 2.5mm above the glottis. The profiles maintained the same top-hat velocity profile as the subglottis velocity profile (Figure 9.1c). Figure 9.3 shows the corresponding TI levels. The solid line is the Gaussian fitted curve for the data. The dashed line shows the fitted curve for the subglottal TI, for reference. Downstream of the glottis, the highest TI remained in the shear layer but was reduced relative to the TI level in the subglottis flow.

The TI reduction is attributed to the area reduction that the flow encounters as it flows into the larynx. Area reduction was quantified by dividing the area encompassed by the inferior border of the cricoid by the glottis opening area (at the superior edge). The inferior border of the cricoid was estimated to be nearly equal to the pipe area.
Figure 9.1: a) Mean velocity and b) TI profiles taken at the exit of the pipe with only axial flow into the pipe. c) Mean velocity and d) TI profiles at the exit of the pipe with minimal flow injected axially and main air source injected tangentially to create swirls. The solid line is the fitted Gaussian curve for the data. Profiles were taken 2mm above the exit of the pipe.
Figure 9.2: Mean velocity profile taken 2.5mm above the glottis of the a) anterior, b) medial, and c) posterior planes
Figure 9.3: TI profiles of the a) anterior, b) medial, and c) posterior planes taken 2.5mm above the glottis. The solid line is the fitted Gaussian curve for the data. The dashed line is the fitted curve for the subglottal TI.
The maximum area reduction for the larynges tested was 35, minimum 15, and average 22. This wide range of area reduction is the main reason for the wide distribution of TI levels above the glottis that is shown in Figure 9.3.

To find the overall average of the TI reduction, we identified the average of the maximum TI level in the shear layers and the average TI at the center of the flow. Figure 9.4 shows the average for the maximum TI levels in the shear layer and the center of the flow in the anterior, medial, and posterior planes. The error bars indicate the standard deviation of the measurements. TI reduction was defined as the difference between the subglottic TI and the supraglottic TI divided by the subglottic TI (in percent). Figure 9.4 shows an average TI reduction of 63% in the shear layer and an average TI reduction of 90% at the center.

These results shows that turbulence entering the subglottis will be substantially reduced when the vocal folds are adducted. It was mentioned in the background that turbulent airflow can produce increased noise; this will lower the harmonics-to-noise ratio (HNR). Turbulent airflow in the glottis may have other deleterious
effects on glottal airflow and the resulting acoustics. In fluid mechanics, it is well known that turbulent airflow will reduce coherent vortical structures. Khosla et al. [80] demonstrated, in an excised canine larynx model, that vortices formed in the superior aspect of the glottis during closing and that these vortices produced significant negative pressure that would result in an increased maximum flow declination rate (MFDR). Therefore, turbulence in the glottis can reduce or eliminate these flow separation vortices, and will reduce the MFDR.

9.2 Intralglottal velocity measurements and pressures computations

9.2.1 Mechanical model measurements and comparison with LES

Figure 9.5 compares profiles of the axial velocity taken along the cross-section at \( x/y_{\text{min}} = -0.6 \). The measurements were taken once with the camera perpendicular to plane x-y (no tilt) and then with the camera at a 40° tilt. In the second case the images were corrected using the Scheimpflug adaptor. The velocity profiles were normalized by the centerline velocity, \( U_{cl} \), defined as the maximum velocity of the jet and as the axial location for \( y = 0 \). The abscissa in the figure was normalized by the half width of the jet, \( y_{1/2} \), defined as the distance where \( U = 0.5U_{cl} \) on each side of the profile. The fact that the profiles are nearly identical shows that the Scheimpflug adaptor corrects for the distortion of the field of view without affecting the velocity measurements. Also shown in the figure is the velocity profile calculated by LES for the same axial location. The LES yielded \( U_{cl} = 53.6 \text{m/s} \) which matched well with the experimental data of \( U_{cl} = 53.4 \text{m/s} \).
Figure 9.5: Velocity measurements at $x/y_{\text{min}}=-0.6$ taken without tilt and with 40° tilt of the PIV camera. The abscissa is normalized based on the half-width of the jet. Dash line shows the velocity profile from LES.

The pressure distribution in the mechanical model is shown in Figure 9.6. These pressure values were computed from the time averaged velocity data taken with no tilt of the camera. The arrows on the figure indicate the pressure measurement on the wall the magnitude of the pressure that was computed from PIV. The difference was 7% and 9.5% at the upper and lower ports, respectively. These results for the pressure distribution show that lower pressure occurs near the inferior edge of the inclined wall. The same results for pressure distribution were predicted by the LES and were shown in Mihaescu et al. [102]. The pressures values in both models are based on a steady flow assumption that is not representative of the dynamic nature of the glottal flow. The impact of the unsteadiness on the intraglottal pressure field is recorded in the instantaneous data.

The instantaneous PIV images capture how the flow separates from the divergent wall, and how vorticity or vortices develop from the entrainment flow. Examples for instantaneous images from PIV (on the left) and LES (right) are shown in Figure
Figure 9.6: Pressure distribution in the mechanical model based on time averaged velocity data. Arrows indicate the pressure measurement on the inclined wall and the pressure computed from PIV. More negative pressure is computed near the inferior edge. $Y_{\text{min}} = 1.5\text{mm}$.

9.7. The image in Figure 9.7a shows instantaneous velocity fields. The flow separates from the wall immediately after the vertex point, which is indicated on the figure. A flow separation vortex is seen around $x/y_{\text{min}} = 0$ in both models. Instantaneous pressure distributions are shown in Figures 9.7b to 9.7d (the pressure distribution in Figure 9.7d is based on the velocity fields shown in Figure 9.7a). All pressure fields were normalized by the magnitude of the lowest negative pressure.

The LES data shows how the vortex that is formed by the flow separation produces negative pressure that spreads in the glottis as the vortex is convected downstream. The lowest negative pressure occurs inside the vortex (presumably at its core) and the images show that negative pressure also extends onto the wall. The instantaneous images show that the lowest negative pressure is computed near the superior edge due
Figure 9.7: Instantaneous (a) velocity field and (b-d) pressure distributions. In each image, the results from the mechanical model are shown on the left and the results predicted by LES are shown on the right. The pressure fields are normalized by the magnitude of the lowest negative pressure. Lower negative pressure is computed near the superior edge due to flow separation vortex. $Y_{min} = 1.5\text{mm}$. 
to the flow separation vortex. The pressure data from the PIV matches qualitatively well with the data from LES.

The mechanical model was used to study the formation of the FSV due to flow separation from the inclined wall. The divergent passage induces an adverse pressure gradient that leads to flow separation. Since the pressure at the superior edge of the mechanical model (i.e. where $x/y_{min} = 0$) is (or near) atmospheric, the pressure at the separation point is negative. These pressure differences cause external flow to be entrained into the separated region. The entrained flow can also roll-up into a vortex. The size of the vortex and the magnitude of the negative pressure grow as the vortex advects downstream. The mechanical and LES models show that the results for the pressure distribution and magnitude can vary greatly between time averaged and instantaneous data. The former shows the lowest negative pressure occurring near the inferior edge, while the latter shows that the most negative pressure occurring near the superior edge. The instantaneous data also yields a larger magnitude of negative pressure, associated with a flow separation vortex, than what was computed from the time-averaged data. The mean pressure field averages the unsteady pressure induced by the convecting flow separation vortices and does not capture the more negative local unsteady pressure that is produce on the superior edge of the model by these vortices.

While the pressure data from PIV was qualitatively the same as the pressure from LES, it differed in the magnitude of the data. This difference probably stemmed from the differences in the geometries of the models. The LES model was based on the computational study of Mihaescu et al. [102], which modeled half a larynx. The flow in this model converged smoothly below the diverging wall and promptly
transitioned from its converging shape (in the subglottal region) to a diverging shape
(in the glottal region) at a vertex point. The LES model also assumed symmetry
about the midline, and the downstream flow was modeled in a duct (which adds
flow inertia). The mechanical model was fitted into a nozzle, and included a straight
wall portion before the inclined wall. There was also a wall opposite to the inclined
wall. The downstream flow in the mechanical model was open to the atmosphere
and no further inertia was added to the flow. The height of the diverging wall in the
mechanical model (5mm) was longer than the height of the diverging wall in the LES
model (4mm).

The difference between the pressure measurements on the inclined wall and the
pressure computed from the (instantaneous) PIV can stem from the limited frequency
response of the pressure port, which is a function of its hole diameter and length (Shaw
[109]. Due to the size and geometry of the pressure transducers, they could not be
placed in the ideal configuration (i.e. flushed with the incline wall). The drop in
pressure that results from the vortex, shown by the instantaneous PIV and LES,
occurs very rapidly and is not captured via the pressure port. The pressure ports
measure the mean pressure values with some small fluctuations around it. This also
explains why the measured pressure values are closer to the pressure values computed
from the time averaged velocity field.

9.2.2 Intraglottal velocity measurements and pressure com-
putations in canines

Phonation of each larynx was tested at three subglottal pressures: low, medium,
and high. The range for the subglottal pressures was 10.0cmH₂O-18.8cmH₂O for
the low, 18.5cmH₂O-22.8cmH₂O for the medium, and 21.5cmH₂O-27.5cmH₂O for the
Table 9.1: Experimental parameters for the study

<table>
<thead>
<tr>
<th>Larynx</th>
<th>Folds length (mm)</th>
<th>Subglottal pressure (cmH₂O)</th>
<th>F₀ (Hz)</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>L1</td>
<td>14.0</td>
<td>10.0</td>
<td>153</td>
<td>Male canine</td>
</tr>
<tr>
<td></td>
<td></td>
<td>19.4</td>
<td>124</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>25.5</td>
<td>126</td>
<td></td>
</tr>
<tr>
<td>L2</td>
<td>14.2</td>
<td>15.1</td>
<td>115</td>
<td>Female canine</td>
</tr>
<tr>
<td></td>
<td></td>
<td>18.5</td>
<td>126</td>
<td>Zipper-effect during closing</td>
</tr>
<tr>
<td></td>
<td></td>
<td>21.5</td>
<td>193</td>
<td></td>
</tr>
<tr>
<td>L3</td>
<td>14.5</td>
<td>14.7</td>
<td>96</td>
<td>Female canine</td>
</tr>
<tr>
<td></td>
<td></td>
<td>19.1</td>
<td>348</td>
<td>Zipper-effect during closing</td>
</tr>
<tr>
<td></td>
<td></td>
<td>24.9</td>
<td>383</td>
<td></td>
</tr>
<tr>
<td>L4</td>
<td>14.0</td>
<td>18.8</td>
<td>87</td>
<td>Male canine</td>
</tr>
<tr>
<td></td>
<td></td>
<td>22.8</td>
<td>118</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>27.2</td>
<td>119</td>
<td></td>
</tr>
<tr>
<td>L5</td>
<td>17.0</td>
<td>15.2</td>
<td>66</td>
<td>Male canine</td>
</tr>
<tr>
<td></td>
<td></td>
<td>20.2</td>
<td>84</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>27.5</td>
<td>104</td>
<td></td>
</tr>
</tbody>
</table>

The values are listed in Table 1 along with some other experimental parameters and observations. The acquisition of the data was initiated about 10sec after the onset of phonation to allow for the vibration frequency to stabilize. Larynges L2 and L3 were harvested from female canines and showed a higher fundamental frequency of vibration particularly at the medium and high subglottal pressures. Titze [83] claimed that gender does not play a role in canine studies, but his earlier studies showed that it does [145]. L2 and L3 were also characterized with a zipper-effect (Granqvist et al. [97]) in the anterior-posterior direction vibration pattern.

The streamlines of the glottal flow and the corresponding pressure distribution at low subglottal pressure in L1 (10.0cmH₂O) are shown for a phase of θ = 197° (Figure 9.8). The phase shown occurs around the middle of the closing cycle (150° < θ <
Figure 9.8: Streamlines of the intraglottal velocity field and pressure distribution during closing ($\theta = 197^\circ$) for low subglottal pressure (10.0cmH$_2$O) in L1. The flow does not separate from the glottal wall. As a result, the lowest pressure proximal to superior aspect of the folds is nearly atmospheric.

250$^\circ$). Figure 9.8 shows minimal lateral displacement at this low subglottal pressure and that the flow does not separate from the glottal wall (Figure 9.8a). Since the flow does not separate, negative pressure is not observed within the glottis (Figure 9.8b). The pressure on the upper boundary is assumed to be atmospheric and the lowest pressure proximal to the superior edge is nearly atmospheric.

The streamlines of the glottal flow and pressure distribution for three phases during closing ($\theta = 128^\circ$, 135$^\circ$, and 137$^\circ$) in L1 at high subglottal pressure (25.5cmH$_2$O) are shown in Figure 9.9. The higher subglottal pressure results in both increased lateral displacement and greater divergence angle of the folds. The mucosal wave in the glottis incites closing at the inferior edge prior to the superior edge, which creates the diverging angle. The initial divergent angle at the beginning of closing is minimal and the flow does not separate (closing began at $\theta = 105^\circ$). The lowest pressure at
the superior edge is nearly atmospheric, which is similar to what was observed in the low subglottal pressure for that larynx. As the closing of the folds continues, the divergence angle of the folds increases. At $\theta = 128^\circ$ there is no evident for intraglottal flow separation (Figure 9.9a), but the vorticity that is present just above the superior edge of the folds creates a small magnitude of negative pressure approximal to the superior edge (Figure 9.9b). By the middle of closing ($\theta = 135^\circ$) the glottal wall forms a larger divergence angle and the glottal flow separates from the wall. Flow separation vortex develops from the entrainment flow near the superior edge of the left fold (Figure 9.9c). The lowest intraglottal negative pressure that is computed from this vortex is -8.8cmH$_2$O (Figure 9.9d). The maximum flow separation in the glottis occurs around $\theta = 137^\circ$ (Figure 9.9e). The vortex strength grew correspondently and the lowest negative pressure that is computed approximal to the superior edge is -15.5cmH$_2$O (Figure 9.9f).

Figure 9.10 plots the lowest levels of the intraglottal negative pressure that were computed from the instantaneous velocity fields for the five larynges at the three subglottal pressures. The open symbols show the results from pressure computations that were based on approximate location of the glottal walls (estimated to be within 0.25mm accuracy). Some of the velocity fields contain sporadic or spurious vectors in them. The closed symbols show pressure results for data that is selected manually from the open symbols. These pressure computations are based on the exact location of the glottal wall and contain no sporadic or spurious vectors. There was no significant difference between pressure computations shown by the open symbols to the ones shown by the closed symbols. The maximum difference between the two
Figure 9.9: Intraleral velocity field and pressure distribution during closing for high subglottal pressure (25.5 cmH$_2$O) in L1. The flow separates from the glottal wall and external flow is entrained into the larynx. A flow separation vortex develops inside the glottis and produces negative pressure on the superior aspect of the folds.
methods was 13%. The horizontal bars on the figure indicate the closing cycle for each case.

At the high subglottal pressure, the most negative pressures values for L1 through L5 were: -14.6, -5.6, -7.9, -13.6, and -12.2cmH₂O, respectively (Figure 9.10a). These magnitudes are close to the negative pressures in the hemilarynx of Alipour and Scherer [124], who measured -6.0 and -15.5cmH₂O on the superior edge for subglottal pressures of 25 and 27cmH₂O, respectively. Negative pressures were also computed for the medium subglottal pressure in L1-L5 with the most negative values of -8.6, -2.6, -4.7, -3.9, and -5.7cmH₂O, receptively (Figure 9.10b). The peak in the negative pressure, and the decline in the magnitude of the negative pressure that follows, also indicates that the vortex had advected out of the glottis. The glottal flow still separates from the diverging wall and entrainment flow continues to enter and to create negative pressure in the glottis.

At the low subglottal pressures, the lowest negative pressures in L3-L5 were -2.8, -1.0, and -1.5cmH₂O, respectively (Figure 9.10c). Intraglottal negative pressures were not observed in L1 and L2. As shown in Figure 9.8, the flow for L1 did not separate from the glottal wall. This was also the case for L2. The divergent angle for larynges 3-5 was slightly higher, enough to cause flow separation and for negative pressure to develop.

The intraglottal pressure distributions for the phases with the lowest negative pressures in the high subglottal cases (i.e. Figure 9.10a) are shown in Figure 9.11. The intraglottal pressure distribution for L1 is shown in Figure 9.9f. The pressure values along the dashed line are shown at the bottom of each image. The data is very similar to what was observed in the mechanical and the LES models. The lowest
Figure 9.10: Intraglottal negative pressures during closing. The value shown in each phase is taken as the lowest the most negative pressure computed near the superior aspect of the folds. Open symbols are for pressure computations based on approximate location of the glottal wall. Closed symbols are for pressure computation based on exact location of location of the glottal wall. Horizontal lines indicate the closing cycle for each case. No negative pressure was observed for L1 and L2 in the low subglottal pressure.
negative pressure occurs approximal to the glottal wall at the vortex. The intraglottal negative pressure then extends to the wall.

The accuracy of the pressure computation will depend on the quality of the velocity data. Near-wall velocity measurements using PIV can be greatly affected by reflections from the wall. This was the case in Figure 9.11d were negative pressure was found only near the left fold, since no entrainment was measured near the right fold.
In Figure 9.11a the intraglottal pressure distribution for L2 shows that the vortex (and the lowest pressure) is located below the superior aspect of the folds. Analyzing subsequent phases showed that the vortex was convected downstream without increasing the magnitude of the negative pressure, which was in contrast to what was seen in L1 (Figure 9.9), L4, and L5. The zipper-like vibration pattern of the folds might be the reason for this observation, but more study is needed to support this claim. The vibration pattern of L2 and L3 might also explain the difference in the phases where the intraglottal negative pressure occurred: For L1, L4, and L5 it occurred early in the vibration cycle ($80^\circ < \theta < 150^\circ$) and later in the cycle for L2 and L3 ($190^\circ < \theta < 230^\circ$).

Figure 9.12 shows the average cycle dynamics of the folds vibrations for the high subglottal pressure cases. The images in the figure indicate the periods of opening, closing, and how long the folds remained closed (before the beginning of opening again). The shaded areas indicate the period and magnitude of the intraglottal negative pressures (based on the lowest negative pressure in L1). The figure shows that the opening and closing cycles for larynges L2 and L3 were longer than their duration in the other larynges. The figure also affirms that intraglottal negative pressures occur prior to the end of closing and attest using the quasi-steady assumption needed for using Eqn. 8.3.

Figure 9.13 shows the lowest negative pressure that occurs near the superior aspect of the folds as a function of the subglottal pressure. The red solid line shows the linear regression fit to the data. It is evident from the figure that increasing the subglottal pressure correlates with increase in the magnitude of the intraglottal negative pressure. Increasing the subglottal pressure causes the velocity of the glottal
Figure 9.12: Cycle dynamics of the folds for the high subglottal pressure cases. Shaded regions indicate the span and magnitude for the intraglottal negative pressure. The radius of the circles is based on the magnitude of the lowest negative pressure in L1. The negative pressures period occur around the mid-closing phase, which makes the quasi-steady state assumption about the flow valid.
jet to increase. Higher jet velocity leads to an increase in the entrainment flow in the superior aspect of the glottis. The entrainment flow is directly related to the magnitude of the negative pressure in the glottis. Hence increasing the subglottal pressure increases the entrainment flow into the glottis, which increases the magnitude of the intraglottal negative pressure.

The flow rates at the medial superior and the medial inferior edges was calculated according to $Q = \int U \, dy \cdot dz$, where $\int U \, dy$ is the intraglottal velocity profiles and $dz$ is the thickness of the PIV laser sheet (assuming 1mm constant). Figure 9.14 shows the flow rates calculated at the inferior and superior edges for the mid-coronal glottal section in L1. It shows that the flow rates do not differ much for low subglottal pressure. However, the flow rate at mid and high subglottal pressures is much greater at the superior aspect of the glottis than at the inferior aspect. The differences are predominantly due to air entrainment into the glottis caused by the flow separation vortices.

Figure 9.13: Maximum magnitude of the intraglottal negative pressure as a function of subglottal pressure. The solid red line shows the linear regression fit to the data. Values are based on the closed symbols in Figure 9.10.
The intraglottal vortices induce significant negative pressures at the superior aspect of the folds. The negative pressure produces suction force on the folds that can contribute to the rapid closing of the folds. This hypothesis augments the myoelastic-aerodynamic theory, which considers the recoil forces in the tissue as the dominant force during closing. The latter, however, refutes the finding of Woo [79] about the correlations with vocal intensity since the maximum lateral displacement is directly related to the recoil forces.

9.2.3 Elasticity measurements of the folds

The stress-strains curves at the superior and inferior aspects of the fold are shown in Figure 9.15. The measurements were taken by indenting the fold (in 0.1mm increments) at its mid-membranous plane using a customized load-cell. The strain was calculated as: $\varepsilon = l/l_0$, where $l_0$ is an initial measure of the fold taken to be its width.
(3.5 mm for the larynx that is shown) and \( l \) is the displacement length. The maximum displacement (i.e. strain) for each measurement was determined based on the maximum distance between the folds, which was extracted from the glottal opening area measurements. The stress in the tissue was calculated as: \( \sigma = \frac{F}{A} \), where \( F \) is the force measurements and \( A \) is the contact area of the probe with the tissue.

The measurements taken based on the low \( P_{SG} \) displacement do not show significant differences in stiffness between the inferior and superior edges (Figure 9.15a). The lateral displacement of the folds was proportional to the subglottal pressure (see glottal opening in Figures 9.8 and 9.9), which yields higher tissue strain. At medium \( P_{SG} \), the maximum strain in the tissue (55%) yielded 20% higher stress values in the inferior edge than the stress in the superior edge (Figure 9.15b). At high subglottal pressure the maximum stress was 30% higher in the inferior edge than the superior edge (for 65% strain, Figure 9.15c).

The unloading curves at the inferior and superior measurement planes are compared in Figure 9.16. The images show that the measured stress values are different for the same strain in the tissue. The discrepancy in the results can stem from two main factors: First the 1 mm tip diameter of the probe is about 30% of the 3.5 mm height of the fold that is shown. A slight deviation in the axial location of the probe between trials might explain why the stress measurement was higher at the superior edge in the low subglottal pressure. The second factor that probably affected the stress measurements stems from the necrosis state of the vocal fold tissue. The tissue was kept in 0.9% saline solution between trials, while other studies kept the tissue in a Krebs solution, which is best used for slowing the decomposition of the tissue. The higher strain conditions probably changed the elasticity of the necrosis tissue (or it
Figure 9.15: Stress-strain measurements for the superior and inferior edges in the mid-membranous plane of the fold. Maximum strain values are based on the displacement extracted from the glottal opening area measurements. The data shows the results from L1.
may required longer time to recover). This might explain why the stress measurements taken at the inferior edge have a good match at low strains ($\varepsilon < 20\%$), but a noticeable difference occurs at higher strains.

The non-linearity of the stress-strain data indicates that the Young’s modulus value of the tissue changes in accordance with the strain in the tissue. The higher stress values measured in the inferior edge signifies stiffer tissue composition for this plane. The unloading curves in Figure 9.16 were used to calculated the Young’s modulus of the tissue at the superior and inferior edges based on Eqn. 8.2. For a 65% tissue strain the Young’s modulus at the superior edge was $1.1 \times 10^3$ kPa and $8.9 \times 10^5$ kPa for the inferior edge. The measurement at the inferior edge is within the range reported by Perlman at al. [125]. His measurements show the longitudinal stress (i.e. along the length of the folds) while the current data shows the transverse stress (i.e. perpendicular to the fold).
Chapter 10: Summary - vortical structures during phonation

This work details a new method to measure intraglottal velocity and compute the corresponding pressure distribution. The merit of this work is that intraglottal flow measurements are taken in a full vibrating larynx. The measurement technique and the pressure computations were validated in a mechanical model and using LES. The results shown to be in good agreement with previous LES computations [102] and measurements in excised hemilarynges [124].

The results from five larynges showed that negative pressure values are formed during closing near the superior aspect of the folds. In terms of the magnitude of the negative pressure, there is good agreement with the values found in computational LES models and in excised hemilarynges. The results show that the glottis has no or minimal divergence angle during closing at low subglottal pressures and no or minimal intraglottal negative pressure values were computed. At moderate and high subglottal pressures, the vocal folds formed larger divergence angles, and larger magnitudes of the intraglottal negative pressure were observed.

The flow separation vortices are not stationary and convect out of the glottis within a short period during the closing cycle. The high negative pressure magnitude produced by these vortices can be captured only by phase averaging or by time dependent analysis and is significantly diminished when the pressure is averaged over
the entire cycle. The latter may lead to the conclusion that the pressure near the inferior edge is lower than the pressure near the superior edge, not recognizing that flow separation vortices induced low pressure at the superior edge.

At low subglottal pressure, negative pressure at the superior edge was not observed since the divergence angle of the wall was minimal and the glottal flow did not separate from the wall.
Chapter 11: Continuation of work

11.1 Vortical structures in pulsatile jets

The current work supports the knowledge that behavior of synthetic jets changes as a function of their $St_D$. The interaction and flow characteristics of adjacent synthetic jets was investigated by Smith and Glezer [4, 3], but the $St_D$ numbers of the jets in their study were matched. It is therefore suggested that the flow characteristics and interaction of adjacent synthetic jets having distinct $St_D$ to be investigated in future work.

The concept that synthetic jets are mostly used for flow control applications implies that they often interact with a cross flow. The seminal work of Smith and Glezer [56] looked at the interaction between a synthetic jet and a cross-stream flow and found that the interaction changes as a function of the primary jet Re number. The current work suggests that this interaction can also vary based on the $St_D$ of the primary jet and also based on the orifice configuration of both jets.

A marked characteristic of synthetic jets is their rapid decay, which limits their practicality in flow control applications. It is recommended that future work be focused on mechanisms that enable synthetic jets to be transferred further downstream and increase their overall effectiveness. One such embodiment was developed as a by-product of the current work and submitted for patent (Gutmark et al. [146]).
11.2 Vortical structures during phonation

While the presence of negative pressures produced by the vortices are clearly demonstrated in this work, the role that these negative pressures play in both vocal fold vibration and sound production has not been addressed. Further work is needed to quantify the relative importance of the pressure forces induced by the flow separation vortices. It is recommended that more experimental data for velocity and pressure values be collected to establish conclusions that can be statistically validated. The dynamic displacement of the folds, the tissue elasticity, and the intraglottal pressure data can then be used to build a numerical model that accounts for the differences between the superior and inferior aspects of the vocal folds, and assess the role, if any, that vortical structures play in the closing mechanism of the folds.

The intraglottal velocity measurements were taken after removing all the structures above the folds. The downstream constriction that is elicited by the vocal tract was not introduced in this work. According to the myoelastic-aerodynamic theory, [78] the added inertia to the flow introduced by the tract plays a significant role during closing of the vocal folds. It is also recommended that additional data be collected using a vocal tract model in order to evaluate its impact on the closing mechanism of the folds and the FSV in particular.

Many voice disorders feature structural vocal fold asymmetries, such as a difference in vocal fold left-right position, height, length or stiffness (e.g. unilateral vocal fold paresis and paralysis, vocal fold polyps, vocal fold scarring, etc.). Previous studies have shown that such asymmetries can reduce or eliminate the FSV [147, 81] and suggested that the modification and/or suppression of these vortices contribute to abnormal voice production. It is proposed that intraglottal flow measurements be
taken using the methodology developed in this work. These results can also be used to characterize the effects of vortices and tissue elasticity on vocal fold vibration and acoustics when asymmetries of the vocal fold are present.
Bibliography


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Appendix A: Engineering Drawings
Polynomial profile:

$$Y = -0.00179893092105 \cdot X^6 + 0.01133326480263 \cdot X^5 + 0.01619037828947 \cdot X^4 - 0.15830592105263 \cdot X^3 + 2$$

$X$ is the horizontal dimension. $Y$ is the vertical dimension.

All dimensions are in inch.

Figure A.1: Nozzle drawing
Figure A.2: Plenum chamber. Flow conditioners are contained within.

Figure A.3: Base cover for the plenum chamber. Dimensions are in inch.
Figure A.4: Pressure ports ring. The enclosure is positioned between the nozzle and the plenum chamber. Dimensions are in inch.

Figure A.5: Seeding ports ring. In the current setup the enclosure is between the plenum chamber and the base cover. Dimensions are in inch.
Figure A.6: Ringlet used to mount screens inside the plenum

Figure A.7: Ringlet used to mount the wedge inside the plenum. Same ring was used to mount the honeycombs. Dimensions are in inch.
Figure A.8: Mechanical model of the fold used for pressure validation experiment. The model is designed to be fitted into the nozzle. Dimensions are in inch.

Figure A.9: Customized load cell made by Sensing Systems Corp. All dimensions are in inch.
Figure A.10: Circular orifice plate used for axisymmetric jet

Figure A.11: Slot orifice plate
Figure A.12: Triangular orifice plate

Figure A.13: Back plate of the synthetic jet actuator