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Fluid-Structure Interactions with Flexible and Rigid Bodies

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Fluid-Structure Interactions with Flexible and Rigid Bodies

David Jesse Daily

A dissertation submitted to the faculty of
Brigham Young University
in partial fulfillment of the requirements for the degree of
Doctor of Philosophy

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May 2013

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ABSTRACT

Fluid-Structure Interactions with Flexible and Rigid Bodies

David Jesse Daily
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Doctor of Philosophy

Fluid structure interactions occur to some extent in nearly every type of fluid flow. Understanding how structures interact with fluids and visa-versa is of vital importance in many engineering applications. The purpose of this research is to explore how fluids interact with flexible and rigid structures.

A computational model was used to model the fluid structure interactions of vibrating synthetic vocal folds. The model simulated the coupling of the fluid and solid domains using a fluid-structure interface boundary condition. The fluid domain used a slightly compressible flow solver to allow for the possibility of acoustic coupling with the subglottal geometry and vibration of the vocal fold model. As the subglottis lengthened, the frequency of vibration decreased until a new acoustic mode could form in the subglottis.

Synthetic aperture particle image velocimetry (SAPIV) is a three-dimensional particle tracking technique. SAPIV was used to image the jet of air that emerges from vibrating human vocal folds (glottal jet) during phonation. The three-dimensional reconstruction of the glottal jet found faint evidence of flow characteristics seen in previous research, such as axis-switching, but did not have sufficient resolution to detect small features.

SAPIV was further applied to reconstruct the smaller flow characteristics of the glottal jet of vibrating synthetic vocal folds. Two- and four-layer synthetic vocal fold models were used to determine how the glottal jet from the synthetic models compared to the glottal jet from excised human vocal folds. The two- and four-layer models clearly exhibited axis-switching which has been seen in other 3D analyses of the glottal jet.

Cavitation in a quiescent fluid can break a rigid structure such as a glass bottle. A new cavitation number was derived to include acceleration and pressure head at cavitation onset. A cavitation stick was used to validate the cavitation number by filling it with different depths and hitting the stick to cause fluid cavitation. Acceleration was measured using an accelerometer and cavitation bubbles were detected using a high-speed camera. Cavitation in an accelerating fluid occurred at a cavitation number of 1.

Keywords: Fluid structure interaction, vocal folds, acoustics, SAPIV, cavitation, slightly compressible
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NOMENCLATURE

\( L \)  
Length of the subglottal vocal tract

\( \alpha \)  
Alpha damping coefficient for Rayleigh damping

\( \beta \)  
Beta damping coefficient for Rayleigh damping

\( \rho_m \)  
Compressible fluid density

\( \rho \)  
Fluid density

\( p \)  
Fluid pressure

\( \kappa \)  
Bulk modulus

\( \vec{v} \)  
Fluid velocity

\( \lambda \)  
Acoustic wavelength

\( \psi \)  
Scaling magnification

\( w_1 \)  
Calibration accuracy

\( w_{L1} \)  
Uncertainty band

\( w_{L2} \)  
Image distortion

\( w_{\lambda} \)  
Calibration positioning

\( w_{i1} \)  
Laser jitter

\( w_{i2} \)  
Timing jitter

\( F_D \)  
Force of drag

\( F_B \)  
Force of buoyancy

\( U \)  
Particle terminal velocity

\( \sigma \)  
Standard deviation of sample data

\( \epsilon \)  
Sampling error

\( C \)  
Cavitation number

\( P_{atm} \)  
Atmospheric pressure

\( P_v \)  
Vapor pressure

\( V \)  
Fluid volume

\( A \)  
Area

\( \ddot{a} \)  
Acceleration

\( h \)  
Fluid depth

\( g \)  
Gravity
CHAPTER 1. INTRODUCTION

Fluids interact with structures in virtually every flow situation. Generally speaking, fluid-structure interactions can be categorized as those which occur with either pliable or rigid structures. Fluid-structure interactions (FSI) occur along a continuum between pliable and rigid structures. Understanding how fluids and structures interact is therefore a fundamental necessity in understanding the physics of many engineering and biological applications.

This research will look at fluid-structure interactions for two extremes of flexible and rigid structures, ranging from compliant vocal folds to glass. Understanding how each of these structures couples with their respective flow fields will be investigated to better understand the interplay between the two domains.

Chapter 2: Acoustically-Coupled Flow-Induced Vibration of a Computational Vocal Fold Model

One such flow structure interaction involves the human vocal folds. The vocal folds are multiple layers of tissue within the neck. During speech, the lungs contract and force air past adducted vocal folds to produce sound for speech. As the vocal folds vibrate, a small jet of air exits from in between the vocal folds (the glottis). This jet of air interacts with the structures above the vocal folds (e.g. epiglottis and false vocal folds). The characteristics of this jet (glottal jet) is thought to influence the quality of speech [3] [4].

Computational models of the vocal folds have been used by many researchers to study the fluid structure interactions between the vocal folds and the air from the lungs. These include multi-mass models, rigid-walled computational fluid dynamics (CFD) models of the subglottis, and combined CFD and finite element (FEA) models of the vocal folds. Each of these models have been used to capture different insights into the vibration of the vocal folds, including the opening of the glottal gap, the effects of supraglottal structures, and fluid phenomena visible in the glottal jet, to name a few.
Chapter 2 describes a set of simulations in which a computational model was used to investigate subglottal acoustic coupling with a vibrating vocal fold model. The two-dimensional (2D) model of the subglottis, glottis and vocal fold was used to complement the research done by Zhang et al. [5] who used synthetic silicone vocal folds with a variable subglottal length to experimentally determine the effect of subglottal resonance on the vibration of the vocal folds. Their research found that as the subglottis was lengthened, the frequency of the vocal fold model vibration would gradually decrease and then suddenly increase in frequency when a new subglottal resonance was achieved. The computational model described in Chapter 2 included a fluid domain to model the flowing air in the subglottis coupled to a solid domain that modeled the compliant vocal fold model. The two domains were coupled using an FSI boundary condition that enforced consistent displacement and shear stress along the fluid-solid interface.

Results from the computational vocal fold model showed resonances were formed in the subglottis that were consistent with 1/4-wavelength and 3/4-wavelength resonators. The change from these resonances corresponded to a sudden increase in model vibration frequency demonstrating the direct coupling of the acoustic-fluid-structure nature of the vibrating vocal fold model. These results were consistent with the experimental results obtained by Zhang et al. The model showed that an incompressible fluid domain was incapable of modeling the acoustic coupling of the subglottal acoustics with the vibration of the vocal fold model.

Chapter 3: Three-Dimensional Whole-Field Measurement of a Glottal Jet from Excised Vocal Folds using Synthetic Aperture Particle Image Velocimetry

Chapter 3 utilizes the SAPIV technique to image the glottal jet emanating from excised human vocal folds. This research was done in collaboration with researchers from the University of Erlangen in Erlangen, Germany and with Joey Nielson from Brigham Young University. The glottal jet was seeded by injecting glass microspheres upstream of the vibrating vocal folds. A detailed uncertainty analysis was performed on the SAPIV data.

The SAPIV results showed good agreement with 2D PIV methods, adding credibility to the SAPIV method. The reconstructed flow field of the glottal jet did not clearly exhibit axis-switching which is seen in other studies. It is thought that this phenomenon was not observed due to the noisy nature of time resolved data and because the resolution of the SAPIV data was too low. The results demonstrated the ability of SAPIV to reconstruct the glottal jet in three dimensions but
lacked sufficient resolution to resolve small flow features. This study represents the first whole-field three-dimensional time-resolved reconstruction of the human glottal jet.

**Chapter 4: SAPIV on Synthetic Silicone Vocal Folds**

Chapter 4 illustrates the SAPIV technique being used to image the glottal jet to obtain a three-dimensional profile of the glottal jet emanating from synthetic silicone vocal folds. Two different types of synthetic vocal folds were used to produce the glottal jet. The jet was imaged using eight high-speed cameras to reconstruct the flow field in three dimensions. Comparing the glottal jets between synthetic vocal folds and the glottal jet produced by the excised vocal folds produced quantitative differences between the two vocal folds and tell us if the synthetic vocal folds can accurately reproduce the glottal jet.

The glottal jets from a two-layer and a four-layer vocal fold model were reconstructed. The glottal jets for both vocal fold models were imaged at 500 Hz, which allowed for the first time-resolved, three-dimensional reconstruction of the glottal jet produced by synthetic silicone vocal folds. The resulting data showed clear evidence of axis-switching. The advantages of increased image resolution and particle seeding methods further improved and developed the SAPIV method for vibrating vocal folds.

**Chapter 5: Catastrophic Cracking Courtesy of Quiescent Cavitation**

Chapter 5 transitions from pliable fluid-structure interactions to rigid fluid-structure interactions. Sometimes fluid-structure interactions can cause total structural failure. One example is to refill a glass bottle with water and hit the top of the bottle with an open hand. The bottom of the bottle will suddenly break. High-speed photography shows that the bottle breaks due to cavitation. However, currently there are no non dimensional numbers that can accurately predict the onset of cavitation in this accelerating fluid scenario.

Chapter 5 explores the events leading up to the bottle breaking and derives a non dimensional cavitation number that defines the relationship between cavitation onset and fluid depth. The cavitation number suggests the acceleration needed for cavitation decreases with increasing fluid depth. The cavitation number was validated experimentally using an acrylic cavitation stick that could be filled with different levels of distilled water with various free surface pressures. The acceleration of the cavitation stick was measured using an accelerometer and a high-speed camera was used to look for formation of cavitation bubbles.
The data taken from the cavitation stick verify the cavitation number and show that cavitation onset occurs at lower accelerations for deeper fluid depths. Additional data obtained using glass bottles show that as the cavitation bubbles grow, the acceleration of the bottle decreases and as the bubbles collapse, the bottle breaks. These data yielded improved understanding of the interplay between the potential energy stored in the bubbles and the kinetic energy in the accelerating bottles.

The purpose of this research was to better understand the interactions between fluids and structures in these applications. To that end, the author hopes that the topics of vocal fold vibration and cavitation will shed light to the reader of the importance of considering the influence of whatever structure is present in a fluid flow.
CHAPTER 2. ACOUSTICALLY-COUPLED FLOW-INDUCED VIBRATION OF A COMPUTATIONAL VOCAL FOLD MODEL

2.1 Introduction

Numerous research studies have been performed to improve our understanding of the physics of human voice production. Many studies have focused on the flow-induced vibration of the vocal folds, a central component of sound production during voiced speech.

The vocal folds are a pair of opposing multi-layer tissue bodies located within the larynx (see Fig. 2.1). Deep within the fold is a muscle layer, which is lined with lamina propria tissue. The lamina propria includes deep, intermediate, and superficial tissue layers that generally progressively become less stiff towards the vocal fold surface. The epithelium is the most superficial layer and consists of a thin (about 50 µm thick) layer of cells. These tissue layers are often grouped into three different structures: body (muscle), ligament (deep and intermediate lamina propria layers), and cover (superficial lamina propria and epithelium) [6].

The space between opposing vocal folds is called the glottis. The regions below and above the glottis are the subglottis and supraglottis, respectively. During voiced speech, forced air from the lungs interacts with adducted vocal folds to initiate flow-induced vocal fold vibration. This creates a fluctuating pressure field in the supraglottis that is the source of sound during voicing.

With the primary aim of improving voice disorder prevention, diagnosis, and treatment, computational and experimental models have been used to study the coupled fluid dynamics, tissue dynamics, and acoustics of voice production. One of the first computer simulations of vocal fold vibration was the two-mass model [7], in which the vocal folds were each represented by two masses interconnected by springs and dampers. This model and subsequent variations [8] [9] were simple and generated output variables that were similar to those that had been measured in

---

human voice production, and were thus helpful in gaining initial insight into the mechanics of voice production.

More recently, two- and three-dimensional finite element and finite volume models have been used to simulate vocal fold vibration [10]. For example, Berry and Titze [11] approximated the vocal folds as two-dimensional parallelepipeds with mechanical properties based on human vocal fold tissue data. The \textit{in vacuo} responses of these models were then analyzed to determine their eigenvalues and eigenfrequencies. A three-dimensional model with realistic vocal fold geometry, multiple layers of material with different properties, and a flow-induced vibratory response was described by Alipour et al. [12]. A three-dimensional model by Rosa et al. [13] simulated vocal fold flow-induced vibration and included the ventricular folds. This model also included three different material properties to simulate the muscle, ligament, and cover layers.
Computational models have been used to better understand the mechanics, acoustics, and fluid dynamics of the larynx and vocal tract. These models have included simple, reduced-order models [7] and more elaborate Finite Element (FE) and Computational Fluid Dynamics (CFD) models. The latter have typically incorporated incompressible flow models for computational efficiency. Since the vocal tract contains an acoustic flow of propagating pressure waves, the incompressible assumption is clearly limiting. Algorithms exist which combine the ability to model compressible flows while still being sufficiently stable to converge if the Mach number is less than 0.3 [14]. These “slightly compressible” algorithms have been used in other fields of study. The purpose of this paper is to report the use of a slightly compressible flow model in simulating the flow induced vibration of synthetic human vocal folds.

Experimental vocal fold models have also been used to study coupled flow-solid-acoustic interactions that are important in voice production. Included in this category are life-size, self-oscillating synthetic models [1] [15] fabricated from silicone rubber materials. These models have been used to conduct parametric studies involving factors such as geometry and material properties. With particular relevance to the present work, Zhang et al. [5] showed that the flow-induced vibration of one synthetic model was acoustically coupled with the subglottal (upstream) flow supply tube. The experimental setup consisted of a flow source connected to an expansion chamber, followed by a subglottal tube of adjustable length. At the downstream end of the subglottal tube was a synthetic silicone model simulating the human vocal folds. The model vibration frequency was recorded for different subglottal tube lengths ranging from 25 cm to 400 cm. The frequency of vibration decreased from 220 Hz to 150 Hz as the subglottal tube was lengthened from 25 cm to 80 cm. At approximately 140 cm, the vibration frequency suddenly increased to 225 Hz and then gradually decreased to 160 Hz at a subglottal tube length of 170 cm. This pattern of generally decreasing frequency with increasing length, but with abrupt increases in frequency at certain lengths, repeated up to 350 Hz. This pattern was attributed to acoustic coupling of the model vibration with the subglottal tube acoustic resonances. This has also been termed “acoustically-driven” vibration [16] [17].

Because acoustic coupling has been shown to play a central role in governing the vocal fold models response, the purpose of the research described in this paper was to develop a complementary computational model that could be used to further characterize and explore the flow-induced
vibratory responses of this and future models. An important part of the development of the com-
putational model was to demonstrate that the model adequately captured the acoustic coupling
seen in experiments [5] [17]. This was accomplished by creating a two-dimensional finite element
model that featured fully-coupled fluid and solid domains. The effects of pressure and velocity
boundary conditions are also compared to determine which boundary condition is most physically
realistic. Results from simulations with incompressible and slightly compressible flow models
were compared. In the following sections, the numerical methods and results are presented, and
it is shown that the slightly compressible model yielded results comparable with the experimental
results of Zhang et al. [5]. Subglottal acoustic wave patterns are presented and the influence of
subglottal acoustics on model vibration frequency are discussed. Recommendations regarding the
use of slightly compressible flow models in vocal fold modeling are then given.

2.2 Methods

2.2.1 Computational Model

The computational model setup was patterned after the experimental setups of Thomson et
al. [1] and Zhang et al. [5]. The Thomson et al. [1] setup (see Fig. 2.2) consisted of a compressed
air supply that fed into a plenum, followed by a tube simulating the subglottal tracheal section, and
a synthetic vocal fold model mounted at the end of the tube. The Zhang et al. [5] setup was similar,
but with a subglottal tube of adjustable length, $L$. In this study the commercial finite element
software code ADINA was used to simulate the flow-induced vibration of a vocal fold model for
difference subglottal tube lengths. The model included distinct but fully-coupled two-dimensional
solid and fluid domains, details of which are given in Sections 2.2.2 and 2.2.3.

The ADINA codes were run on the Fulton Supercomputer at Brigham Young University.
All codes were run in batch processing using a unix script file called AdinaRun.sh (see Appendix
A.0.1). The script file called for four processors on a single node with 2 GB of memory on each
processor to run the simulation. A wall-time of 50 hours was prescribed for each simulation run to
accommodate simulation times that ranged from 30-45 hours. Each model was run for 15,000 time
steps with a time step of $1.25 \times 10^{-5}$ sec (see Sec. 2.2.3). The AdinaRun.sh file then called the
Figure 2.2: Experimental setup of the airway used by Thomson et al. [1], including a compressed air source, a plenum, and a “tracheal” tube which led to a synthetic, self-oscillating silicone vocal fold model.

ADINA codes for the simulation and ran all of the post processing codes (see Appendices A.0.5, A.0.6).

Both the fluid and solid domains were programmed to be parametric using a single parameter file (called parameter.in, see Appendix A.0.2). The parameter file was called to generate both the fluid and solid domains. The parameters in this file included vocal fold geometry, grid meshing, time step control, boundary conditions, damping ratios and importantly the length of the vocal tract. This file allowed the user to modify both the fluid and solid domains of the model by altering parameters in a single file.

2.2.2 Solid Domain

The solid domain (see Fig. 2.3) included two layers of different material properties to simulate the “body-cover” tissue layers of the human vocal folds [18]. The cover was 2 mm thick. Note
that the synthetic, self-oscillating vocal fold models of Thomson et al. [1] and Zhang et al. [5] were one-layer (i.e., homogeneous) models; however, it has been shown that two-layer models exhibit similar acoustic coupling as one-layer models [15]. For computational efficiency, only one vocal fold was modeled using prescribed symmetry.

A hyperelastic Ogden material model [19] was used to allow for large strain. Linear stress-strain curves were used to define the equivalent Young's modulus values of 15 kPa and 5 kPa for the body and cover layers, respectively. These are similar to the corresponding values of other previously-studied two-layer synthetic (silicone) vocal fold models [3] [15]. The density, Poisson's ratio, and bulk modulus values of both layers were 1070 kg/m$^3$, 0.49, and $1 \times 10^5$ Pa, respectively. Damping was simulated using a Rayleigh damping scheme with coefficients $\alpha = 24.19$ and $\beta = 1.27 \times 10^{-4}$, corresponding to damping ratios of about 6% at the solid models first two in vacuo modal frequencies of 46.5 Hz and 103.5 Hz.

The solid domain was meshed with 4710 three-node triangular elements (see Fig. 2.4). All solid domain elements were mixed interpolated elements that interpolate the pressure and displacement separately. Boundary conditions for the solid domain were as follows. The wetted perimeter was treated as a fluid-structure interaction (FSI) boundary, which enforced consistent fluid and solid displacements and stresses along the fluid-solid interface. A zero-displacement boundary condition was applied to the non-wetted lateral edge of the model to simulate fixed mounting of the synthetic model. As shown in Fig. 2.3, a contact line was defined in the solid domain to limit
the model medial motion and prevent complete collapse of the fluid domain mesh. This contact line was placed 75 µm from the fluid domain symmetry line (described below). Previous studies have shown that a contact line 50 µm from the slip plane gives reasonably accurate results [20] [21]. However, due to the large displacements caused by resonance (see Section 2.3.3) a larger gap was chosen to make the model more stable.

The solid domain was generated using an ADINA command file called s.in (see Appendix A.0.4). The s.in command file referenced the parameter file parameter.in (see Appendix A.0.2) to generate the solid domain of the model such as the basic geometry of the vocal fold, the solid domain mesh, model boundary conditions, and vocal fold model stiffness parameters.

2.2.3 Fluid Domain

The fluid domain (Fig. 2.5) was governed by the two-dimensional, unsteady, laminar Navier-Stokes equations. The working fluid was defined to be air with a density of 1.21 kg/m³, a viscosity of $1.79 \times 10^5$ N s/m², and a bulk modulus of $1.41 \times 10^5$ Pa. The initial distance between the symmetry line and the nearest point on the vocal fold was 0.1 mm, for an effective initial pre-vibratory glottal gap of 0.2 mm. All elements in the fluid domain were mixed elements [22] [23] [24]. A
Figure 2.5: Outline of the two-dimensional computational fluid domain (not to scale). Assuming symmetry, only half of the airway was modeled, as shown.

A constant, uniform pressure of 900 Pa was applied at the inlet. This pressure was chosen from experimental observations of onset pressure from synthetic silicone vocal folds [15].

Table 2.1: Computational domain dimensions and boundary conditions.

<table>
<thead>
<tr>
<th>Line Segment</th>
<th>Length (m)</th>
<th>Boundary Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>AB</td>
<td>0.308</td>
<td>Wall</td>
</tr>
<tr>
<td>BC</td>
<td>0.14944</td>
<td>Wall</td>
</tr>
<tr>
<td>CD</td>
<td>$L = 0.1$ to $3.0$</td>
<td>Wall</td>
</tr>
<tr>
<td>DE</td>
<td>0.0042</td>
<td>Wall</td>
</tr>
<tr>
<td>EF</td>
<td>0.011</td>
<td>FSI</td>
</tr>
<tr>
<td>FG</td>
<td>0.0021</td>
<td>FSI</td>
</tr>
<tr>
<td>GH</td>
<td>0.0085</td>
<td>FSI</td>
</tr>
<tr>
<td>HI</td>
<td>0.1536</td>
<td>Wall</td>
</tr>
<tr>
<td>IJ</td>
<td>0.1</td>
<td>Zero Pressure</td>
</tr>
<tr>
<td>JK</td>
<td>0.1507</td>
<td>Zero Pressure</td>
</tr>
<tr>
<td>KM</td>
<td>$L + 0.1107$</td>
<td>Slip Wall</td>
</tr>
<tr>
<td>MN</td>
<td>0.308</td>
<td>Slip Wall</td>
</tr>
<tr>
<td>AN</td>
<td>0.1507</td>
<td>900 Pa Pressure</td>
</tr>
<tr>
<td>EH</td>
<td>0.0107</td>
<td>Fixed (Solid Domain)</td>
</tr>
</tbody>
</table>
The fluid domain dimensions are given in Table 2.1. In the Zhang et al. [5] experiments, the flow supply tube (one wall of which is represented by line CD in Fig. 2.5) had a cross-sectional area of \(5.06 \text{ cm}^2\), while the expansion chamber cross section measured \(23.5 \text{ cm} \times 25.4 \text{ cm}\), for a cross-sectional area of \(596.9 \text{ cm}^2\). The area ratio between the cross section of the flow supply tube and that of the expansion chamber is important because large area ratios cause strong acoustic reflections. The ratio of the areas of the expansion chamber to the flow supply tube in the Zhang et al. [5] experiments was 117.96. Because the computational model in this study was two-dimensional, line BC (Fig. 2.5) was lengthened to create the same area change as found in the experiments. To explore the influence of changing subglottal duct length on model vibration frequency, the length of line CD (Fig. 2.5), here denoted \(L\), was varied from 40 cm to 150 cm in 10 cm increments and from 160 cm to 300 cm in 20 cm increments.

The Mach number of the glottal jet in these simulations was on the order of 0.1. However, an incompressible flow model was not thought to be appropriate because of the previous experimentally-observed significance of acoustic effects, i.e., fluid compressibility associated with acoustic wave propagation but not high velocities. To model acoustic compressibility effects, a slightly compressible solver [25] [26] was used. While it may have been desirable to also compare the results with those obtained using a fully-compressible flow solver, convergence difficulties at this low Mach number were encountered when using a compressible flow solver. The compressible continuity and incompressible Navier-Stokes equations that govern unsteady, viscous, incompressible flow in the absence of body forces are, respectively:

\[
\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{v}) = 0, \tag{2.1}
\]
\[
\rho \left( \frac{\partial \vec{v}}{\partial t} + \vec{v} \cdot \nabla \vec{v} \right) = -\nabla p + \mu \nabla^2 \vec{v}, \tag{2.2}
\]

where \(\rho\) is the constant (incompressible) fluid density, \(\vec{v}\) is the velocity vector, \(t\) is time, \(p\) is pressure, and \(\mu\) is viscosity. In the slightly compressible flow solver formulation, a compressible density, \(\rho_m\), is defined as [26]

\[
\rho_m = \rho \left(1 + \frac{p}{\kappa}\right), \tag{2.3}
\]
where $\kappa$ is the fluid bulk modulus. Inserting Eq. (2.3) into the continuity Eq. (5.5) yields

$$\frac{\partial \rho_m}{\partial t} + \vec{v} \cdot \nabla \rho_m + \rho_m \nabla \cdot \vec{v} = 0. \tag{2.4}$$

Equation (2.4) can be written as

$$\frac{\rho}{\kappa} \left( \frac{\partial p}{\partial t} + \vec{v} \cdot \nabla p \right) + \rho_m \nabla \cdot \vec{v} = 0. \tag{2.5}$$

Use of this form of the continuity equation allows for density variation but without the need to solve the energy equation, often leading to more readily attainable convergence. The compressible density term is used in the continuity equation but not the momentum equations, which is a reasonable approximation as long as $p/\kappa \ll 1$ [26]. For air with $\kappa = 1.41 \times 10^5$ Pa, this corresponds to a maximum allowable pressure of less than about 14 kPa. In these simulations the maximum pressure was approximately 4 kPa, satisfying this $p/\kappa \ll 1$ requirement. Note that while the slightly compressible model was expected (and found) to yield the desired model response that compared well with experimental observations, simulations with an incompressible flow solver were also performed for comparison and are discussed in Sec. 2.3.2.

The fluid domain was created using the ADINA command file f.in (see Appendix A.0.3). This file referenced the parameter.in file to ensure the vocal fold geometry between the fluid and solid domains was consistent. The f.in file was responsible for generating the geometry of the subglottis, meshing the fluid domain, assigning a slightly compressible solver to the domain and assigning boundary conditions to the model.

### 2.2.4 Post Processing

While ADINA was used to solve the fluid and solid domain interactions of the vocal folds, the results were post processed in Ensight (CEI Software, NC). Ensight was chosen because it was more flexible and powerful at extracting complex data from CFD analyses. The results from ADINA were formatted to Ensight readable files in the f.in file with the command ‘ENSIGHT=FORMATTED’ (see Appendix A.0.3). This would cause .ens and .case files to be generated that could be read by Ensight.
Ensight has the ability to be controlled by either a command file (.enc file) or a Python api file. Two files were made in Ensight to post process the ADINA data. The first file was the iterate_Ensight.py file (see Appendix A.0.5). This file is a Python script that calculated the pressure along the slip wall of the model. The Python script does four things: 1) loads the .case file (called f.case) which in turn loads all of the .ens files, 2) changes the perspective of the CFD data (defunct for batch processing, but useful when debugging), 3) inserts a line tool that monitors pressure in the fluid domain along the slip wall, and 4) iterates in time and writes the pressure results to an output.txt file.

The iterate_Ensight.py file recorded the pressure along a line that was located at (0, \(-L - 0.3, 0.00849\)) to (0, 0.1, 0.00849). Five hundred data points were recorded along the line at equally spaced intervals for each time step. To reduce the amount of data for each run, only every fifth time step was processed from the time steps 800 to 1495. This reduction in post processed data sped up the computation time, and decreased the amount of output files without noticeably reducing the resolution of the data.

Glottal_Gap.enc is an Ensight command file that was generated by Ensight (see Appendix A.0.6). The file determined the minimum glottal gap by measuring the maximum height of the FSI surface (Coordinates[Z]). The maximum height was subtracted from the height of the glottis (0.0085) and multiplied by two to account for the other vocal fold. The file wrote a text file of glottal gap vs. time. The Glottal_Gap.enc file only generated one output text file per data set.

2.2.5 Verification

Model verification was performed by refining grid and time step sizes. All verification studies were conducted with a subglottal length of \(L = 60\) cm. Waveforms of glottal width (defined as twice the distance between the symmetry line and the closest point on the vocal fold model) were used to determine time step and grid size independence. Time steps of \(2.5 \times 10^{-5}\) s, \(1.25 \times 10^{-5}\) s, and \(6.25 \times 10^{-6}\) s were tested; \(1.25 \times 10^{-5}\) s was determined to be suitable. Grids with 9,696, 37,043, and 145,629 linear elements in the fluid domain were tested. The grid with 37,043 elements (37,740 nodes) was selected as it yielded a waveform determined to be suitably similar to that of the refined grid (see Fig. 2.6 and Table 2.2).
Figure 2.6: Glottal width waveforms for time/grid model verification. The left column of the figure shows verification for the time step verification for the glottal width, pressure and velocity vs. time for three different time step sizes. (···) $2.5 \times 10^{-5}$ s; (- - -) $1.25 \times 10^{-5}$ s; (-) $6.25 \times 10^{-6}$ s. The right column of the figure shows verification for the grid size with the glottal width, pressure and velocity vs. time for three different fluid domain grid densities. (—) 9,696 elements; (- - -) 37,034 elements; (···) 145,629 elements.
Table 2.2: The frequency and amplitude of vocal fold vibration were compared to determine if the model was grid and time step independent. A time step of $1.25 \times 10^{-5}$ and a grid with 37,034 elements were chosen since they model experiences only minor variation with finer time steps and grid sizes.

<table>
<thead>
<tr>
<th>Case</th>
<th>Frequency (Hz)</th>
<th>Max Glottal Width (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$2.5 \times 10^{-5}$ s $\Delta t$, 37,034 elements</td>
<td>105.263</td>
<td>$1.76 \times 10^{-3}$</td>
</tr>
<tr>
<td>$1.25 \times 10^{-5}$ s $\Delta t$, 37,034 elements</td>
<td>105.263</td>
<td>$1.80 \times 10^{-3}$</td>
</tr>
<tr>
<td>$6.125 \times 10^{-6}$ s $\Delta t$, 37,034 elements</td>
<td>105.263</td>
<td>$1.82 \times 10^{-3}$</td>
</tr>
<tr>
<td>$1.25 \times 10^{-5}$ s $\Delta t$, 9,969 elements</td>
<td>100</td>
<td>$1.79 \times 10^{-3}$</td>
</tr>
<tr>
<td>$1.25 \times 10^{-5}$ s $\Delta t$, 37,034 elements</td>
<td>105.263</td>
<td>$1.76 \times 10^{-3}$</td>
</tr>
<tr>
<td>$1.25 \times 10^{-5}$ s $\Delta t$, 145,629 elements</td>
<td>107.527</td>
<td>$1.81 \times 10^{-3}$</td>
</tr>
</tbody>
</table>

2.3 Results and Discussion

2.3.1 Slightly Compressible Model Response

Figure 2.7: Vocal fold model positions at several phases of one cycle of vibration for a 60 cm subglottal length. Simulation time between consecutive images is 1.25 ms.
Figure 2.7 shows the solid domain outline at six instances of a typical vibration cycle with a slightly compressible flow model and $L = 60$ cm. The model motion is qualitatively similar to that which has been reported in other experiments using one-layer [1] and two-layer [3] [15] models. Reasonable quantitative agreement was also observed. During vibration, the model attained a maximum glottal width of around 1.5 to 3 mm, depending on subglottal length, which compares favorably with the maximum glottal width produced by the model of Thomson et al. [1] of about 2 mm. As in section 2.3.3, the model frequency, which was a function of subglottal length, was also in the range of theoretical and experimental predictions.

2.3.2 Slightly Compressible vs. Incompressible Flow Models

![Graph of Glottal Width vs. Time](image)

Figure 2.8: Glottal width vs. time for slightly compressible (---) and incompressible (···) flow models, each with $L = 50$ cm.

Predicted model vibrations were compared for incompressible and slightly compressible flow models using $L = 50$ cm. The glottal width waveforms yielded by the two models are shown in Fig. 2.8. For the slightly compressible case, the model exhibited an initial “dwell time” during which the pressure wave traveled downstream along the subglottis before interacting with the vocal
fold model. This was followed by a transient vibratory phase, followed by steady-state, self-sustained vibration. In contrast, for this subglottal length, the incompressible model only yielded transient vibration before decaying, and immediately after time $t = 0$ the pressure field caused deformation of the vocal fold model.

Figure 2.9 shows the pressure along the subglottal symmetry line (line NMK, Fig. 2.5), from the pressure inlet to 10 cm downstream of the vocal fold model, as a function of time predicted by the incompressible flow solver. Note that the location of 0 cm in the distance axis corresponds to the streamwise location of point E in Fig. 2.5. With $L = 50$ cm the model did not self-oscillate and no standing waves were formed in the subglottis. With $L = 100$ cm the model self-oscillated and periodic sharp rises in pressure are seen to have formed in the subglottis. The pressure spatially increased linearly from the inlet pressure (900 Pa) at the subglottal entrance, and the peak pressure was always located at the end of the subglottis near the vocal fold model and occurred near times of glottal width closing. Similar behavior was observed for the $L = 150$ cm and $L = 300$ cm cases. The model frequencies for the three vibrating cases were 108 Hz, 111 Hz, and 108 Hz for
subglottal lengths of 100, 150, and 300 cm, respectively, indicating near-independence of model vibration frequency with subglottal length. Thus while this model did vibrate for some values of $L$, the results are not consistent with expected frequency vs. $L$ variations based on the previous experimental results of Thomson et al. [1] and Zhang et al. [5]. Further, the subglottal pressure fields are not consistent with expectations based on acoustic wave propagation theory (discussed below).

2.3.3 Subglottal Acoustic Coupling in Slightly Compressible Flow Model

By contrast, the slightly compressible flow model yielded solid model responses and subglottal pressure fields that are consistent with experimental results and analytical predictions. As with the incompressible model results, the pressure was monitored along the fluid domain symmetry line at several phases over several steady-state vibration cycles. Figure 2.10 shows the pressure along the subglottal symmetry line as a function of time predicted by the slightly compressible flow model simulations.

Figure 2.10: Pressure along the symmetry line over time for $L = 50$ cm, 100 cm, 150 cm, and 300 cm subglottal lengths from the slightly compressible flow model simulations.
Figure 2.11: Pressure along the symmetry line over a single steady-state vibration cycle from the slightly compressible flow model simulations for several subglottal lengths.
flow solver. Pressure results at different phases superimposed on each other are shown in Fig. 2.11 for duct lengths ranging from $L = 40$ cm to $L = 300$ cm. For the models that vibrated, the pressure at the subglottis inlet was 900 Pa, and along the subglottal length, the pressure oscillated about a mean value of approximately 900 Pa.

The model failed to self-oscillate with $L \leq 40$ cm. This is consistent with the report of Zhang et al. [5] that their model did not vibrate with $L \leq 40$ cm. With $L = 50$ cm a standing wave formed within the subglottis during self-sustained model oscillation. The shape of the standing wave suggests that the subglottis somewhat resembled that of a resonating duct with a rigid termination. It is noted, however, that during vibration, the vocal fold model was opening and closing, such that the effective acoustic termination boundary was changing over time. With subglottal lengths around 80 cm, the standing wave resembled that of the first mode of a 1/4-wavelength resonator. As $L$ increased from 100 cm to 160 cm, the standing wave shape was similar to that at $L = 80$ cm, but with increasingly different fluctuations. With $L = 220$ cm a 3/4-wavelength mode was beginning to form, and around $L = 260$ cm this mode was clearly visible and evidenced by presence of a pressure node. This pattern persisted through the $L = 300$ cm case.

Figure 2.12 shows the model vibration frequency vs. subglottal length. Also shown are measured data from Zhang et al. [16]. The solid and dashed lines in the main figure are the analytical solutions for 1/4- and 3/4-wavelength resonators, respectively, found using the relationship $f = c/\lambda$ where $f$ is the frequency, $c$ is the speed of sound (343 m/s), and $\lambda$ is the wavelength. For a 1/4-wavelength resonator, $\lambda = 4L$ and for a 3/4-wavelength resonator, $\lambda = 4L/3$. The smaller graphs inlaid into Fig. 2.12 show the approximate maximum (solid lines) and minimum (dotted lines) pressure waveforms along the subglottis (similar to the waveforms in Fig. 2.11).

The computational model frequencies generally (but not precisely) follow the resonator frequency curves. The difference between computational and analytical predictions is likely attributable to the resonator curves being based on the assumption of a rigid termination. Importantly, the slightly compressible model vibration frequency jump decreases with increasing subglottal length, with a jump from about 56 Hz to 94 Hz when the length changes from $L = 220$ cm to $L = 260$ cm. (It is noted that the 240 cm case experienced erratic vibration that caused the model to fail due to excessive mesh deformation before it reached steady-state vibration; hence no data
Figure 2.12: Frequency of vibration vs. subglottal length, $L$. (+) computational results; (□) experimental results from Zhang et al. [5]; (−) analytical result for a 1/4-wavelength resonator; (−−−) analytical result for a 3/4-wavelength resonator. Inlaid graphs show pressures predicted from the computational model along the symmetry line at selected subglottal lengths.

point is shown for the 240 cm case.) As can be seen in Fig. 2.11 and in the inlaid graphs in Fig. 2.12, this jump occurs as the second acoustic mode forms.

Similar to the computational model, the vocal fold models in the experiments from Zhang et al. [5] also generally followed the predicted resonator frequencies, although at a higher overall frequency. A jump in frequency is also seen, although it occurred at a different subglottal length. The higher frequency of the experimental model is likely a result of different material properties and the increased effective stiffness of the experimental models. Regarding the latter, the computational models were two-dimensional, whereas the experimental models possessed a finite length of approximately 1.7 cm and were rigidly fixed at their ends. Consequently, the effective stiffness of the two-dimensional model was lower than that of the synthetic model. Notwithstanding these differences in frequency magnitudes, these results show the ability of the slightly compressible
flow model to capture (1) the subglottal acoustics and (2) the acoustic coupling between subglottal acoustics and model vibration in a manner consistent with experimental observations and expectations based on acoustic resonance theory. For this vocal fold model, this acoustic coupling is a critical governing factor of model self-oscillation.

2.4 Conclusions

The slightly compressible model demonstrated the ability to predict the effects of subglottal acoustics that have been previously seen in experimental studies. As the computational model vibrated, standing pressure waves were seen in the subglottis for certain lengths. As the subglottal length increased, the flow-induced vibration frequency changed, and the standing pressure waves changed from approximately following a 1/4-wavelength resonator pattern to that of a 3/4-wavelength resonator. The results also show how this coupling is related to the subglottal acoustic modes. The incompressible flow model did not produce results that were consistent with experiment or theory.

A few suggestions for further development and testing of this model are recommended. First, the model was only two-dimensional, such that anterior-posterior rigid boundaries could not be modeled. Including these boundaries in a three-dimensional model would increase the model effective stiffness. Second, the model did not include supraglottal structures, such as the vocal tract or the false vocal folds. This was done to match the published experimental setup [1] [5]; however, including these structures in future work would allow for exploration of possible acoustic coupling with the supraglottis.
CHAPTER 3. THREE-DIMENSIONAL WHOLE-FIELD MEASUREMENT OF A GLOTTAL JET EMANATING FROM EXCISED VOCAL FOLDS USING SYNTHETIC APERTURE PARTICLE IMAGE VELOCIMETRY

3.1 Introduction

The previous chapter investigated the fluid-acoustic-structure interaction of the vibrating vocal folds using a computational model of the vocal fold model. This chapter leaves computational fluid dynamics and uses experimental techniques to visualize the glottal jet formed by excised vocal folds.

During speech, the lungs contract and cause air to flow between the vocal folds. The air flowing between the vocal folds causes the folds to vibrate and produce sound. As the vocal folds vibrate, they produce a pulsatile jet (glottal jet) that interacts with the throat and mouth (supraglottis). It is thought that the formation of the glottal jet affects the quality of speech.

The location of the human vocal folds within the larynx makes it difficult to characterize the nature of the glottal jet. Consequently, excised human larynges are often used, in which case the tissues above the vocal folds are removed to expose the glottal jet for measurement. A common experimental method for quantifying the glottal jet is particle image velocimetry.

Drechsel et al. [15] used particle image velocimetry (PIV) on the pulsatile air jet emanating from a silicone vocal fold model. Their 2D-PIV data showed several flow characteristics of the glottal jet including vortex structures, intraglottal flow separation, and glottal jet skewing. Triep et al. [27] performed multiple 2D-PIV passes on a cam-driven vocal fold model in a water tunnel. This allowed them to reconstruct the three-dimensional flow field of the glottal jet. They showed that the elliptical orifice of the vocal folds created a jet that exhibited axis switching. However, since multiple 2D-PIV passes were needed to reconstruct the flow field, they were unable to obtain time resolved whole-field measurements of the velocity field.
Krebs et al. [28] used stereoscopic PIV (SPIV) to image a glottal jet in three dimensions. Their setup used self-oscillating silicone vocal folds. The flow was illuminated with a laser sheet that was swept through the field of interest. This technique yielded three-dimensional flow field data, phase locked with the vocal fold model vibration. Krebs et al. were therefore unable to obtain time-resolved whole field three-dimensional flow field measurements.

Whole-field, time-resolved measurements of the glottal jet would be a significant advancement in reconstructing the glottal jet and understanding how the glottal jet is formed by the vocal folds. Several methods exist that use multiple cameras to track seed particles in three dimensions. A few recent examples are provided here.

Pereira et al. [29] developed a PIV method called defocused digital particle image velocimetry (DDPIV). DDPIV uses an array of three cameras arranged in a planar equilateral triangle. In this formation, the resulting overlapping image space forms a tetrahedral volume. By observing blur patterns on the CCD chip of a camera, seed particles within this volume can be tracked in three dimensions.

Elsinga et al. [30] developed a different algorithm for recovering three-dimensional velocity data using a method called tomographic PIV. Tomographic PIV typically uses an array of four cameras to observe a fluid flow from different perspectives. Each camera captures pixel intensities that relate to voxel intensities through a weighting coefficient. This method yielded three-dimensional data capable of very high seeding densities (0.05 particles per pixel). Unfortunately, background light and noise strongly influenced the fundamental algorithms. Furthermore, as particle density increased, the tomographic PIV algorithm would find false ghost particles that had to be filtered out.

Holographic PIV (HPIV) is a technique that used the principle of constructive/destructive interference of light to reconstruct a three-dimensional flow field [31]. In holographic PIV, a coherent light source (laser) illuminates seed particles in a flow. The illuminated particles expose a light sensitive device (i.e. photographic film or high density CCD camera). A second coherent light source was placed such that the light interfered with the scattered light impinging on the photoreceptor. The waves from the reference light and scattered light superimposed to create constructive/destructive interference aberrations. These aberrations could be used to recover depth information of the scattered light from the particles, and therefore the depth of the particle itself.
However, HPIV required high-resolution photoreceptors making traditional film the ideal choice for measuring the aberrations, rather than digital techniques.

Synthetic aperture particle image velocimetry (SAPIV) uses an array of high-speed cameras to artificially create a single camera with a variable focal length [32]. This is accomplished by overlapping the images from all the cameras to form a refocused “focal stack.” As the images are overlapped more, a more distant image plane comes into focus. The focal stack is then used to construct a three-dimensional particle volume. 3D-PIV is then performed on the particle volume to reconstruct the flow field. SAPIV has the ability to capture whole-field three-dimensional time-resolved data of a flow field even in the presence of very high particle seeding densities (0.13 particles per pixel).

The purpose of this research was to demonstrate the use of SAPIV to quantify the three-dimensional velocity field of the glottal jet emanating from excised human vocal folds. The results will be compared and validated against traditional 2D PIV techniques.

3.2 Methods

The process of performing SAPIV on excised vocal folds can be broken down into three main steps: the experimental setup, data acquisition and post processing. The following sections cover the basic theory of SAPIV, but does not give an in-depth theoretical development of the techniques, see [32].

3.2.1 Experimental Setup

Excised vocal folds were first prepared by removing excess tissue above the vocal folds (see Fig. 3.2). The larynx was then mounted on a 16 mm diameter stainless steel pipe and sealed with a hose clamp. The pipe was connected to a pressurized air supply. Tension was applied to the vocal folds by embedding prongs into the arytenoid cartilage that could be rotated for increased or decreased tension on the vocal folds (see [33] for details).

The laser used in this experiment was a Darwin-Duo neodymium-doped yttrium lithium fluoride (Nd:YLF) laser from Quantronix (Setauket, NY). The laser was set to fire two 30 mJ pulses at 1 kHz. The laser produced a 527 nm beam with a pulse width of 3 to 5 ns. The laser was
double pulsed with a Δt of 10 µs between the first and second laser pulses. This time delay was chosen to allow the particles to move several pixels for the cross correlation algorithm to track the particles.

The fluid flow was seeded with helium-filled glass microspheres (Expancel, Sundsvall Sweden, product number 461 DE 40 d25). The microspheres had an average diameter of 45 µm with a density of 25 kg/m³. The glass microspheres were chosen because they were large enough to be seen by the cameras while still following the flow of the jet with minimal momentum effects from the mass of the spheres (see section 3.3.1).

### 3.2.2 Data Acquisition

An array of eight Photron SA3 Fastcam cameras were used to image the cloud of microspheres exiting the glottal gap between the vocal folds. The cameras imaged the flow field at 2000 fps with a resolution of 640 × 640 pixels. Each camera was fitted with a fixed focal length 105 mm Sigma lens (model number: 258205). The cameras were synchronized with the laser using a digital delay/pulse generator (BNC, model 575). The lasers were triggered with a 1 kHz pulses. A manual trigger was used to start all of the cameras recording at once.

A camera rig was made for mounting the eight cameras in front of the vocal fold setup (see Fig. 3.1). The rig was made from extruded aluminum (80/20, Columbia City, IN) to allow the entire rig to be adjusted. The rig was bolted to an optics table to keep it stationary throughout the experiment. The cameras were mounted on the rig in two rows of four. The four lower cameras were at roughly the same elevation as the vocal folds while four cameras were mounted looking down on the vocal folds from an angle of approximately 35°.

### 3.2.3 Data Processing

The data processing can be divided into four main steps: calibration, homography calculation, image overlap, and 3D-PIV.

**Calibration:** The cameras were calibrated using a technique that allowed all eight cameras to be calibrated at once. A checkerboard target was placed in the viewing volume of all eight cameras. The size of the checkerboard squares was 2 mm with a total size of 20 × 20 mm (for
Figure 3.1: Diagram of the SAPIV experimental setup. Eight high-speed Photron SA3 cameras were used for SAPIV. The ninth camera was mounted vertically above the vocal folds for tracking their movement and was not used for SAPIV. The laser was used to laterally illuminate the glottal jet.

a 10 × 10 checkerboard target). The images of the checkerboard targets were passed to a Harris corner detector [34] to find the corners on the target. Further calibration details are provided in Chapter B. The calibration images were then used to calculate the homographies.

**Homography Calibration:** A homography is a mapping of planar surfaces under projection. In computer vision it is a matrix that describes how different images overlap each other. Corresponding points were selected between each of the calibration images to calculate the homographies. These points were passed to the Svoboda calibration code [35] that was used to solve a set of direct linear transformation equations that yielded the homographies. For each camera, the
different elements of the homography, $H$, give details of the rotation ($\theta$), translation ($t_x, t_y$), scaling ($s$), and projection ($h_{20}, h_{21}$) to correctly map each camera image to an arbitrary reference plane:

$$H = \begin{pmatrix} s\cos(\theta) & s\sin(\theta) & t_x \\ -s\sin(\theta) & s\cos(\theta) & t_y \\ h_{20} & h_{21} & 1 \end{pmatrix}. \quad (3.1)$$

A unique homography was calculated for each camera at each of the five different calibration depths. The five homographies for each camera were then curve fit through depth for each camera for any depth within the viewing volume (see [32] for details).
Figure 3.3: Overlapped images from all eight cameras. The images from the eight cameras were mapped to have the same projection as the reference image. The mapped images could be overlapped various amounts to change the focal length of the camera array. The overlapped images were then thresholded to yield a single ‘refocused’ image. The image shown has been color inverted so the individual particles are more visible during printing.

**Image Overlap:** The homographies were used to map the images from the eight cameras throughout the volume of interest. Overlapping the images from the eight cameras and adding the images together effectively refocused the entire camera array onto a single focal plane. Multiple refocused planes could then be generated for the volume of interest. These refocused planes are referred to as the “focal stack.” Since the homographies were curve fit in depth, the focal stack could be refocused at any arbitrary focal plane within the volume of interest.

As the focal stack was refocused, certain particles came into sharp focus creating a bright spot in the image, whereas all of the particles that were out of focus were dim and blurry (see Fig. 3.3). The overlapped images were then thresholded to eliminate all of the particles that were out of focus. The resulting refocused and thresholded images only showed the particles that were in the desired focal plane of the camera array. Refocusing allowed the creation of three-dimensional intensity voxels. For data with dense particle seeding, the refocused images are thresholded to a pixel value of 60 to remove dimly lit particles that were not in the refocused plane.

**3D PIV:** The refocused images were processed by MatPIV [36], a traditional PIV tracking method that uses pixel cross correlation to track particles in PIV images. MatPIV was modified to
cross correlate voxels in three dimensions and post process the data. Four basic post processing algorithms were implemented in MatPIV.

1. Cross Correlation – The MatPIV code was modified to translate an interrogation volume over the volume of interest. The volume of interest was cross correlated with the interrogation volume to track seed particles in the volume of interest. A three-dimensional window size of $64 \times 64 \times 32$ for the first pass and $32 \times 32 \times 16$ were used for the next two passes to process this data.

2. NaN interpolation – The cross correlation method produced NaNs for dark areas without any particles of the focal stack. The function sorted all spurious vectors based on the number of spurious neighbors to a point. Interpolation starts with the NaNs that have the least number of outliers in their neighborhood and loops until no NaNs are present in the field.

3. Masking – The NaN interpolation produces unrealistic results in the areas with low correlation. These artifacts were removed using a simple masking process.

4. Median Filtering – Spurious vectors were then removed using a moving median filter. This allowed spurious vectors to be removed from the data while still preserving strong velocity gradients.

3.3 Results

3.3.1 Uncertainty Analysis

Two-dimensional PIV data were taken to verify the SAPIV method. This was done by comparing the velocity vectors from a single refocused plane of SAPIV data to a set of traditional PIV data taken at the same plane location. It was decided that a steady, non-vibrating glottal jet would be used for verification due to the difficulty of phase matching two separate data sets. The vocal folds used in the verification study were from a female who died at the age of seventy two from an aneurism of the aorta. The vocal folds were equally tensioned.

The uncertainty of the SAPIV was determined using the method outlined by Lazar et al. [37]. The total uncertainty can be divided into four main sources: uncertainty due to equipment
limitations, uncertainty due to particle settling, uncertainty due to sampling, and uncertainty due
to correlation.

The uncertainty analysis by Lazar et al. [37] was for 2D PIV data. Since the SAPIV data is
inherently three-dimensional, the error analysis was performed on a single two-dimensional slice
of the glottal jet. The vector field for that plane of data is shown in Fig. 3.5. The figure shows the
glottal jet forming at the bottom center of the figure and propagating upward and to the right with
the highest velocity in the core of the jet.

2D PIV: The slice of SAPIV data in Fig. 3.5 was also compared to traditional 2D PIV of the
glottal jet. Unfortunately, there were no cameras that were positioned orthogonal to the light sheet.
This was corrected by rectifying the image data using a simple reverse warp bilinear interpolation
scheme. The resulting rectified image is shown in Fig. 3.4.

PIV was performed with rectified image data for comparison with the SAPIV data and is
shown in Fig. 3.6. The PIV used a four pass method with window sizes of $64 \times 64$, $64 \times 64$, $32 \times 32$
and $32 \times 32$ with no mask. The figure shows contours of velocity magnitude overlaid with velocity
vectors.

**Equipment Uncertainty:** The uncertainty of the equipment was determined by examining
the accuracy of the calibration and the timing. The uncertainty resulting from calibration consists
of calculating the scaling magnification ($\psi$), calibration accuracy ($w_l$), uncertainty band ($w_{L1}$), im-

Figure 3.4: Calibration target rectified to simulate orthographic projection of the camera to the
laser sheet.
Figure 3.5: Two-dimensional slice of the SAPIV data. These data were averaged over 20 images to achieve an averaged velocity field. The heat-map contour background shows the vector magnitude.

Figure 3.6: Two-dimensional PIV data as calculated by MatPIV. The steady-state jet was averaged over 20 image pairs.

...age distortion ($w_L^2$) and calibration positioning ($w_L$). The equations and values of these variables are given in Table 3.1.

The scaling magnification factor relates physical lengths to pixel units. The scaling magnification factor ($\psi$) is a ratio of the length of the calibration scale in physical units to the length of the calibration scale in pixels. For the scaling magnification, $l$ is the size of the squares on the
Table 3.1: SAPIV uncertainty due to equipment. Uncertainty in the imaging and timing devices are both considered for determining the total uncertainty.

<table>
<thead>
<tr>
<th>Name</th>
<th>Equation</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scaling magnification</td>
<td>$\psi = \frac{l}{f} = \frac{\Delta}{f}$</td>
<td>0.02985 mm/pixel</td>
</tr>
<tr>
<td>Calibration Accuracy</td>
<td>$w_l = \psi \times \Delta$</td>
<td>0.1515 mm</td>
</tr>
<tr>
<td>Uncertainty band</td>
<td>$w_{L1} = 2 \times \Delta$</td>
<td>10 pixels</td>
</tr>
<tr>
<td>Image distortion</td>
<td>$w_{L2} = L \times 0.5%$</td>
<td>0.33 pixels</td>
</tr>
<tr>
<td>Calibration positioning</td>
<td>$w_{\lambda}$</td>
<td>2 mm</td>
</tr>
<tr>
<td>Laser jitter</td>
<td>$w_{t1} = T_{\text{pulse}} \times \text{stability}_{\text{pulse}}$</td>
<td>1.5 ns</td>
</tr>
<tr>
<td>Timing jitter</td>
<td>$w_{t2}$</td>
<td>50 ps</td>
</tr>
</tbody>
</table>

The total uncertainty due to the equipment is shown in Fig. 3.7.

checkerboard target in mm and $L$ is the corresponding size in pixels. In this case, $l = 2$ mm and $L = 67$ pixels. The calibration accuracy ($w_l$) is the distance for which the calibration target is assumed to be accurate. This value was estimated to be approximately 0.1515 mm. The uncertainty band ($w_{L1}$) is essentially the smallest resolution of the particles in the camera which is ten pixels. Image distortion value ($w_{L2}$) is determined by assuming that the calibration scale be distorted by 5% which is a conservative estimate given the focal lengths used on the cameras in this experiment. Lastly, the error in calibration positioning ($w_{\lambda}$) is the error in positioning the calibration target and assumed to be 2 mm. The laser jitter ($w_{t1}$) of the Quantronix Darwin Duo is 1.5 ns and the timing jitter ($w_{t2}$) of the pulse generator was 50 ps.

The total uncertainty due to the equipment was then calculated using

$$
\varepsilon_e = \sqrt{\left(\frac{\partial u}{\partial l} w_l\right)^2 + \left(\frac{\partial u}{\partial L} w_{L1}\right)^2 + \left(\frac{\partial u}{\partial L} w_{L2}\right)^2 + \left(\frac{\partial u}{\partial \lambda} w_{\lambda}\right)^2 + \left(\frac{\partial u}{\partial t} w_{t1}\right)^2 + \left(\frac{\partial u}{\partial t} w_{t2}\right)^2}, \quad (3.2)
$$

which can be rewritten using the variables $\psi, w_{L1}, w_{L2}, w_{\lambda}$ as

$$
\varepsilon_e = \sqrt{u^2 \left[ \left(\frac{l}{L} w_l\right)^2 + \left(\frac{-l}{L^2} w_{L1}\right)^2 + \left(\frac{-l}{L} w_{L2}\right)^2 + \left(\frac{-l}{\lambda L} w_{\lambda}\right)^2 \right] + \left(\frac{-ul}{\Delta L}\right)^2 [w_{t1}^2 + w_{t2}^2]. \quad (3.3)
$$

The total uncertainty due to equipment is shown in Fig. 3.7.
Figure 3.7: Uncertainty due to equipment over the velocity field. The maximum error is around 4.73% of the maximum velocity.

**Particle Settling:** To determine the importance of particle settling we stray from the derivation supplied by Lazar et al. [37] since their derivation dealt with supersonic flows. We instead consider particle dynamics using stokes flow. Using potential flow theory, Stokes derived the drag force on a spherical particle at low Reynolds [38] number as

$$F_D = 6\pi \mu U r,$$  \hspace{1cm} \text{(3.4)}

where $\mu$ is the viscosity of air, $r$ is the radius, and $U$ is the terminal velocity of the particle. The terminal velocity can then be calculated by Newton’s third law,

$$mg = F_D + F_B,$$  \hspace{1cm} \text{(3.5)}

$$F_B = \rho_f V_p g,$$  \hspace{1cm} \text{(3.6)}

$$U = \frac{2(\rho_p - \rho_f)g r^2}{9\mu},$$  \hspace{1cm} \text{(3.7)}
Figure 3.8: Uncertainty due to particle settling. The terminal velocity of the glass micro spheres used here was 0.0015 m/s. This figure shows the uncertainty due to particle settling increases outside the jet where the velocity is close to zero. However, the uncertainty approaches zero in the vicinity of the jet indicating that the particle settling velocity is negligible here.

where $F_B$ is the buoyancy force, $\rho_p$ is the density of the particle (25 kg/m$^3$), $\rho_f$ is the density of the fluid (1.21 kg/m$^3$), $V_p$ is the volume of the particle, $r$ is the radius of the particle ($22.5 \times 10^{-6}$ m), and $\mu$ is the density of the fluid (in this case air). The terminal velocity was calculated to be 0.0015 m/s. The terminal velocity was then divided by the maximum velocity magnitude $V$ of the vector field (see Fig. 3.8).

Figure 3.8 shows that the uncertainty due to settling reaches its maximum well outside the region of the jet. This is where particle settling dominate the flow since the air is quiescent. However in the jet, the uncertainty approaches zero as the momentum of the jet dominates the movement of the particles.

**Sampling:** Sampling uncertainty can be defined as uncertainty derived from the turbulent nature of fluid flow. Since the jet is not exactly the same in time, multiple image pairs were captured and ensemble averaged. If the jet is erratic, then the averaging will show a wide jet plume and high
The sampling uncertainty can then be calculated by

$$
\varepsilon_s = \frac{\sigma}{\sqrt{n}},
$$

(3.9)

The sampling uncertainty is shown in Fig. 3.9 and shows a fairly stable jet with approximately 0.6% uncertainty of the maximum jet velocity in the shear layer of the jet.

The uncertainty for SAPIV was based on the general uncertainty approach given by Lazar et al. [37]. Four sources of uncertainty were considered: equipment, particle settling, sampling and image processing. The uncertainty of the image processing algorithms were determined using
Figure 3.10: Total uncertainty. All of the uncertainty of the data from sampling, particle settling and equipment are shown. There is additional uncertainty from the correlation algorithm that is not represented in this plot. The author refers the reader to the paper by Belden et al. [32] for a report on uncertainty due to correlation.

synthetic PIV images for flow around a cylinder from Carlier [39]. The maximum total uncertainty of the 2D PIV image in Fig. 3.6 was found to be 4.73% of the maximum velocity.

Figure 3.5 shows a two-dimensional slice of the glottal jet at approximately the same plane as the 2D-PIV data. The data were obtained by ensemble averaging 20 SAPIV vector fields. Figure 3.5 shows a jet moving up and to the right much like the jet seen in Fig. 3.6 validating the SAPIV method. The 2D-PIV in Fig. 3.6 shows a narrower jet then the more fanned out jet in Fig. 3.5. The PIV results in Fig. 3.6 also show a “kink” in the lower part of the jet that is not present in Fig. 3.5. This is because large bright objects in the cameras tended to confuse the thresholding SAPIV algorithms. This was solved by masking the laser light with a piece of paper which also blocked light from reaching the base of the glottal jet. No such problem was encountered for collecting the 2D-PIV data (see Fig. 3.6). However, both images show a jet that is moving up and to the right with approximately the same velocity magnitudes (approx. 30 m/s maximum velocity).
3.3.2 Results with Vibrating Vocal Folds

SAPIV was used to measure the glottal jet of an excised human vocal fold. The vocal folds used were from a female who died at the age of sixty from a heart failure with a tumor in the pancreas. The vocal folds in this experiment were equally tensioned.

Figure 3.11 shows SAPIV vector field results for four time steps of a typical vibration cycle taken 1 millisecond apart. Each time step is represented by six two-dimensional vector fields to illustrate the flow. The first three plots show vector field slices in the XY plane spaced 4 mm apart. For each time step, these planes are shown as three green lines in the top image of Fig. 3.11. The last three plots for each time steps are vector field slices in the YZ plane spaced 4 mm apart. For each time step, these planes are shown as three red lines in the top image of Fig. 3.11.

The vector fields in Fig. 3.11 show the evolution of the glottal jet. The second time step (Time: 0.001 sec) shows the formation of the glottal jet while the third time step (Time: 0.002 sec) shows a fully formed glottal jet propagating downstream. The final time step (Time: 0.003 sec) shows the entire glottal jet has disappeared. These results represent the first whole-field time-resolved three-dimensional velocity measurements of the glottal jet.

3.3.3 Flow Analysis

Three different flow features are commonly observed in the glottal jet: vortex structures, axis switching, jet skewing and vena contracta. Drechsel et al. [15] used synthetic vocal folds made of silicone and found that when the false vocal folds were not present, large vortices were created in the shear layer of the jet. Conversely, they found that the false vocal folds had a stabilizing effect on the glottal jet that obstructed the vortices in the shear layer. The vector fields shown in Fig. 3.11 were obtained with an excised larynx without any false vocal fold structures. Even without false vocal folds, the excised vocal folds produced a glottal jet that did not have large vortex structures seen by Drechsel et al. [15]. One of the possible differences that explain the presence of these vortex structures are the fundamental differences in the way human and synthetic vocal folds vibrate. The excised vocal folds vibrate with high medial lateral movement while the excised vibrate with more of a anterior posterior wave. It is thought that this large medial lateral movement is responsible for these vortex structures.
Figure 3.11: SAPIV results for a vibrating excised human vocal fold. The image on top is a top-down view of the vocal folds. The image shows three green lines that represent data slices in the XY plane and three red lines that represent data slices in the YZ plane. Vector fields for four time steps are shown. Each time step has six vector fields slices of the three-dimensional data. The first three slices are vector fields in the XY plane spaced 4 mm apart (planes 3, 7, 11) while the last three vector fields are data slices in the YZ planes spaced 4 mm apart (planes 18, 22, 26). In each vector field the vocal folds are illustrated in green.
Axis-switching is when the major axis of an elliptical jet changes as the jet progresses downstream. This phenomenon has been seen in glottal jets created by elliptical orifices created by synthetic vocal fold models in at least two previous studies [27] [28]. These phenomena are not clearly present in the data presented here; there are a few reasons why this may be; the studies by Triep et al. [27] and Krebs et al. [28] both used synthetic vocal models. Triep used driven vocal folds while Krebs used self-oscillating synthetic vocal folds. The aspect ratios of the glottal opening in their studies ranged from 1:6 to 1:8. Previous research suggests that the wavelength of the axis-switching can be predicted for small aspect ratios [40] [41]. However, the aspect ratio of glottal opening for the excised vocal folds was nearly twice as large on the order of 1:15. The high aspect ratio of the glottal jet may produce an axis-switching wavelength that is much larger than the volume of interest. Furthermore, if the wavelength is long compared to the inertia of the fluid, then the viscosity of the air may cause mixing that masks any evidence of axis-switching. Furthermore, the studies by Triep [27] and Krebs [28] phase locked the PIV data with the vibration of the vocal folds allowing for PIV ensemble averaging for a single phase producing much cleaner data than time resolved PIV.

Vena contracta is the narrowing of a jet after it emerges from an orifice and has been observed by researchers in glottal jets [27]. In this data it is unclear if the phenomena of vena contracta is present. The author believes this is due to the fact that the effects of vena contracta would be minimal since the vocal folds form a converging nozzle that would minimize vena contract effects.

Glottal jet skewing happens when the glottal jet adheres to one vocal fold and skews the glottal jet. This due to the fact that as the two folds vibrate, one fold will deform more during a given vibration cycle. The SAPIV results for the XY planes in Fig. 3.11 show the glottal jet is slightly skewed up and to the right. This is consistent with the computational results from Scherer et al. [2].

### 3.4 Summary & Conclusions

The purpose of this research is to detail how to use SAPIV to quantify the three-dimensional velocity field of the glottal jet emanating from excised human vocal folds. The excised vocal folds were driven with pressurized air to induce vibration. The glottal jet was seeded with glass
microspheres and the jet was imaged with eight high-speed cameras. Synthetic aperture particle image velocimetry (SAPIV) was used to reconstruct the flow field in three dimensions. SAPIV was used on a steady jet for validation with traditional 2D-PIV. The SAPIV results showed good agreement with the 2D-PIV methods adding credibility to the SAPIV data. The reconstructed flow field of the glottal jet did not show axis-switching. It is thought that this phenomenon was not observed due to the noisy nature of time resolved data.

Drechsel et al. [15] used silicone vocal folds to study the flow characteristics of the glottal jet. Their data showed large vortex structures in the shear layer in the glottal jet that are not present in the SAPIV data presented here. This suggests that the silicone vocal fold models used by Drechsel et al. yielded a fundamentally different glottal jet than the jets produced by excised vocal folds.

Other researchers have also observed the flow phenomenon of vena contracta in the glottal jet. This phenomenon could not be seen in the 3D reconstructed glottal jet from the data presented here. It is thought that this is due to the fact that the vocal folds form converging nozzle that would minimize the effects of vena contracta. SAPIV demonstrated its ability to reconstruct the glottal jet in three dimensions and was able to capture several flow features created by the glottal jet. This study represents the first whole-field three-dimensional time-resolved reconstruction of the human glottal jet.

Observing varying flow fields is an instance where SAPIV excels because SAPIV can capture time resolved 3D vector fields. For future work, the author recommends that SAPIV be used to show how the glottal jet changes with vocal fold tension for both symmetric and asymmetric tension cases. This would give insight to the characteristics of a glottal jet with patients who cannot tension their vocal folds equally and what the possible medical action should be. Further SAPIV studies could also be conducted on the vocal folds with other medical problems (e.g. subglottal stenosis, nodules).
CHAPTER 4. SAPIV ON SYNTHETIC VOCAL FOLD MODELS

4.1 Introduction

In Chapter 3, use of the SAPIV technique on excised human vocal folds to reconstruct the glottal jet in three dimensions was discussed. However, excised human vocal folds are expensive, difficult to prepare, and do not have consistent properties or responses across specimens. Consequently, researchers have developed synthetic vocal fold models to study voice production.

Synthetic vocal fold models with simplified geometry and material properties, are used to study the flow induced response of human vocal folds. One well known example is the rigid M5 model. Developed by Scherer et al. [2] pressure taps were placed along the medial surface of the vocal folds to measure the pressure change through the glottal gap. These pressures were compared with a computational model.

Drechsel et al. [15] improved upon the fixed vocal fold model by Scherer et al. [2] by making self-oscillating vocal folds out of a silicone rubber material. The glottal jet from this model was reconstructed using particle image velocimetry (PIV). Their 2D-PIV data showed several flow characteristics of the glottal jet, including vortex structures, intraglottal flow separation, and glottal jet skewing. Triep et al. [27] performed multiple 2D-PIV passes on a cam-driven vocal fold model in a water tunnel. This allowed them to reconstruct the three-dimensional flow field of the glottal jet. They showed that the elliptical orifice created by vocal folds created a jet that exhibited axis-switching. However, since multiple 2D-PIV passes were needed to reconstruct the flow field, they were unable to obtain time resolved whole-field measurements of the velocity field.

Krebs et al. [28] used stereoscopic PIV (SPIV) to image a glottal jet in three dimensions. Their setup used self-oscillating liquid-filled vocal folds. The flow was illuminated with a laser sheet that was swept through the field of interest. This technique yielded three-dimensional flow field data, phase locked with the vocal fold model vibration (i.e. not time resolved).
Murray et al. [42] [43] developed an improved four-layer synthetic vocal fold model that consisted of body, cover, epithelium and ligament layers. They showed that the four-layer model yielded more realistic vocal fold motion, including mucosal wave-like motion that is typical of human vocal fold vibration.

The method for using SAPIV on excised human vocal folds was outlined in chapter 3. The results from that chapter indicate that the SAPIV did not achieve sufficient resolution to detect small scale flow features. Furthermore, the experiments in chapter 3 were conducted on excised vocal folds. The purpose of this chapter is to further develop SAPIV techniques on a glottal jet produced by synthetic two- and four-layer silicone vocal fold models. The results will be compared with PIV data from chapter 3 and from previous studies [27] [28] for flow features such as vortex structures and axis-switching. The reconstructed glottal jet generated by the silicone vocal folds is analyzed to determine if synthetic models can simulate the glottal jet produced by excised vocal folds.

4.2 Methods

4.2.1 Vocal Fold Models

The vocal fold model geometry was based on that described by Scherer [2] (see Fig. 4.1). Two different vocal fold models were used: a two-layer and a four-layer model. The two-layer model consisted of body and cover layers that were made of silicone rubber. The four-layer model consisted of the epithelium, superficial lamina propria, intermediate and deep lamina propria and muscle. The two- and four-layer models were chosen because they are two commonly used synthetic vocal fold models.

The left and right folds were mounted on an acrylic holder. A constant pressurized air supply was fed into a plenum simulating the lungs (see figure 4.2). The plenum was approximately 30.48 \times 30.48 \times 30.48 \text{ cm} to approximate the lungs. A flexible pipe extended from the top of the plenum to the vocal fold mount. The pipe was 50 \text{ cm} long and imitated the human trachea. Just upstream of the vocal fold holder was a pressure tap (Omega Engineering, model PX-138) that measured the pressure 3 \text{ cm} upstream of the vocal folds. The pressure tap signal was sent to a
LabVIEW program which would synchronize the subglottal pressure with the laser pulses used for SAPIV. All vocal fold models were driven at their onset vibration pressure.

### 4.2.2 SAPIV Setup

The airflow was seeded using atomized olive oil with a LaVision seeder (model number 1108926). The particles were entrained in the pressurized air supply upstream of the vocal folds. The size of the oil particles was estimated to be between 10-50 µm.

The cameras and laser were triggered using a pulse generator (Berkeley Electronics, Model 575 Digital Delay / Pulse Generator). This was done by sending a 500 Hz pulse to fire the laser while a 500 Hz signal offset by 5 µs was sent to the cameras as a synchronization signal (see Fig. [4.1]).

---

**General vocal fold surface design equations:**

\[
\begin{align*}
R_0 &= 0.0987 \text{ cm} \quad T = 0.3 \text{ cm} \quad -40^\circ \leq \Psi \leq 40^\circ \\
R_{\Psi} &= R_\Psi / \left( 1 - \sin \left( \frac{\Psi}{2} \right) \right) \quad R_L = R_{40} = T/2 \\
B &= \sqrt{2} R_{\Psi} / \sqrt{1 + \sin \left( \frac{\Psi}{2} \right)} \\
&= R_0 \sec \left( \frac{\Psi}{2} \right) / \sqrt{\left( 1 - \sin \left( \frac{\Psi}{2} \right) \right) / 2} \\
Q_1 &= \left( T - R_{\Psi} \right) \sec \left( \frac{\Psi}{2} \right) + \left( R_{\Psi} - R_L \right) \tan \left( \frac{\Psi}{2} \right) \\
&= \left( T - R_0 - R_L \sin \left( \frac{\Psi}{2} \right) \right) \sec \left( \frac{\Psi}{2} \right) \\
Q_2 &= R_L \sin \left( \frac{\Psi}{2} \right) \\
Q_3 &= Q_1 \cos \left( \frac{\Psi}{2} \right) \\
Q_4 &= R_0 \\
Q_5 &= R_L \sin 50^\circ
\end{align*}
\]

Figure 4.1: Vocal fold model taken by Scherer et al. [2].
Figure 4.2: SAPIV setup. Eight cameras were used (four on top and four on the bottom). The laser was mounted from the side to illuminate the oil tracer particles. The cameras were synchronized with a 1 kHz pulse from a pulse generator (solid line) and the both the cameras and the lasers were triggered with 500 Hz pulses (dotted line). The cameras were daisy-chained together through the “TTL in” and “TTL out” cable connections. The cameras were synchronized to a 500 Hz pulse through the “sync in” cable.

4.3). The cameras were daisy chained from the “TTL out” cable to the “TTL in” cable and all of the cameras were connected to the synchronization signal using the “sync in” cable.

Eight Photron SA3 high-speed cameras were used to image the volume of interest (see Fig. 4.2). The cameras were arranged so that four cameras looked down on the vocal fold models from approximately a 45° angle and four cameras were level with the models. Because the lasers fired at 500 Hz, the frame rate of the cameras was 1 kHz to capture both laser pulses (see Fig. 4.3).
Figure 4.3: Diagram of the trigger timing for SAPIV. A 500 Hz synchronization signal was used as the master signal to synchronize all of the high-speed cameras. A second slave signal was delayed by 5 µs for the laser double pulse. A third 500 Hz signal was delayed by 1997.5 µs to trigger the cameras. The cameras were set to a double shutter with each trigger signal.

The resolution of the cameras was 1024 × 1024 pixels. All eight cameras were fitted with 105 mm Sigma macro lenses. The cameras were placed about 25 cm away from the vocal fold models.

The seeding particles were illuminated laterally with an Nd:YLF Quantronix Darwin Duo laser. The laser was set to the maximum current output of 25 amps for both lasers to illuminate the seed particles as brightly as possible. A beam expander (Edmund Optics, #64-418) was used to expand the laser beam to a column of light approximately 2.5 cm in diameter and directed to the volume of interest just above the vocal folds. The laser was double-pulsed with a time delay of 5 µs between lasers one and two. Both lasers fired at 500 Hz.

The high-speed cameras were calibrated using a simple checkerboard calibration target. The target was a 10 × 10 checkerboard with 1.5 mm squares (see Fig. 4.4). The target was placed in the volume of interest at four different positions in the anterior-posterior direction of the vocal
folds in 5 mm increments. Cameras 1 and 4 had reflections of the calibration target that were visible in the acrylic mounting plate. The reflections were removed manually (highlighted in red in Fig. 4.4) so they wouldn’t interfere with the calibration algorithm (see appendix B).

The calibration code from Svoboda et al. [35] was used to determine the three-dimensional location of all eight cameras. The code was run for a single iteration without accounting for lens distortion. Lens distortion compensation was ignored because the cameras were using 105 mm lenses which have little radial distortion. With 81 interior calibration points per calibration plane and 4 calibration planes, the code used a total of 324 calibration points per camera. No outliers were detected during the calibration. The 2D reprojection error for all eight cameras was 0.27 pixels on average with a standard deviation of 0.25 pixels. The calibration errors for each camera are shown in Table 4.1.
Figure 4.5: Unprocessed image pair for a single time step. The figure on the left shows the particles illuminated during the first laser and the image on the right shows the particles illuminated by laser two 5 μs later. Note that laser 2 is significantly brighter than laser 1 with the result being that noticeably more particles are visible in the second time step. Also, a faint outline of the vocal folds is visible in image c) for laser 2.
Table 4.1: Two-dimensional reprojection error for each camera. The mean error and standard
deviation in pixels is given for each camera along with the number of calibration points
that were kept for each camera. A mean error of less than 1 pixel
is acceptable for SAPIV [32].

<table>
<thead>
<tr>
<th>Cam ID</th>
<th>Mean Error (pixels)</th>
<th>std (pixels)</th>
<th>#Inliers</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.76</td>
<td>0.34</td>
<td>324</td>
</tr>
<tr>
<td>2</td>
<td>0.36</td>
<td>0.19</td>
<td>324</td>
</tr>
<tr>
<td>3</td>
<td>0.35</td>
<td>0.19</td>
<td>324</td>
</tr>
<tr>
<td>4</td>
<td>0.12</td>
<td>0.05</td>
<td>324</td>
</tr>
<tr>
<td>5</td>
<td>0.32</td>
<td>0.19</td>
<td>324</td>
</tr>
<tr>
<td>6</td>
<td>0.27</td>
<td>0.16</td>
<td>324</td>
</tr>
<tr>
<td>7</td>
<td>0.20</td>
<td>0.12</td>
<td>324</td>
</tr>
<tr>
<td>8</td>
<td>0.14</td>
<td>0.05</td>
<td>324</td>
</tr>
</tbody>
</table>

4.2.3 Preprocessing

The PIV data needed to be preprocessed before the SAPIV algorithms could accurately
track the particles. The raw images are shown in Fig. 4.5a. The first step to preprocess the data
was to remove the illuminated vocal fold models using morphological processes of erosion and
dilation [44].

Erosion is an image processing technique that removes pixels around the border of a par-
ticular image feature. Suppose that $A$ is a white feature (pixel value 255 for grayscale) of a binary
image $I$ with pixel dimensions of $a \times a$. Feature $A$ can be eroded by a smaller square matrix $B$ (the
erosion operator being denoted as $\ominus$) with the following operation

$$A \ominus B = \{ z | (B)_{z} \subseteq A \}, \quad (4.1)$$

or in other words, the erosion of $A$ by $B$ is the set of all pixels ($z$) that are contained in $B$ as $B$
translates over $A$. For example, if $A$ were eroded by $B$ (dimensions $b \times b$), the dimensions of
eroded $A$ feature would be $a - b/2 \times a - b/2$. If the dimensions of feature $A$ is less than half the
size of matrix $B$, erosion of feature $A$ by $B$ would yield a matrix of zeros, effectively erasing feature
$A$. Conversely, feature $A$ may be dilated by a matrix $B$ (the dilation operator being denoted as $\oplus$)

51
with the following operation
\[
A \oplus B = \{ z | (\hat{B})_z \cap A \neq \emptyset \},
\] (4.2)

or in other words, the dilation of \( A \) by \( B \) is the set of all pixels \( (z) \) that share at least one common pixel as \( B \) translates over \( A \).

The morphological processes of erosion and dilation were used together to remove the vocal fold models in the image data without removing any of the seed particles (see Fig. 4.5a). The image data were eroded by a \( 5 \times 5 \) matrix that effectively removed all of the small illuminated seed particles, leaving only the illuminated vocal folds. The resulting image was then dilated back 5 pixels to restore the bright vocal folds to their original size. This image was used as a mask and subtracted from the original data to remove the vocal folds (see Fig. 4.5b).

Once the illuminated vocal folds were removed from the image data, the data were further preprocessed by an algorithm written by Belden et al. [32] to enhance the seeding particles in the image data. The algorithm searched all of the image data to find the image of highest contrast. This image was used as a template to histogram equalize all of the images. The images were then filtered with a Gaussian filter to make an unsharp mask. A sample preprocessed image is shown in Fig. 4.5c. Note how the particles in the raw image data have different intensities between laser one and laser two (Fig. 4.5a). After preprocessing, the particles between the double laser pulse are nearly identical (Fig. 4.5c). This preprocessing improves the overall performance of the SAPIV algorithms, specifically refocusing and particle tracking.

### 4.2.4 SAPIV Settings

The image data were refocused with 129 focal planes in a 15 mm volume depth such that the spacing between each focal plane was 116 µm. The data were refocused using an additive technique that added the images from each camera to create each focal stack. For a more information regarding refocusing, see Section 3.2.3.

The refocused focal planes were thresholded to a constant pixel value of 60 to only keep particles that were in focus in a given focal plane. A 3D version of the MatPIV code [45] was used to track the particles on all of the focal planes. The PIV code used a three stage PIV process with
window sizes of $128 \times 128 \times 64$, $64 \times 64 \times 32$ and $32 \times 32 \times 16$. These window sizes resulted in a $63 \times 63 \times 15$ vector volume of data points.

The PIV data were post processed to remove outliers and spurious vectors. Spurious vectors were removed using a median filter with a $5 \times 5$ filter block. The post processing codes available in the SAPIV code release were not used because the post processing codes assumed a dense seeding field. The data in this case was dense only in the glottal jet and sparse (no particles) outside of the jet. The assumption of a dense seeding jet in the post processing codes would introduce various artifacts into the flow field that were not actually present. The median filter effectively removed spurious vectors while preserving the hard velocity edges such as are seen in the shear layer of the glottal jet.

4.3 Results

SAPIV data were taken of the glottal jet created by two-layer and four-layer vocal fold models (see Table 4.2). Both models were run at their respective onset pressures. The onset RMS pressures for the two- and four-layer only differed by 70 Pa. While the subglottal pressures were similar, the flow rate for the two-layer model was more than three times less than the four-layer model. The glottal gap in the two-layer model had an elliptical profile while the glottal gap of the four-layer models opened almost evenly across the medial surface of the vocal folds. This difference in glottal opening could account for the different flow rate between the vocal fold models. Because the four-layer model had a higher flow rate it also produced better SAPIV data by allowing more seed particles to flow out of the vocal folds. The two-layer model vibrated about 15 Hz faster than the four-layer model which can be attributed to the stiffer silicone in the two-layer model.

Table 4.2: Experimental metrics of the two- and four-layer vocal fold models.

<table>
<thead>
<tr>
<th></th>
<th>Two-Layer Model</th>
<th>Four-Layer Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Onset Pressure</td>
<td>0.78 kPa</td>
<td>0.71 kPa</td>
</tr>
<tr>
<td>Flow Rate</td>
<td>6.2 l/min</td>
<td>21.7 l/min</td>
</tr>
<tr>
<td>Vibration Frequency</td>
<td>150.32 Hz</td>
<td>137.67 Hz</td>
</tr>
</tbody>
</table>
SAPIV data were collected in three dimensions for both the two- and four-layer models for comparison. The three-dimensional data were subdivided into XY, YZ and ZX image planes (see Fig. 4.6). The SAPIV data from both the two- and four-layer models contained NaNs as a result of areas with low correlation in the refocused data. These NaNs were removed and set to zero.

### 4.3.1 Two-Layer Model

Four time steps of SAPIV data were used to visualize the glottal jet. Figure 4.6 shows XY planes of the glottal jet at different Z depths produced by the two-layer vocal fold model. Five XY planes are shown for each time step with a ΔZ between each plane of 2 mm. The XY 1 plane is located 4 mm into the refocused volume and XY 5 is 3 mm from the back of the refocused volume. Planes XY 1-5 span 8 mm of refocused depth in the volume of interest. Each XY plane shows contours of velocity and velocity vector fields. The vocal fold model is located just below each velocity field plot as shown in the bottom of Fig. 4.6.

In Fig. 4.6 the glottal jet is visible at $t = 0.794$ s and $t = 0.800$ s in XY planes 2-4. In the core of the glottal jet the fluid velocity is between 10-14 m/s with a glottal jet diameter of about 2-3 mm. The glottal jet can be seen forming in plane XY 3 as the XY planes move in the Z direction. Time $t = 0.796$ s and 0.798 s show nearly empty vector fields because the model orifice is closed and therefore there is no glottal jet.

Time $t = 0.794$ s and $t = 0.800$ s show velocity contours with very high velocities near the base of the model. Closer inspection of the refocused images showed these areas of high velocity are due to the illuminated vocal fold model rather than seeding particles. These areas can therefore be disregarded.

Figure 4.7 shows YZ planes of the glottal jet at different X distances for the two-layer vocal fold models. Three YZ planes are shown for each time step with a ΔX between each plane of 1.6 mm. The YZ 1 plane is located 19.5 mm from the right of the refocused volume and the YZ 3 plane is 11.4 mm from the left side of the refocused volume. Planes YZ 1-3 span 3.25 mm of the width in the X direction. Each YZ plane shows contours of velocity and velocity vector fields. In Fig. 4.7 the glottal jet is visible at time $t = 0.794$ s and 0.800 s. The velocity contours show the glottal jet moving from the front of the refocused volume to the back. This is most likely due to inconsistencies in the production of the synthetic vocal fold models. Similar areas of dark
Figure 4.6: Velocity vectors of the glottal jet in the XY planes. Five XY planes are shown (XY 1-5) for four time steps ($t = 0.794 \, \text{s}, 0.776 \, \text{s}, 0.798 \, \text{s}, 0.800 \, \text{s}$) with velocity contours and vector fields. The XY planes are in the anterior-posterior direction of the vocal folds. High velocity areas are visible in some of the XY planes (XY 5 at $t = 0.794 \, \text{s}$, XY 4 & XY 5 at $t = 0.8$) are an artifact of the vocal fold model being refocused and not a velocity of the glottal jet.
Figure 4.7: Velocity vectors of the glottal jet in the YZ planes. Three YZ planes are shown (YZ 1-3). The glottal jet can be clearly seen in time $t = 0.794$ s with the glottal jet showing a slight velocity skewness towards the rear of the reconstructed volume. The jet has completely disappeared during $t = 0.796$ s, is beginning to reappear during time $t = 0.798$ s, and has fully reformed by time $t = 0.800$ s.

Red in the velocity contour plots can be seen in the YZ planes that are also visible in the XY planes. These areas can be disregarded because they are artifacts of refocusing.

Figure 4.8 shows ZX planes of the glottal jet at different Y heights for the two-layer vocal fold model. Seven ZX planes are shown for each time step with a $\Delta Y$ of 2.2 mm between each plane. The ZX 1 plane is located 13.5 mm from the top of the refocused volume and the ZX 7 plane is 0.54 mm from the top of the refocused volume. Planes ZX 1-7 cover 22.2 mm of height in the Y direction. Each ZX plane shows velocity contours of the glottal jet. No vectors were shown in the ZX data because the flow is out of the page.
Figure 4.8: Velocity contours of the glottal jet in the ZX planes for a two-layer model. Seven ZX planes are shown for each time step. Each plane shows contours of velocity magnitude. Some spurious high velocity areas shown in dark red during the $t = 0.794$ s in plane ZX 2 and ZX 7 and $t = 0.800$ s in plane ZX 6 can be disregarded as they are artifacts of refocusing.
Figure 4.9: Velocity contours of the glottal jet in the ZX plane for a two-layer vocal fold model showing axis-switching. The data in this figure is same data from Fig. 4.8. The core of the jet is outlined by hand in black ellipses and shows axis-switching.

The ZX planes show the cross-section of the glottal jet as it progresses downstream. The glottal jet is clearly visible at $t = 0.794$ s and $t = 0.800$ s time steps. Both time steps show the phenomenon of axis switching. For time $t = 0.794$ s, the glottal jet is oriented in the 10 o’clock to 4 o’clock position (see Fig. 4.9) in the ZX 1 plane. In the ZX 3 plane, the glottal jet is almost circular and at the ZX 6 plane the circular jet has flattened out. A similar pattern of axis switching is visible at $t = 0.800$ s time step with the jet transitioning from a 9 to 3 o’clock orientation in ZX 1 to the 10 o’clock to 4 o’clock orientation by plane ZX 4 (see Fig. 4.9).

Velocity results for the glottal jet emanating from a two-layer vocal fold model for ten time steps are shown in Fig. 4.10. The results show the evolution of the formation and destruction of the glottal jet. The figure shows the evolution of the jet for the XY, YZ and ZX planes.

4.3.2 Four-Layer Model

Four time steps of SAPIV data were used to visualize the glottal jet from a four-layer synthetic vocal fold model. Figure 4.11 shows XY planes of the glottal jet at different Z depths.
Figure 4.10: 3D PIV results of the glottal jet produced by a two-layer vocal fold model for 10 time steps. Results are shown for XY, YZ, and ZX planes as defined in the previous figures for the two-layer vocal fold models. The upstream pressure waveform is shown at the bottom of the figure.
Figure 4.11: Velocity vectors of the glottal jet in the XY planes for the four-layer model. Five XY planes are shown for each time step. Each plane shows contours of velocity magnitude and vectors of velocity. Some high velocity areas are shown in dark red during time $t = 0.236-0.238$ s in the XY 4-5 planes. These areas are due to the refocusing of the focal stack and can therefore be ignored.
Figure 4.12: Velocity contours of the glottal jet in the YZ plane for a four-layer vocal fold model. Three YZ planes are shown for each time step.

produced by the four-layer vocal fold model. The data presented in Fig. 4.11 has similar XY plane spacing and location as the XY planes in Fig. 4.6. The glottal jet is visible during $t = 0.236$ s and $0.238$ s time steps and partially visible during $t = 0.242$ s. Plane XY 2 at $t = 0.236$ s shows a clearly formed glottal jet with a maximum jet velocity of approximately 24 m/s. This velocity is substantially higher than the velocity found in the glottal jet of the two-layer model.

The dark red high velocity areas in the XY 4-5 planes are artifacts of refocusing and can be ignored. The XY 3 planes show minor artifacts in the velocity profile due to refocusing but the high velocity areas in the XY 1-2 planes are correct velocity profiles.

Figure 4.12 shows YZ planes of the glottal jet at various X distances for the four-layer vocal fold models. The spacing and position of each plane is identical to those in Fig. 4.7. The time $t = 0.238$ s shows evidence of axis-switching when the jet necks just above the vocal folds
Figure 4.13: Velocity contours of the glottal jet in the ZX plane for a four-layer vocal fold model. Seven ZX planes are shown for four time steps. The figure shows the ZX planes for approximately a single vibration cycle. Axis-switching can be seen between planes ZX 2-6 for time $t = 0.236$ s and 0.238 s.
then fans out farther downstream. When $t = 0.242$ s, the vocal folds are just beginning to open and the glottal jet beginning to form. At this time step, the YZ 2-3 planes show the jet forming first at the back of the vocal folds.

Figure 4.13 shows ZX planes of the glottal jet at various Y heights for the four-layer vocal fold model. The spacing and position of each plane is identical to those in Fig. 4.7. The XZ planes of the glottal jet for the four-layer model also shows evidence of axis switching. Time step $t = 0.236$ s the jet has a 10 to 4 o’clock orientation (see Fig. 4.14) in the ZX 2 plane with the jet axis changing to a core in the ZX 4 plane. By the ZX 6 plane, the jet axis has a 9 to 3 o’clock orientation. Similar flow characteristics are seen for time $t = 0.238$ s. Time $t = 0.240$ s shows a velocity field when the vocal folds are closed and no glottal jet is present. The glottal jet is beginning to reform at time $t = 0.242$ s.

Velocity results for the glottal jet emanating from a four-layer vocal fold for ten time steps are shown in Fig. 4.15. The results show the evolution of the formation and destruction of the glottal jet. The figure shows the evolution of the jet for the XY, YZ and ZX planes.
Figure 4.15: 3D PIV results of the glottal jet produced by a four-layer vocal fold for 10 time steps. Results are shown for XY, YZ, and ZX planes as defined in the previous figures for the four-layer vocal fold models. The upstream pressure waveform is shown at the bottom of the figure.
4.4 Conclusions

The glottal jets from two-layer and four-layer vocal fold models were reconstructed in three dimensions using synthetic aperture particle image velocimetry (SAPIV). The glottal jets for both vocal fold models were imaged at 500 Hz which allowed for the first time-resolved, three-dimensional reconstruction of the glottal jet produced by synthetic silicone vocal folds. The resulting data were analyzed for evidence of axis-switching. This research has paved the way for future researchers to take 3D SAPIV data of the glottal jet produced by vibrating vocal folds. Future research will focus on asymmetric vocal fold vibration due to asymmetric vocal fold stiffness or other pathologies. This type of vocal fold vibration produces glottal jets that can only be reconstructed with time-resolved PIV methods such as what was outlined in this chapter.

The SAPIV data in this study was superior to the data in chapter 3 in a few different ways. In chapter 3, the camera frame rate was 2000 fps which limited the resolution of the cameras to 640×640 pixels. This had two drawbacks: 1) the reduced resolution of the image data corresponded to a reduced resolution of the PIV algorithm and 2) because the image resolution of the cameras was reduced, the cameras had to be moved farther away to fit the glottal jet in the camera frame. Both of these drawbacks hindered the ability of the SAPIV codes to resolve the flow features of the glottal jet. In contrast, the data for synthetic models was acquired at a frame rate of 1000 fps. This reduced the temporal resolution of the data but allowed higher spatial resolution (1024×1024 pixels), hence higher PIV resolution, and allowed the cameras to be closer to the glottal jet. Also, the seeding method for the synthetic models used olive oil which was significantly more user friendly than the glass microspheres. The microspheres were expensive, difficult to entrain in the fluid flow, hazardous to breathe, dried out the excised vocal folds, and a coated nearly all of the equipment with a fine dust. The olive oil had none of these drawbacks and only one disadvantage worth mentioning. The oil particles did not reflect light nearly as well as the glass microspheres. This was due in part to the smaller size of the oil particles and because the oil was not as effective at scattering light as the glass microspheres. Proper experimental setup and preprocessing the images ultimately resolved the issue of the dimly lit oil particles (see Section: 4.2.3). The advantages of increased image resolution and particle seeding methods further improved and developed the SAPIV method for vibrating vocal folds.
Both the two- and four-layer models began to vibrate at approximately the same pressure (0.78 kPa and 0.71 kPa) respectively. However, the four layer model had significantly higher flow rate (21.7 l/min for the four-layer model versus 6.2 l/min for the two-layer model). The discrepancy in the flow rate between the two models can be explained by the difference in the glottal gap profile between the two models. The vocal folds of the four-layer model vibrated like flaps that opened equally along the vocal folds creating a nearly square glottal gap. In contrast, the vocal folds from the two-layer model formed a small elliptical orifice that produced the glottal jet.

A few problems were encountered while taking the SAPIV data. There were some problems getting the SAPIV data in focus. The calibration data is typically used to focus the cameras. This is done by opening the lens as wide as possible and focusing on the calibration target. However, this method was less effective for the olive oil particles because they were so small. To obtain the best data, it is better to focus on the oil particles and not worry if the calibration data is a little blurry. Another problem was illuminating the small oil particles. Cameras 4 and 8 were able to image the particles illuminated very well, but cameras 1 and 4 could not. This problem could potentially be solved by bouncing the laser light back on itself using a mirror. Because the particles were dim in several cameras, the f-stop had to be set at 11 rather than 32. The larger aperture made a narrower depth of field in the cameras, which is not ideal for SAPIV. The SAPIV particles were so small the cameras had to be brought in close to resolve the individual particles. However, because the cameras were so close, the cameras were shuttered at 1 kHz to image at maximum resolution (1024×1024). Faster cameras would allow a higher image resolution at a faster frame rate and improve both the temporal and spatial data resolution.

The time resolution of the SAPIV data was limited by the frame rate of the cameras. At 500 Hz, the cameras were only capturing four or five SAPIV data sets per vibration cycle. Faster cameras could yield 8 or 10 data sets per cycle, thereby providing a more complete picture of the formation of the glottal jet.
CHAPTER 5. CATASTROPHIC CRACKING COURTESY OF QUIESCENT CAVITATION

5.1 Introduction

In this chapter, the author looks at fluid structure interactions with rigid bodies. More specifically, the purpose of this chapter is to investigate a fluid that interacts with a rigid structure through cavitation.

A popular party trick is to refill a glass bottle with water and hit the top of a bottle with an open hand. The bottle will accelerate downwards and then the bottom of the bottle will suddenly break. Some have casually observed this phenomenon [46] and determined that cavitation was responsible for breaking the bottle. Jung et al. [47] presented some of the first research using high-speed cameras to understand how the bottles break. They found the cavitation bubbles were formed when the bottle was accelerated downwards faster than gravity, significantly reducing the pressure near the bottom of the bottle. As the cavitation bubbles collapsed, the force from the collapsing bubbles broke the bottle. However, they did not quantify the relationship between the acceleration of the bottle and the formation of the cavitation bubbles.

Cavitation is quantified in a moving liquid using the cavitation number, which is a form of the Euler number that can be easily derived from Bernoulli’s equation. The dimensionless cavitation number is typically in the form

\[ C = \frac{\Delta P}{\frac{1}{2} \rho v^2}, \]  

(5.1)

where \( \Delta P \) is pressure difference between the surrounding and the local pressure, \( \rho \) is the density of the liquid (1000 kg/m\(^3\)) and \( v \) is the local velocity. Cavitation is likely as the cavitation number approaches zero. However, in the case of the bottle, the water in the bottle was initially quiescent
(\(C = \infty\)). After the bottle was struck, the velocity of the bottle was so low (\(v_{\text{max}} = 0.2\) m/s, \(C = 5 \times 10^3\)) that the cavitation number in Eq. 5.1 was not appropriate for this system.

Batchelor [48] showed that the onset of cavitation could be predicted using the following formula:

\[
h = \frac{1020}{n} \text{cm,}
\]

(5.2)

with an acceleration of

\[
a = ng \frac{\text{cm}}{s^2},
\]

(5.3)

where \(g\) is the acceleration of gravity and \(n\) is the amount of \(g\) the system experiences. This derivation assumes cavitation will occur when the pressure at the base of the fluid column goes to zero absolute pressure. Batchelor does not elaborate where these equations come from nor does he account for any change in atmospheric pressure or fluids with high vapor pressures. Therefore these questions can only predict cavitation due to acceleration for a few cases.

Another dimensionless number is the acceleration number that is used in compressible flow situations. The acceleration number is defined using the bulk modulus, viscosity, density and acceleration of gravity. While the acceleration number uses acceleration for the dimensionless number, it does not account for any external acceleration nor can it predict cavitation. While the author is not familiar with any dimensionless number that will accurately predict cavitation due to acceleration ([49], [50], [51], [52], [53], [54], [55]), there have been several experiments over the years that have observed bulk cavitation or cavitation in accelerating liquids. A brief overview is given of these experiments.

One of the first observations of cavitation associated with liquid tension was by Christiaan Huygens in 1672 [56]. Huygens observed fluid tension using a four-foot long glass tube open at one end. The tube was filled with water and inverted over a water bath. As the bath was drained, the water in the tube remained suspended in the tube creating tension on the water column. The tension in the fluid column could eventually result in the formation of cavitation bubbles. This experiment was reproduced later by Donny [57] and Reynolds [58] [59].

Richards et al. [60] generated tension in a column of deionized water using a sealed vertical tube. The top of the tube was filled with a combustible gas, while the lower part of the tube had the water column supported by a thin mylar film. When the gas was detonated, a shockwave
propagated through the water column and reflected off the mylar film. The water column section of the shock tube also contained a symmetric converging-diverging nozzle that enhanced the tension in the water column. The tension created by the shock wave would produce cavitation bubbles when the wave reflected off a rigid boundary. Pressure taps and high-speed cameras with a schlieren setup were used to measure the tension wave in the shock tube. The results of their research focused on the pressure in the column but did not attempt to quantify cavitation.

Overton and Trevena [61] used a tube to put tension on a water column. The tube was suspended from the ceiling with rubber bands, pulled down and released so the tube accelerated upward to hit a plate, putting tension on the column of liquid. The pressure at the base of the water column was measured using a pressure transducer. Unfortunately, their research could not shed much light regarding the onset of cavitation in a fluid column since their research focused only on the pressure at the base of the tube.

Driels [62] researched cavitation formation as a function of depth for underwater explosions. The pressure wave from an underwater detonation would travel to the free surface of the ocean where part of the pressure wave would propagate into the air and the rest of the wave energy would reflect back into the ocean. The reflecting wave created a tension in the water causing cavitation. Driels made an improved prediction of the cavitation depth [63] and made an experimental setup with a shock tube to validate his model.

Cavitation in a static fluid has also been the topic of study in biological applications. Versluis et al. [64] found cavitation was responsible for the snapping sound of snapping shrimp. They found the snapping sound was generated from the rapid closure of the shrimps snapper claw. High-speed photography revealed the closure of the claw created a cavitation bubble that would travel short distances and collapse to stun and even kill prey. They also investigated the bubble and pressure dynamics of the cavitation bubbles generated by the snapping shrimp.

Unsworth et al. [65] studied the cracking of joints, such as the knuckles. The clicking noise heard during joint cracking is thought to be cavitation of the synovial fluid. They also found that once a joint is cracked, it couldn’t be “recracked” for approximately 20 minutes, presumably because the gas in the synovial fluid cannot be sufficiently dissolved in less than 20 minutes.

Kurosawa et al. [66] used a skull equivalent model to investigate the effects of cavitation in the cranial fluid when the skull is subjected to violent impacts. They tested a moving model
skull hitting a stationary object (coup) and a stationary model skull being hit by a moving object (contrecoup). At a 2.78 m/s impact speed, cavitation in the cranial fluid produced cranial pressures of 400 kPa for both the coup and contrecoup cases. They concluded that these high pressures could be responsible for brain damage. Unfortunately, they did not investigate the acceleration of the skull model versus cavitation onset in the cranial fluid.

Cochard et al. [67] researched the presence of cavitation in the xylem of yew trees (Taxus baccata). It was thought that the height of the trees would cause low pressure in the sap leading to cavitation. The results showed cavitation in the sap of the xylem, but the cavitation occurred due to the loss of adhesion at the walls of the xylem rather than tension in the fluid column.

Each of these studies investigated various situations where cavitation interacted with structures. While these previous studies of cavitation have been great contributions to understanding of cavitation, they have not investigated how cavitation is affected by fluid depth of an accelerating fluid. The purpose of this research is to determine the relationship between fluid depth and cavitation onset in an accelerating fluid. This is accomplished by deriving a dimensionless number to predict cavitation as a function of pressure head and acceleration and verifying this relationship experimentally. The effects of cavitation are then observed to document the events leading up to and causing a rigid structure to fail.

5.2 Methods

A theoretical development of cavitation in an accelerating fluid is discussed to determine the relationship between cavitation and pressure head. This relationship will be defined with a dimensionless number. The experimental methods are then described to validate the dimensionless cavitation number.

5.2.1 Theoretical Development

A free-body diagram of the fluid column is shown in Fig. 5.1. The depth of the fluid column is $h$ and $y$ is defined as positive down. The pressure at the top and bottom of the column are shown as $P_{top}$ and $P_b$ respectively. Using differential fluid mechanics, the incompressible Navies-Stokes
equation in the \( y \) direction for the fluid column is

\[
\rho \left( \frac{\partial v}{\partial t} + u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} + w \frac{\partial v}{\partial z} \right) = -\frac{\partial P}{\partial y} + \mu \left( \frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} + \frac{\partial^2 v}{\partial z^2} \right) + \rho gh,
\]

(5.4)

where \( u, v, w \) are the fluid velocity components in the \( x, y, z \) directions, \( P \) is the pressure in the fluid, \( \mu \) is the viscosity, \( \rho \) is the density, and \( h \) is the depth of the water column. Because the fluid is considered to be incompressible, the continuity equation is

\[
\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0.
\]

(5.5)

The fluid is assumed to be cylindrical in shape, inviscid with no surface tension, and of low dissolved gas content. The fluid flow is assumed to be irrotational such that \( u = w = 0 \) and therefore \( \frac{\partial v}{\partial y} = 0 \). With the velocity and gravity in the negative \( y \) direction, equation 5.4 thus becomes

\[
-\rho \frac{dv}{dt} = -\frac{dP}{dy} - \rho g,
\]

(5.6)
where \( \frac{dv}{dt} \) is the fluid acceleration, \( a \). Equation 5.6 can be simplified to

\[
\frac{dP}{dy} = \rho(a - g),
\]

\[
dP = \rho(a - g)dy.
\]

Integrating both sides yields

\[
\int_{P_b}^{P_{top}} dP = \rho(a - g) \int_0^h dy,
\]

\[
(P_{top} - P_b) = \rho h(a - g),
\]

Equation 5.10 shows that there is a force balance between the pressure difference from the top of bottom of the fluid column and the acceleration in the fluid column. Dividing right-hand-side of the equation by itself yields

\[
\frac{P_{top} - P_b}{\rho h(a - g)} = C_q.
\]

For the remainder of this paper the constant \( C_q \) will be referred to as the quiescent cavitation number. This cavitation number suggests that an increase in fluid depth (\( h \)) decreases the amount of acceleration needed to initiate cavitation. The cavitation number is independent of cross-sectional area (see Eq. 5.11), which may seem to be counterintuitive. While the area does not affect acceleration required to cause cavitation, an increase in area will result in more mass, and will thus require a larger force to accelerate the fluid and cause cavitation.

Equation 5.11 can also be derived using Newton’s second law and the Reynolds transport theorem. Both of these derivations require the fluid to move as a lumped mass which, is synonymous to saying the fluid is irrotational. It should be noted that this derivation will break down the moment cavitation bubbles form. The cavitation bubbles violate the incompressible assumption as the water undergoes a phase change and therefore a density change in the cavitation bubbles.
5.2.2 Experimental Method

A cavitation stick was made to study how pressure head affects cavitation and to validate the quiescent cavitation number (see Fig. 5.2). The cavitation stick was an acrylic tube with an outside diameter of 7.5 cm and a wall thickness of 1 cm. A 2.5 cm thick piece of acrylic was glued to the bottom of the tube. The length of the cavitation stick was 27 cm. The top of the cavitation stick had a removable air-tight cap so that the pressure inside the cavitation stick could be reduced. An accelerometer was attached to the bottom of the cavitation stick to measure the acceleration (PCB model number 303A03, with a rated maximum load of 1000 g).

A Photron APX high-speed camera was used to image the cavitation stick at 3000 fps with an image resolution of $512 \times 512$ pixels. The camera used a 105 mm Nikon macro lens. The images from the high-speed camera were used to visually detect the presence of cavitation bubbles. The
camera was triggered manually after each data run using end triggering to allow the user to trigger
the camera after the cavitation event by having the camera continuously buffer image data. The
camera was triggered using a pedal switch which allowed the experimentalist to trigger the camera
at will without having to use their hands. The cavitation stick was backlit using a halogen light so
the cavitation bubbles could be clearly seen.

A LabVIEW program was used to record the accelerometer signal (see block diagram in
Appendix E) and was synchronized with the high-speed camera. This was done by using the end
trigger signal from the camera to also trigger the LabVIEW program. The accelerometer was
sampled at 50 kHz with a one second data buffer. When the trigger was received, the program
stopped the buffer and wrote a text file of the acceleration. Buffering both the camera image data
and the accelerometer data with respect to a single trigger made it possible to align both data sets
and observe the relationship between the cavitation event and the acceleration.

The top of the cavitation stick was tapped with a rubber mallet to accelerate the stick and
initiate cavitation. The cavitation stick was filled with various levels of distilled water between
1 cm and 20 cm in increments of 1 cm (see Table 5.1). The cavitation stick was struck 10 times
at each depth. It was not deemed necessary to wait in between data runs so they were run as
quickly as possible. The pressure at the top of the liquid was then reduced by 250 mmHg inside
the cavitation stick and the experimental procedure was repeated between 5 cm and 20 cm of depth
in increments of 5 cm. This was repeated for 500 mmHg pressure.

Table 5.1: Experimental data for cavitation stick.

<table>
<thead>
<tr>
<th>Pressure (mmHg)</th>
<th>Data Points</th>
<th>Depths</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>200</td>
<td>1-20 cm in increments of 1 cm</td>
</tr>
<tr>
<td>-250</td>
<td>20</td>
<td>5-20 cm in increments of 5 cm</td>
</tr>
<tr>
<td>-500</td>
<td>20</td>
<td>5-20 cm in increments of 5 cm</td>
</tr>
</tbody>
</table>
5.3 Results

5.3.1 Uncertainty Analysis

The uncertainty of the accelerometer was determined using the magnitude ratio, defined as

\[
M(\omega) = \frac{1}{\sqrt{1 - \left( \frac{\omega}{\omega_n} \right)^2 + \left( 2 \zeta \frac{\omega}{\omega_n} \right)^2}}.
\] (5.12)

In physical terms, the magnitude ratio can be thought of as the output of a system over the input as a function of frequency. Hence, at resonance, the magnitude ratio goes to infinity for a second order system with no damping. The natural frequency of the accelerometer (\(\omega_n\)), according to the accelerometer data sheet, was 70 kHz. The damping ratio, \(\zeta\), was determined using additional information from the accelerometer data sheet. The data sheet defines the frequency range for ±5% for up to 10 kHz. These data were input into the magnitude ratio to solve for \(\zeta\),

\[
M(\omega) = 0.95 = \frac{1}{\sqrt{1 - \left( \frac{10\text{kHz}}{70\text{kHz}} \right)^2 + \left( 2 \zeta \frac{10\text{kHz}}{70\text{kHz}} \right)^2}}. \quad (5.13)
\]

The damping ratio \(\zeta\) was found to be \(\zeta = 1.35\). A characteristic operating frequency \(\omega_e\) was measured by looking at the first impact of the accelerometer and measuring the acceleration from peak to peak to measure the period of vibration. The inverse of the period yielded an operating frequency of 6250 Hz. At 6250 Hz and a damping ratio of 1.35 the uncertainty calculated by the magnitude ratio was 2% of the measured acceleration. According to the manufacturer, the total uncertainty was found using the formula

\[
\text{Uncertainty} = \sqrt{(1\% \times \text{full scale})^2 + (2\% \times \text{measured acceleration})^2 + (\text{resolution})^2} \quad (5.14)
\]

The full scale and resolution values of the accelerometer were 1000 g and 0.01 g respectively. Using Eq. 5.14, uncertainty of ±22 g was found for accelerations of 1000 g, ±14 g for accelerations of 500 g, ±11 g for accelerations of 200 g, ±10 g for accelerations less than 100 g.
5.3.2 Cavitation Stick

Example high-speed images of the cavitation events are shown in Fig. 5.3 for depths of 7 cm, 15 cm, and 16 cm. The cavitation bubbles varied in size and location. The 7 cm depth shows cavitation occurring at the bottom of the cavitation stick. The 16 cm depth has cavitation bubbles a few centimeters above the base of the stick. The 15 cm depth shows cavitation occurring both at the bottom of the cavitation stick and a few centimeters above the bottom. All of the cavitation events seen for this study were one of these three types. There was no apparent correlation between the acceleration or the depth and where the cavitation bubbles formed. The author speculates that the location of cavitation onset is possibly due to the location of small bubbles of dissolved gas present in the liquid. The argument could also be made that the locations of the cavitation sites correspond to small surface imperfections that become nucleation sites. However, were that the case it would be logical to see the bubbles forming at the same place every time, which was not the case. The cavitation bubbles usually ranged from around 0.5 mm to 1 cm in diameter.

Figure 5.4 shows acceleration vs. depth with both the cavitation stick data and the theoretical cavitation threshold as defined by Eq. 5.11. The open circles in the graph indicate data points from the cavitation stick. Open circles indicate accelerations that resulted in cavitation bubbles.
while the “×” symbols indicate accelerations that failed to generate visible cavitation bubbles. The solid line shows the theoretical cavitation threshold as defined by the quiescent cavitation number with $C_q = 1$. The data indicate that the threshold of cavitation decreases with increasing depth. The data match the theoretical line fairly well except the data has a slightly higher threshold of cavitation. This suggests the acceleration required for cavitation decreases with increasing depth and occurs at a cavitation number of about one for fluid depths deeper than 3 cm.

At depths less than 3 cm, the water surface sloshed vigorously which violated the assumption of irrotational flow (see Fig. 5.5). As a result, the data shown in Fig. 5.4 do not match the theoretical cavitation line below about 3 cm of fluid depth. It is hypothesized that cavitation at these shallow depths is less likely to occur because the energy from the strike goes into deforming the fluid rather than accelerating the fluid mass. Furthermore, if the fluid can flow in a direction other than in the direction of the cavitation stick, then the cavitation stick will be unable to pull a tension on the fluid column.

Figure 5.6 plots the nondimensional acceleration versus nondimensional pressure change for pressures of 0 mmHg, -250 mmHg and -500 mmHg. The open circles in Fig. 5.6 are data where
cavitation was observed and the “×” symbols are data where cavitation was not observed. The solid line in the figure is the theoretical cavitation threshold. The atmospheric pressure data suggest the onset of cavitation should occur between 5 and 10 g higher than the theoretical prediction, whereas the data for the -250 mmHg case were 5 to 10 g lower than the theoretical prediction. Both of these discrepancies can be contributed to accelerometer error.

5.3.3 Breaking Bottles

The same procedure that was used to correlate acceleration, fluid depth and cavitation was applied to a structure that would fail due to the collapse of the cavitation bubbles. Here, glass soda bottles were used to demonstrate how cavitation can cause failure in a rigid structure. High-speed photography showed four main events that occur during cavitation in a glass bottle (Fig. 5.7). When the bottle was hit, small cavitation bubbles initially formed near the bottom of the bottle
Figure 5.6: Non dimensional acceleration versus non dimensional pressure change. The open circles indicate that cavitation was observed whereas, the “×” symbols indicate that no cavitation bubbles were seen by the high-speed camera data. The solid line is the theoretical cavitation threshold defined by Eq. 5.11. Three pressures data sets are shown for 0 mmHg, -250 mmHg and -500 mmHg.

followed by bubble growth. The bubbles reached their maximum size and then began to collapse. After the cavitation bubbles collapsed, the entire bottle experienced structural failure.

An accelerometer was attached to the bottom of a bottle to measure the acceleration of the bottle during the cavitation event. The bottle was filled with 250 ml of distilled water. A LabVIEW program was used to record the acceleration and synchronized the camera and accelerometer. The high-speed video and accelerometer data are shown in Fig. 5.8.

Figure 5.8 shows six frames of the bottle leading up to and after the bottle breaks. Each frame is denoted in the plot with a vertical red line. Frame 1 shows the still bottle before it has been struck. The bottle is struck by the mallet 800 µs later, creating a spike in acceleration and initiating cavitation bubbles at the base of the bottle as shown in frame 2. The cavitation bubbles have
Figure 5.7: Montage of a bottle breaking due to cavitation. The sequence illustrates the cavitation bubbles formation, growth, collapse and eventual failure of the bottle itself.

Figure 5.8: Relationship between the acceleration of the bottle and the events that break the bottle. The first frame shows the bottle before it is struck by the mallet. The second frame shows the formation of cavitation bubbles near the base of the bottle 800 µs after the bottle is struck. After 1200 µs the cavitation bubbles have grown to their maximum size (frame 3). The cavitation bubbles have completely collapsed 2800 µs later (frame 4). Frame 5 shows the first cracks propagating through the bottle 200 µs later (a single frame at 5000 fps). The last frame shows the bottle has failed completely (frame 6).

grown to their maximum size 1200 µs after frame 2 (frame 3). During this time the accelerometer measured a diminishing oscillatory acceleration. The high frequency oscillations suggest that the bottom of the bottle was behaving as a vibrating membrane. By frame 4 (2800 µs after frame
Figure 5.9: Cavitation with a carbonated liquid. A carbonated liquid will cavitate when accelerated but the fluid will degas, preventing the cavitation from breaking the bottle. The image on the left shows the carbonated fluid with cavitation bubbles at the base of the bottle. The image on the right shows the carbonation degassing after the cavitation bubbles have collapsed.

3), the cavitation bubbles have completely collapsed and accelerated the bottle to the maximum measured acceleration of 1064 g. In the next camera frame (200 s after frame 4), the high-speed camera shows the first cracks propagating throughout the bottle (frame 5). The last frame shows the complete failure of the bottle. It should also be noted that only acceleration data was taken for bottles that broke. A study that determined the acceleration required to break the bottle was considered to be too cost-prohibitive with too many uncontrollable variables such as the thickness and consistency of the glass.

These data show two things about the relationship between cavitation and acceleration. First, the collapse of the cavitation bubbles is what breaks the glass bottle and not the initial mallet strike. The data also indicate that the acceleration due to collapse of the cavitation bubbles is greater than the acceleration that formed the bubbles. Second, the size of the cavitation bubbles is inversely related to the acceleration of the bottle. As the bubbles grow (see frame 3 in Fig. 5.8), the acceleration of the bottle decreases and as the bubbles collapse the bottle undergoes rapid acceleration (see frame 4 in Fig. 5.8).
High-speed image data were also taken when the liquid inside the bottle was carbonated (see Fig. 5.9). During the initial cavitation, the dissolved carbon dioxide in the liquid becomes insolvent and large amounts of bubbles form all throughout the liquid. This degassing of the liquid prevented bubbles from collapsing and the bottle from breaking. However, while the first strike could not break the bottle, by the second or third strike the liquid had been sufficiently degassed to allow cavitation to break the bottle.

### 5.4 Conclusions

The purpose of this research was to determine the relationship between fluid depth and cavitation onset in an accelerating fluid. To this end, a theoretical development of cavitation in an accelerating fluid yielded a quiescent cavitation number that included acceleration and fluid depth (Eq. 5.11). The new cavitation number suggested that the acceleration needed to cause cavitation decreased with increasing fluid depth. This hypothesis was validated experimentally by cavitating a column of water at various depths and atmospheric pressures.

From Fig. 5.8 we gain a few insights into the physics occurring before and while the bottle is breaking. When the bottle is struck the acceleration spikes, but decreases as the cavitation bubbles grow, suggesting that the kinetic energy of the bottle is being stored as potential energy in the cavitation bubbles. When the bubbles collapse, the acceleration spikes for a second time indicating the energy has transferred back from the potential energy stored in the bubbles to the kinetic energy of the bottle.

This research also sheds light on the cavitation research of Kurosawa et al. [66]. Their experiment used an 18 cm cylinder to approximate the human skull that would impact or be impacted by a wall to simulate coup/contracoup impacts, respectively. Their results were used to compare cavitation pressure to impact velocity. However, the present study suggests impact velocity was not the proper metric because fluid acceleration (or deceleration) likely caused cavitation in their studies. The acceleration needed to cavitate the cranial fluid (approximated as water) can be calculated using Eq. 5.11 for 18 cm of fluid depth to be 48 g of acceleration. This conclusion compares favorably with experimental data from Zhang et al. [68] who found that a linear acceleration of 47 g was needed to cause concussions in football players. Car manufacturers could use this data
Figure 5.10: Sample image from the cavitation stick with only one cavitation bubble. Only a single cavitation bubble was visible in this image for a single time step at the bottom of the cavitation stick on the right side. If bubbles formed in less time that the frame rate of the camera then the bubbles would appear blurred and not like a bubble. A camera with a higher frame rate and temporal resolution would be needed to ensure no bubbles formed in less than 1/3000 sec and were smaller than 0.5 mm.

to determine if the acceleration imparted to a passenger is below this g threshold to avoid brain damage due to cavitation of the cranial fluid.

There were bubbles present in the fluid for both the 250 mmHg and 500 mmHg negative gauge pressure cases (see Fig. 5.11). Removing the bubbles proved to be difficult because each cavitation event introduced hundreds of small bubbles back into the fluid. The bubbles could be reduced by slowly moving the liquid free surface past the bubbles. The surface tension of the free surface moving along the side walls of the stick would rupture larger bubbles. Removing these bubbles entirely proved so difficult that eventually the cavitation research was performed with the bubbles present in the fluid. During the experiment, the bubbles already present in the fluid would grow during the initial acceleration of the cavitation stick. Only bubbles that were created during the acceleration of the cavitation stick were considered as evidence of cavitation. Further research could be expended to resolve this issue and remove all bubbles in the cavitation stick.
Three main problems were encountered in detecting cavitation bubbles in this research. One, the high-speed camera had insufficient pixel resolution for imaging bubbles that were smaller than about 0.5 mm in diameter (see Fig. 5.10). Onset cavitation bubbles on the order of microns would not even be detected, suggesting the data in Fig. 5.4 might be skewed with higher accelerations than are needed to initiate cavitation. Two, the small cavitation bubbles collapsed so quickly that at a frame rate of 3000 fps, the bubbles were sometimes only visible for a single frame. It is possible that some bubbles were not seen due to the slow frame rate. These bubbles could be resolved using a higher frame rate camera and may increase the accuracy of detecting the onset of cavitation. Finally, the curvature of the cavitation stick refracted light so as to occlude bubbles near the side walls (see the side walls of the cavitation stick in Fig. 5.10). These factors introduce additional uncertainty; further research could resolve these issues.
CHAPTER 6. CONCLUSIONS AND CONTRIBUTIONS

6.1 Acoustically-Coupled Flow-Induced Vibration of a Computational Vocal Fold Model

The purpose of this research was to better understand the acoustic-fluid-structure interaction of models of the vibrating vocal folds and the subglottis. This was done using a two-dimensional computer model that included coupled fluid and solid domains using a fluid-structure boundary condition along the surface of the vocal fold. Flow field predictions were obtained using a slightly compressible solver that allowed for compressibility in the fluid domain without having to solve the energy equation.

Subglottal pressure waveforms were compared for both slightly compressible and incompressible fluid domains. It was found that incompressible flow solvers could not model subglottal acoustic modes. This is noteworthy given that many previous computational models of the vocal folds have used incompressible fluid domains. This research concludes that incompressible flow solvers give physically unrealistic subglottal pressure waveforms and are therefore inappropriate for modeling vocal fold vibration.

The computational model was compared with the experimental results of Zhang et al. [5] in which it was found the vocal folds vibrated at different frequencies depending on the subglottal length. The computational vocal fold model with a slightly compressible solver exhibited similar behavior. As the subglottal length increased, the frequency of vibration dropped until a subglottal acoustic mode was reached and a jump in the frequency of vibration occurred. Pressure waveforms from the computational model of the subglottis clearly showed these acoustic modes and were used to explain why the frequency of the vocal fold model vibration changed with subglottal length. These results emphasize the importance of using slightly compressible flow solvers for modeling fluid-structure interactions that are also acoustically coupled.

The results show the ability of the slightly compressible flow model to capture (1) the subglottal acoustics and (2) the acoustic coupling between subglottal acoustics and model vibration in
a manner consistent with experimental observations and expectations based on acoustic resonance theory. For this vocal fold model, this acoustic coupling is a critical governing factor of model self-oscillation.

6.2 Three-Dimensional Whole-Field Measurement of a Glottal Jet using Synthetic Aperture Particle Image Velocimetry

The flow through vibrating vocal folds creates a glottal jet that is associated with the quality of voiced speech. The glottal jet of excised human vocal folds was reconstructed in three dimensions using synthetic aperture particle image velocimetry (SAPIV). The results from this study represent the first three-dimensional whole-field time-resolved reconstruction of the glottal jet. The ability to perform time resolved SAPIV allows researchers to reconstruct transient glottal jets rather than being limited to ensemble averaging.

The glottal jet was reconstructed for four time steps. The data show a glottal jet with a core velocity of approximately 25 to 30 m/s, consistent with approximations that can be conducted using Bernoulli’s equation. Axis-switching and vena contracta, phenomena which have been seen in other studies, were not seen in the SAPIV data, presumably due to the lower resolution of the SAPIV. This low resolution issue was exacerbated due to the fact that the volume of interest was large compared to the scale of the flow phenomenon.

6.3 SAPIV on Synthetic Silicone Vocal Folds

A glottal jet produced by synthetic vocal folds was reconstructed using SAPIV. Two- and four-layer vocal fold models were used to generate the glottal jet. Both vocal fold models were driven at their onset pressure. The glottal jet was imaged with eight high-speed cameras at 500 Hz.

The SAPIV results from the glottal jet showed a core glottal jet velocity ranging from 18-25 m/s for the four-layer vocal fold model and 12-15 m/s for the two-layer vocal fold model. Both models show evidence of axis switching.

The glottal jets from the two- and four-layer model showed glottal jets with similar jet profiles to that of the excised glottal jet in the previous chapter. However, the synthetic vocal fold models had a lower glottal jet velocity than that of an excised vocal fold. This could be due to the
fact that the excised vocal folds were being actively tensioned using the setup from Luegmair et al. [33]. This tensioning would create a higher subglottal pressure and therefore a higher glottal jet velocity.

These data captured the fluid-structure interaction between the vibrating vocal folds and the glottal jet using time-resolved three-dimensional PIV. This research can be expanded to study the fluid-structure interaction between the glottal jet and vocal folds with various pathologies to better understand their influence on the glottal jet. Such information has the potential for helping in the treatment and diagnosis of various voice related issues.

### 6.4 Catastrophic Cracking Courtesy of Quiescent Cavitation

Cavitation is a fluid phenomenon that interacts with rigid structures such as pumps and propellors. Existing cavitation prediction methods are not suitable for accelerating flows. The purpose of this research was to determine what parameters influence cavitation in an accelerating fluid and determine the relationship between those parameters to predict when cavitation will occur.

A new cavitation number was derived based on the Navier-Stokes equation that modeled cavitation as a function of acceleration, pressure head, atmospheric pressure and fluid vapor pressure. The derivation of this cavitation number suggested the onset of cavitation required less acceleration with increasing pressure head. This equation was validated experimentally using a cavitation stick which confirmed the relationship between acceleration and pressure head (see Fig. 5.4). These data also suggested that cavitation occurs at a cavitation number of 1 independent of pressure head. This new cavitation number has shown that it can accurately predict cavitation onset for an accelerating fluid.

This research also sheds light on the cavitation research of Kurosawa et al. [66]. Their experiment used an 18 cm cylinder to approximate the human skull that would impact or be impacted by a wall to simulate coup/contracoup impacts, respectively. Results compared cavitation pressure to impact velocity. However, impact velocity is a poor metric because fluid acceleration (or deceleration) likely caused cavitation in their studies. The acceleration needed to cavitate the cranial fluid (approximated as water) can be calculated using Eq. 5.11 for 18 cm of fluid depth to be 48 g of acceleration. This conclusion compares favorably with experimental data from Zhang et al. [68] who found that a linear acceleration of 47 g was needed to cause concussions in football players.
Car manufacturers could use this data to determine if the acceleration imparted to a passenger is below this g threshold to avoid brain damage due to cavitation of the cranial fluid.

6.5 Future Work

One of the biggest drawbacks to the computation model of the vocal folds in Chapter 2 was the two-dimensionality of the model. While the model provided meaningful insight into the fluid-acoustic-structure interactions of vocal fold models and decreased the computational effort required, the two-dimensional model lacked the fixed boundary conditions on the anterior-posterior surfaces that would influence the stiffness of the vocal fold model and therefore its vibration. A three-dimensional model would address this issue and thus more closely approximate the true physics present in the experimental setup. To do this, future researchers would need to better understand how to run ADINA on multiple nodes. The process for efficiently coding the model into ADINA and submitting these jobs to a supercomputer would need to be documented. It would also be beneficial to run a supercomputer study to investigate how many nodes are truly effective at increasing model solution time.

This research was the first time three-dimensional velocity fields were measured in the glottal jet above the Nyquist frequency using SAPIV. Even with the capabilities of the high-speed cameras used here, resolution and frame rate were still the biggest impediments for taking the data. The cameras could only take data at 500 Hz (just over twice the Nyquist frequency) at full resolution (one megapixel). These experiments could be repeated using higher frame rate cameras (e.g. Photron SA-X 12,500 fps at full resolution) to capture higher resolution data both temporally and spatially. These data could potentially reconstruct smaller flow structures such as vena contracta and vortices.

The cavitation study looked at acceleration for cavitation onset vs. fluid depth in a fluid column. However, it did not consider what acceleration was needed to break a glass bottle because there was too much variability in most bottles. Furthermore, if insufficient acceleration were imparted to a bottle to break the bottle, the collapse of the cavitation bubbles would still cause microscopic damage to the bottle that would change the requisite force to break the bottle on subsequent cavitation testing. The large amount of bottles needed for this testing rendered doing so infeasible. It is possible to collect these data using test tubes since they are both cheap and
more uniform. A complementary study would be to measure the maximum pressure on the bottom surface of the cavitation stick. This pressure could be related to the required pressure to break whatever structure would be in contact with the cavitation bubbles. It would also be potentially worthwhile to extend this study to the area of cavitation-induced dramatic brain injury.
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APPENDIX A. ADINA/ENSIGHT CODE

A.0.1 AdinaRun.sh

The AdinaRun.sh is the file that was submitted to the supercomputer to run the ADINA codes. These codes include the f.in, s.in and parameter.in files. The .in files would generate a .por and .ens files. The .ens files are the ensight files that are analyzed with the Glottal_Gap.enc and iterate_Ensight.py files.

#!/bin/sh
# -l Batch system details
# -N Name of my output files
# -m Email options:
# a sends email if job is aborted
# b sends email when job begins
# e sends email when job ends
# -M Specify Email address

#PBS -l nodes=1:ppn=4,pmem=2gb,walltime=50:00:00
#PBS -N Length_060cm
#PBS -m e
#PBS -M dai01001@gmail.com

# Execute fsi simulations. Change 1GB for memory allocation as needed.
# Note that the -t 4 stands for 4 processors ("t" = threads). Use -t 4
# on the linux machines since they have 2 dual-core processors.

PROG1="/fslapps/adina_8.6.2/tools/aui8.6"
PROGARGS1="-m 2GB -cmd -s f.in"
OUTFILE1="fmake.out"
PROGARGS2="-m 2GB -cmd -s s.in"
OUTFILE2="smake.out"

PROG2="/fslapps/adina_8.6.2/tools/adina8.6"
PROGARGS3="-m 2GB -t 4 f s"
OUTFILE3="frun.out"
# The following line changes to the directory that you submit your job from

cd $PBS_O_WORKDIR

$PROG1 $PROGARGS1 > $OUTFILE1
$PROG1 $PROGARGS2 > $OUTFILE2

# FSI Simulation
$PROG2 $PROGARGS3 > $OUTFILE3

rm *.txt

/fslapps/ensight/bin/ensight90 -batch -X -p Glottal_Gap.enc
/fslapps/ensight/bin/ensight90 -batch -X -p iterate_Ensight.py

rm *.por
rm Length*
A.0.2 parameter.in

The parameter.in file controls all of the vocal fold model parameters. These parameters include geometry, grid, meshing, time step, boundary conditions, damping ratios and more. The parameter file allows the user to see all of the model parameters in a single file.

***********************************************************************
* File name: parameter.in
* 
* Created by: Scott Thomson
* Purpose of file: This file contains parameters used in the
* 2-D model of the vocal folds and vocal tract. Parameters
* are used in both the fluid and solid domains.
* 
* Last modified by: Jesse Daily
* Last modified: 5-16-2010
* Purpose for latest modification: 1) Include a larger plenum,
* 2) Updated damping ratios noted below, 3) Using different vocal
* tract lengths
* 
* History of modifications:
* 5-15-2010, 1) Include a larger plenum, 2) Updated damping
* ratios noted below, 3) Using different vocal fold material properties
* 
* end header
***********************************************************************

*** SUBGLOTTAL DUCT LENGTH
*Duct Length = 22''
PARAMETER DuctLength '0.6'

*** TIME STEPS
PARAMETER NSteps '15000'
PARAMETER dt '0.0000125'
PARAMETER MaxATS '20'

*** INLET PRESSURE BC
PARAMETER Pressure '-900'

*** ALPHA, BETA: RAYLEIGH DAMPING CONSTANTS
* Damping ratio’s for Ebody= 15kPa, Ecover=5kPa
* 1% - alpha=4.03192, beta=2.12e-5, fails immediately
* 2% - alpha=8.06384, beta=4.24e-5, fails eventually
* 3% - alpha=12.0958, beta=6.36e-5
* 4% - alpha=16.1277, beta=8.48e-5
* 5% - alpha=20.1596, beta=1.06e-4, Chosen as the damping ratio for our models
* 6% - alpha=24.1915, beta=1.27e-4

*** RAYLIEGH DAMPING COEFFICIENTS
PARAMETER ALPHA '24.1915'
PARAMETER BETA '0.000127'

*** COVER MODULUS & POISSON'S RATIO
PARAMETER Ec '5000'
PARAMETER Nuc '0.49'

*** BODY MODULUS & POISSON'S RATIO
PARAMETER Eb '15000'
PARAMETER Nub '0.49'

*** EPITHELIUM MODULUS & POISSON'S RATIO
* Now defunct
*PARAMETER Ee '5000'
*PARAMETER Nue '0.49'

*** CALCULATIONS FOR STRESS_STRAIN CURVES
PARAMETER EcNeg '-$Ec/10'
PARAMETER EcNegS '-$Ec/2'
PARAMETER EcPos '$Ec/10'
PARAMETER EcPosS '$Ec/2'
PARAMETER EbNeg '$Eb/10'
PARAMETER EbNegS '$Eb/2'
PARAMETER EbPos '$Eb/10'
PARAMETER EbPosS '$Eb/2'

*** BULK MODULI
*PARAMETER Kappac '$Ec/(3*(1-2*$Nuc))'
*PARAMETER Kappab '$Eb/(3*(1-2*$Nub))'
PARAMETER Kappac '1E5'
PARAMETER Kappab '1E5'

*** INLET DISPLACEMENT BC
PARAMETER TFTime '0.2'
PARAMETER TFdisp '0.01'

*** SOLID GRID DEFINITIONS
PARAMETER GridS '0.00005'
PARAMETER GridS2 '0.00002'
*** FLUID GRID DEFINITIONS
*.005
* Grid 1 originally set to be 0.005
PARAMETER Grid1 '0.005'
PARAMETER Grid2 '8'
***Grid Modify
PARAMETER NDIV1v '40'
PARAMETER NDIV2v '20'
PARAMETER NDIV3v '80'
PARAMETER NDIV4v '3'
PARAMETER NDIV1h '8'
***Grid Modify
PARAMETER NDIV2h '80'
PARAMETER NDIV3h '40'
PARAMETER NDIV4h '4'
PARAMETER NDIV5h '20'
PARAMETER NDIVTube '120'

*** SYMMETRY PLANE
PARAMETER zt '0.0084'
PARAMETER dg '0.0001'
PARAMETER zc '$zt+$dg'
PARAMETER zContact '$zt+.000025'

*** POINT DEFINITIONS
PARAMETER y1 '0'
PARAMETER z1 '0'
PARAMETER y2 '0.00659883'
PARAMETER z2 '0.00786418'
PARAMETER y3 '0.0077479'
PARAMETER z3 '0.0084'
PARAMETER y4 '0.00976183'
PARAMETER z4 '0.0084'
PARAMETER y5 '0.00976183+0.000987*cos(45*2*3.14159/360)'
PARAMETER z5 '0.007413+0.000987*sin(45*2*3.14159/360)'
PARAMETER y6 '0.01074883'
PARAMETER z6 '0.007413'
PARAMETER y7 '0.01074883'
PARAMETER z7 '0'
PARAMETER y7a '0.00261081'
PARAMETER z7a '0'
PARAMETER y8 '0.0077479'
PARAMETER z8 '0.0069'
PARAMETER y9 '0.00976183'
PARAMETER z9 '0.007413'
PARAMETER y10 '0.00785616'
PARAMETER z10 '0.00625116'
PARAMETER y11 '0.0082517'
PARAMETER z11 '0.00640005'
PARAMETER y12 '0.00849224'
PARAMETER z12 '0.0064'
PARAMETER y13 '0.00874883'
PARAMETER z13 '0.00614342'
PARAMETER y14 '0.00874883'
PARAMETER z14 '0'
PARAMETER y15 '0.0082517'
PARAMETER z15 '0.0058005'
PARAMETER y16 '0.00849224'
PARAMETER z16 '0.00614342'
PARAMETER y17 '0.006'
PARAMETER z17 '$zContact'
PARAMETER y18 '0.012'
PARAMETER z18 '$zContact'
PARAMETER yf10 '(-DuctLength-0.308')
* Change zf10 value to make the plenum area bigger
* Originally set to:
*PARAMETER zf10 '$zc-10*0.01524'
* The new parameter is:
PARAMETER zf10 '((-1.27e-2)*118'
PARAMETER yf11 '$yf10'
PARAMETER zf11 '(-0.0731063'
PARAMETER yf12 '$yf10'
PARAMETER zf12 ' -0.0604063'
PARAMETER yf13 '$yf10'
PARAMETER zf13 '$zc-0.0127'
PARAMETER yf14 '$yf10'
PARAMETER zf14 '$zc'
PARAMETER yf15 '(-DuctLength'
PARAMETER zf15 '$zf10'
PARAMETER yf16 '$yf15'
PARAMETER zf16 '$zf11'
PARAMETER yf17 '$yf15'
PARAMETER zf17 '$zf12'
PARAMETER yf18 '$yf15'
PARAMETER zf18 '$zf13'
PARAMETER yf19 '$yf15'
PARAMETER zf19 '$zf14'
PARAMETER yf20 '(-0.0032625'
PARAMETER zf20 '$zf13'

100
PARAMETER yf21 '$yf20'
PARAMETER zf21 '$zf14'
PARAMETER yf22 '0'
PARAMETER zf22 '$zf13'
PARAMETER yf23 '0'
PARAMETER zf23 '$zf14'
PARAMETER yf24 '$y3'
PARAMETER zf24 '$zf14'
PARAMETER yf25 '$y4'
PARAMETER zf25 '$zf14'
PARAMETER yf26 '$y6'
PARAMETER zf26 '$zf10'
PARAMETER yf27 '$y6+0.001'
PARAMETER zf27 '$zf10'
PARAMETER yf28 '$yf27'
PARAMETER zf28 '$z6'
PARAMETER yf29 '$yf27'
PARAMETER zf29 '$zf14'
PARAMETER yf30 '$y6+0.002'
PARAMETER zf30 '$zf10'
PARAMETER yf31 '$yf30'
PARAMETER zf31 '$z6'
PARAMETER yf32 '$yf30'
PARAMETER zf32 '$zf14'
PARAMETER yf33 '$y6+0.1'
PARAMETER zf33 '$zf10'
PARAMETER yf34 '$yf33'
PARAMETER zf34 '$z6'
PARAMETER yf35 '$yf33'
PARAMETER zf35 '$zf14'
PARAMETER yf36 '$yf27'
PARAMETER zf36 '$z7-0.001'
PARAMETER yf37 '$yf30'
PARAMETER zf37 '$zf36'
PARAMETER yf38 '$yf33'
PARAMETER zf38 '$zf36'

*** How many steps to save
PARAMETER NodeStepSkip '10'
PARAMETER ElementStepSkip '10'
A.0.3  f.in

The f.in file constructs the fluid domain of the vocal tract model. This file references the parameter.in file to generate the model.

*  
*  
DATABASE NEW SAVE=NO PROMPT=NO  
FEPROGRAM ADINA-F  
CONTROL FILEVERSION=V84  
*  
MASTER ANALYSIS=TRANSIENT MODEX=EXECUTE TSTART=0.00000000000000,  
IDOF=10001 TURBULEN=NO HYDRO=YES STREAM=YES TRACTB=YES,  
IRINT=DEFAULT AUTOMATI=YES SOLVER=SPARSE COMPRESS=SLI,  
FSINTERA=YES NMASS=0 MASSCOUP=NO MAP-OUTP=NONE MAP-FORM=NO,  
NONDIMEN=NO MAXSOLME=0 MTOTM=2 RECL=3000 ALE=NO THERMAL-=NO,  
UPWINDIN=CONTROL-VOLUME MESHUPDA=ORIGINAL MESHADAP=NO,  
COUPLING=DIRECT POROUS-C=NO CELL-BCD=YES VOF=NO FCBI=NO,  
TURB-ITE=Coupled EM-MODEL=NO ALE-CURV=YES ADAPTIVE=''' ENSIGHT-=FORMATTED  
*  
READ parameter.in  
*  
COORDINATES POINT SYSTEM=0  
@CLEAR  
1 0.0 $y1 $z1 0  
2 0.0 $y2 $z2 0  
3 0.0 $y3 $z3 0  
4 0.0 $y4 $z4 0  
5 0.0 $y5 $z5 0  
6 0.0 $y6 $z6 0  
7 0.0 $y7 $z7 0  
8 0.0 $y8 $z8 0  
9 0.0 $y9 $z9 0  
10 0.0 $yf10 $zf10 0  
11 0.0 $yf11 $zf11 0  
12 0.0 $yf12 $zf12 0  
13 0.0 $yf13 $zf13 0  
14 0.0 $yf14 $zf14 0  
15 0.0 $yf15 $zf15 0  
16 0.0 $yf16 $zf16 0  
17 0.0 $yf17 $zf17 0  
18 0.0 $yf18 $zf18 0  
19 0.0 $yf19 $zf19 0
20 0.0 $yf20 $zf20 0
21 0.0 $yf21 $zf21 0
22 0.0 $yf22 $zf22 0
23 0.0 $yf23 $zf23 0
24 0.0 $yf24 $zf24 0
25 0.0 $yf25 $zf25 0
26 0.0 $yf26 $zf26 0
27 0.0 $yf27 $zf27 0
28 0.0 $yf28 $zf28 0
29 0.0 $yf29 $zf29 0
30 0.0 $yf30 $zf30 0
31 0.0 $yf31 $zf31 0
32 0.0 $yf32 $zf32 0
33 0.0 $yf33 $zf33 0
34 0.0 $yf34 $zf34 0
35 0.0 $yf35 $zf35 0
36 0.0 $yf36 $zf36 0
37 0.0 $yf37 $zf37 0
38 0.0 $yf38 $zf38 0
@
*
LINE STRAIGHT NAME=1 P1=1 P2=2
LINE ARC NAME=2 MODE=1 P1=2 P2=3 CENTER=8 PCOINCID=YES, PTOLERAN=1.0E-05
LINE STRAIGHT NAME=3 P1=3 P2=4
LINE ARC NAME=4 MODE=1 P1=4 P2=5 CENTER=9 PCOINCID=YES, PTOLERAN=1.0E-05
LINE ARC NAME=5 MODE=1 P1=5 P2=6 CENTER=9 PCOINCID=YES, PTOLERAN=1.0E-05
LINE STRAIGHT NAME=6 P1=6 P2=7
LINE STRAIGHT NAME=7 P1=10 P2=11
LINE STRAIGHT NAME=8 P1=11 P2=12
LINE STRAIGHT NAME=9 P1=12 P2=13
LINE STRAIGHT NAME=10 P1=13 P2=14
LINE STRAIGHT NAME=11 P1=10 P2=15
LINE STRAIGHT NAME=12 P1=11 P2=16
LINE STRAIGHT NAME=13 P1=12 P2=17
LINE STRAIGHT NAME=14 P1=13 P2=18
LINE STRAIGHT NAME=15 P1=14 P2=19
LINE STRAIGHT NAME=16 P1=15 P2=16
LINE STRAIGHT NAME=17 P1=16 P2=17
LINE STRAIGHT NAME=18 P1=17 P2=18
LINE STRAIGHT NAME=19 P1=18 P2=19
LINE STRAIGHT NAME=20 P1=18 P2=20
LINE STRAIGHT NAME=21 P1=19 P2=21
SURFACE PATCH NAME=8 EDGE1=27 EDGE2=28 EDGE3=29 EDGE4=50
SURFACE PATCH NAME=9 EDGE1=29 EDGE2=30 EDGE3=31 EDGE4=3
SURFACE PATCH NAME=10 EDGE1=31 EDGE2=32 EDGE3=33 EDGE4=4
SURFACE PATCH NAME=11 EDGE1=33 EDGE2=39 EDGE3=34 EDGE4=5
SURFACE PATCH NAME=12 EDGE1=6 EDGE2=34 EDGE3=53 EDGE4=35
SURFACE PATCH NAME=13 EDGE1=35 EDGE2=38 EDGE3=37 EDGE4=36
SURFACE PATCH NAME=14 EDGE1=39 EDGE2=42 EDGE3=44 EDGE4=41
SURFACE PATCH NAME=15 EDGE1=41 EDGE2=43 EDGE3=40 EDGE4=38
SURFACE PATCH NAME=16 EDGE1=44 EDGE2=47 EDGE3=49 EDGE4=46
SURFACE PATCH NAME=17 EDGE1=43 EDGE2=46 EDGE3=48 EDGE4=45
SURFACE PATCH NAME=18 EDGE1=53 EDGE2=41 EDGE3=54 EDGE4=51
SURFACE PATCH NAME=19 EDGE1=38 EDGE2=51 EDGE3=43 EDGE4=40
SURFACE PATCH NAME=20 EDGE1=54 EDGE2=46 EDGE3=55 EDGE4=52
SURFACE PATCH NAME=21 EDGE1=43 EDGE2=52 EDGE3=48 EDGE4=45
*
BOUNDARY-CON WALL NAME=1 GTYPE=LINES SLIPC=0 MOVING=NO,
   VTYPE=CONVENTIONAL VT=0 NCURVT=0 DX=1 DY=0 DZ=0 X0=0, 
   Y0=0 Z0=0 ALL-EXT=NO THERMAL=HEAT-FLUX TVALUE=0 NCURT=0
@CLEAR
7 0
9 0
8 0
11 0
16 0
17 0
18 0
20 0
23 0
26 0
36 0
@
*
BOUNDARY-CON WALL NAME=2 GTYPE=LINES SLIPC=1 MOVING=NO,
   VTYPE=CONVENTIONAL VT=0 NCURVT=0 DX=1 DY=0 DZ=0 X0=0, 
   Y0=0 Z0=0 ALL-EXT=NO THERMAL=HEAT-FLUX TVALUE=0 NCURT=0
@CLEAR
15 0
21 0
25 0
28 0
30 0
32 0
42 0
47 0
@
* 
BOUNDARY-CON FLUID-STRUCTURE NAME=3 GTYPE=LINES SLIPC=0, 
FSBOUNDDA=1 VTYPE=CONVENTIONAL VT=0 NCURVT=0 DX=0 DY=0, 
DZ=0 X0=1 Y0=0 Z0=0 ALL-EXT=NO THERMAL=HEAT-FLUX TVALUE=0 NCURT=0
@CLEAR
50 0
3 0
4 0
5 0
6 0
@
* For this area ratio, 0.001 m / 0.005 s is good
TIMEFUNCTION NAME=2
@CLEAR
#READ swept_sine.txt
#0 0
#$TFTime $TFDisp
#1.E+20 $TFDisp
1.E+20 1
@
zBOUNDARY-CON WALL NAME=4 GTYPE=LINES SLIPC=0,
MOVING=YES NCURX=0 NCURY=2 NCURZ=0 START=0,
STOP=1.0E+12 VTYPE=CONVENTIONAL VT=0.0,
NCURVT=0 DX=1.0 DY=0.0 DZ=0.0 X0=0.0 Y0=0.0, 
Z0=0.0 ALL-EXT=NO THERMAL=HEAT-FLUX TVALUE=0.0 NCURT=0
@CLEAR
8 0
@
*
LEADER-FOLLOW
@CLEAR
1 3 24 1 0
2 4 25 1 0
3 5 29 1 0
4 5 32 1 0
5 6 28 1 0
6 6 31 1 0
@
*
LOAD NORMAL-TRACTION NAME=1 MAGNITUD=$Pressure
*
APPLY-LOAD BODY=0
@CLEAR
1 'NORMAL-TRACTION' 1 'LINE' 10 0 1 0 0 0 0 0
2 'NORMAL-TRACTION' 1 'LINE' 9 0 1 0 0 0 0 0

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3 'NORMAL-TRACTION' 1 'LINE' 8 0 1 0 0 0 0 0
4 'NORMAL-TRACTION' 1 'LINE' 7 0 1 0 0 0 0 0
@
*
FIXITY NAME=ZEROPRES
@CLEAR
'X-VELOCITY'
'PRESSURE'
'TEMPERATURE'
'TURBULENT-K'
'TURBULENT-E'
@ FIXBOUNDARY LINES FIXITY=ALL
@CLEAR
37 'ZEROPRES'
40 'ZEROPRES'
45 'ZEROPRES'
48 'ZEROPRES'
49 'ZEROPRES'
55 'ZEROPRES'
@
MATERIAL CONSTF NAME=1 XMU=1.8E-05 CP=0,
   XKCON=0.0 BETA=0.0 QB=0.0 RH0=1.2 TREF=0.0,
   GRAV-X=0.0 GRAV-Y=0.0 GRAV-Z=0.0 SIGMA=0.0,
   KAPPA=141000 CV=0.0 MDESCRIP='Air'
*
SUBDIVIDE SURFACE NAME=1 MODE=LENGTH SIZE=$Grid1
@CLEAR
2 3 4 5
@
SUBDIVIDE SURFACE NAME=6 MODE=DIVISIONS NDIV1=$NDIV1h NDIV2=$NDIV1h,
   RATIO1=1 RATIO2=1 PROGRESS=GEOMETRIC EXTEND=NONE CBIAIS1=NO CBIAIS2=NO
SUBDIVIDE SURFACE NAME=7 MODE=DIVISIONS NDIV1=$NDIV1v NDIV2=$NDIV1h,
   RATIO1=1 RATIO2=1 PROGRESS=GEOMETRIC EXTEND=NONE CBIAIS1=NO CBIAIS2=NO
SUBDIVIDE LINE NAME=20 MODE=DIVISIONS NDIV1=$NDIVTube RATIO=0.05,
   PROGRESS=ARITHMETIC CBIAIS=NO
@CLEAR
21
@
SUBDIVIDE LINE NAME=29 MODE=DIVISIONS NDIV1=$NDIV1v RATIO=1,
   PROGRESS=ARITHMETIC CBIAIS=NO
@CLEAR
30 31 33 34
@
SUBDIVIDE LINE NAME=50 MODE=DIVISIONS NDIV1=$NDIV1v RATIO=1,
PROGRESS=ARITHMETIC CBIAS=NO
@CLEAR
28 3 30 4 32 5 39 41 42 44
@SUBDIVIDE LINE NAME=28 MODE=DIVISIONS NDIV=$NDIV2h RATIO=0.4,
    PROGRESS=ARITHMETIC CBIAS=NO
SUBDIVIDE LINE NAME=50 MODE=DIVISIONS NDIV=$NDIV2h RATIO=0.25,
    PROGRESS=ARITHMETIC CBIAS=NO
SUBDIVIDE LINE NAME=6 MODE=DIVISIONS NDIV=$NDIV1v RATIO=10,
    PROGRESS=ARITHMETIC CBIAS=NO
SUBDIVIDE LINE NAME=53 MODE=DIVISIONS NDIV=$NDIV1v RATIO=0.1,
    PROGRESS=ARITHMETIC CBIAS=NO
@CLEAR
54
@SUBDIVIDE LINE NAME=35 MODE=DIVISIONS NDIV=$NDIV4h RATIO=1,
    PROGRESS=ARITHMETIC CBIAS=NO
@CLEAR
51
@SUBDIVIDE LINE NAME=36 MODE=DIVISIONS NDIV=$NDIV2v RATIO=0.05,
    PROGRESS=ARITHMETIC CBIAS=NO
@CLEAR
38 43 48
@SUBDIVIDE LINE NAME=46 MODE=DIVISIONS NDIV=$NDIV3v RATIO=50,
    PROGRESS=ARITHMETIC CBIAS=NO
@CLEAR
47 52
SUBDIVIDE LINE NAME=45 MODE=DIVISIONS NDIV=$NDIV5h RATIO=1,
    PROGRESS=ARITHMETIC CBIAS=NO
SUBDIVIDE LINE NAME=55 MODE=DIVISIONS NDIV=$NDIV4v RATIO=1,
    PROGRESS=ARITHMETIC CBIAS=NO
*
EGROUP TWODFLUID NAME=1 SUBTYPE=PLANAR MATERIAL=1 INT=3,
    RESULTS=STRESSES DEGEN=NO DISSP=NO SOLID=NO UPWINDIN=DEFAULT,
    OPTION=NONE FLOWTYPE=DEFAULT VOF-MATE=1 DESCRIPT='NONE'
*
GSURFACE NODES=4 PATTERN=AUTOMATIC NCOINCID=BOUNDARIES NCEDGE=1234,
    NCVERTEX=1234 NCTOLERA=1.00000000000000E-05 SUBSTRUC=0 GROUP=1,
    PREFSHAP=AUTOMATIC MESHING=MAPPED SMOOTHIN=NO DEGENERA=NO,
    COLLAPSE=NO MIDNODES=CURVED METHOD=ADVFRONT FLIP=NO
@CLEAR
1 2 3 4 5 6 7 8 9 10 11 12 13 14 16 18 19 20 21
@
ANALYSIS TRANSIENT ALPHA=0.707106781186547 METHOD=COMPOSI

* TIMESTEP NAME=DEFAULT
  @CLEAR
  $NSteps $dt
  @
  *
  AUTOMATIC TIME-STEPPING MAXSUBD=$MaxATS ICOUR=ATS,
  COURAN=1.0E+20 ITMAXC=100000
  *
  ITERATION METHOD=NEWTON MAX-ITER=300 ITM-SPEC=1
  *
  TOLERANCES FLUID-STRUCTURE CONVERGE=FD ITLIM=300,
  DTOTD=0.01 DTOTF=0.01 RLXFORCE=1 RLXDISPL=1,
  COUPLING=DIRECT
  *
  ELEMSAVE-STE NODESAVE=NO
  @CLEAR
  1 1 $NSteps $ElementStepSkip
  @
  NODESAVE-STE ELEMSAVE=NO
  @CLEAR
  1 1 $NSteps $NodeStepSkip
  @
  *
  ANALYSIS TRANSIENT ALPHA=1.0 METHOD=EULER
  *
  *** WRITE OUTPUT FILES
  ADINA-F OPTIMIZE=SOLVER FILE='f.dat' FIXBOUND=YES,
  MIDNODE=NO OVERWRIT=YES FORMATTE=YES
  *
  DATABASE SAVE PERMFILE='f.idb' PROMPT=NO
  *END SAVE=NO IMMEDIATE = NO
A.0.4  s.in

The s.in file constructs the fluid domain of the vocal tract model. This file references the parameter.in file to generate the model.

**********************************************************************************************
* File name: s.in
*
* Created by: Scott Thomson
* Purpose of file: This file contains ADINA commands for generating
* the model and its definitions for the solid domain only.
*
* Last modified by: Jesse Daily
* Last modified: May 29, 2010
* Purpose for latest modification: The epithelium was eliminated
* because it was thought that the epithelium would add extra
* stiffness to the model. Originally I was using Tim Shurtz's model
* but I had so many problems with it that I decided to just modify
* my model which I knew worked. That also means that this model does
* not include tim's fluid domain mesh update. Which was causing the
* problems.
*
* History of modifications:
* May 29, 2010 - Elimination of epithelium layer
*
* end header
**********************************************************************************************

** DATABASE NEW SAVE=NO PROMPT=NO
** FEPROGRAM ADINA
** CONTROL FILEVERSION=V84
*
** MASTER ANALYSIS=DYNAMIC-DIRECT-INTEGRATION MODEX=EXECUTE,
** TSTART=0.00000000000000 IDOF=100011 OVALIZAT=NONE,
** FLUIDPOT=AUTOMATIC CYCLICPA=1 IPOSIT=STOP REACTION=YES,
** INITIALS=NO FSINTERA=YES IRINT=DEFAULT CMASS=NO,
** SHELLNDO=AUTOMATIC AUTOMATI=ATS SOLVER=SPARSE,
** CONTACT-=CONSTRAINT-FUNCTION TRELEASE=0.00000000000000,
** RESTART-=NO FRACTURE=NO LOAD-CAS=NO LOAD-PEN=NO MAXSLME=0,
** MTOTM=2 RECL=3000 SINGULAR=YES STIFFNES=1.00000000000000E-09,
** MAP-OUTP=NONE MAP-FORM=NO NODAL-DE='' POROUS-C=NO ADAPTIVE=0,
** ZOOM-LAB=1 AXIS-CYC=0 PERIODIC=NO VECTOR-S=GEOMETRY EPSI-FIR=NO,
** STABILIZ=NO STABFACT=1.00000000000000E-12 RESULTS=PORTHOLE
*
READ parameter.in
*
COORDINATES POINT SYSTEM=0
@CLEAR
  1 0.0 $y1 $z1 0
  2 0.0 $y2 $z2 0
  3 0.0 $y3 $z3 0
  4 0.0 $y4 $z4 0
  5 0.0 $y6 $z6 0
  6 0.0 $y7 $z7 0
  7 0.0 $y8 $z8 0
  8 0.0 $y9 $z9 0
  9 0.0 $y7a $z7a 0
 10 0.0 $y10 $z10 0
 11 0.0 $y11 $z11 0
 12 0.0 $y12 $z12 0
 13 0.0 $y13 $z13 0
 14 0.0 $y14 $z14 0
 15 0.0 $y15 $z15 0
 16 0.0 $y16 $z16 0
 17 0.0 $y17 $z17 0
 18 0.0 $y18 $z18 0
@
*
LINE STRAIGHT NAME=1 P1=1 P2=2
LINE ARC NAME=2 MODE=1 P1=2 P2=3 CENTER=7 PCOINCID=YES, PTOLERAN=1.0E-05
LINE STRAIGHT NAME=3 P1=3 P2=4
LINE ARC NAME=4 MODE=1 P1=4 P2=5 CENTER=8 PCOINCID=YES, PTOLERAN=1.0E-05
LINE STRAIGHT NAME=5 P1=5 P2=6
LINE STRAIGHT NAME=6 P1=9 P2=10
LINE ARC NAME=7 MODE=1 P1=10 P2=11 CENTER=15 PCOINCID=YES, PTOLERAN=1.0E-05
LINE STRAIGHT NAME=8 P1=11 P2=12
LINE ARC NAME=9 MODE=1 P1=12 P2=13 CENTER=16 PCOINCID=YES, PTOLERAN=1.0E-05
LINE STRAIGHT NAME=10 P1=13 P2=14
LINE STRAIGHT NAME=11 P1=1 P2=9
LINE STRAIGHT NAME=12 P1=6 P2=14
LINE STRAIGHT NAME=13 P1=14 P2=9
LINE STRAIGHT NAME=14 P1=17 P2=18
LINE COMBINED NAME=15 COUPLED=YES RESTRICT=NO
@CLEAR
  1 2 3 4 5 12 10 9 8 7 6 11
@ LINE COMBINED NAME=16 COUPLED=YES RESTRICT=NO
@CLEAR
6 7 8 9 10 13
@
*
BODY SHEET NAME=1 LINE=15 DELETE-L=YES
BODY SHEET NAME=2 LINE=16 DELETE-L=YES
*
SUBDIVIDE FACE NAME=1 BODY=1 MODE=LENGTH SIZE=$GridS
SUBDIVIDE EDGE NAME=12 BODY=1 MODE=LENGTH SIZE=$GridS2
@CLEAR
11 10 9 8 7 6
@
SUBDIVIDE EDGE NAME=1 BODY=2 MODE=LENGTH SIZE=$GridS2
@CLEAR
2 3 4 5 6
@
*
FIXBOUNDARY EDGES FIXITY=ALL BODY=1
@CLEAR
6  'ALL'
12  'ALL'
@
FIXBOUNDARY EDGES FIXITY=ALL BODY=2
@CLEAR
6  'ALL'
@
*
FSBOUNDARY TWO-D NAME=1
@CLEAR
1 1
2 1
3 1
4 1
5 1
@
*
KINEMATICS DISPLACE=LARGE STRAINS=LARGE PRESSURE=NO INCOMPAT=NO
*
* Cover stress-strain curve
SSCURVE NAME=1 CONSTANT=YES NU=0.495
@CLEAR
-0.5 $EcNegS 0
-0.1 $EcNeg 0
0 0 0
0.1 $EcPos 0
0.5 $EcPosS 0
1.0 $Ec 0
@
*
* Body stress-strain curve
SSCURVE NAME=2 CONSTANT=YES NU=0.495
@CLEAR
-0.5 $EbNegS 0
-0.1 $EbNeg 0
0 0 0
0.1 $EbPos 0
0.5 $EbPosS 0
1.0 $Eb 0
@

CURVE-FITTIN NAME=1 TENSION=-1 SHEAR-CU=0 EQUIBIAX=0 ORDER=6,
WEIGHTIN=NO CURVE-TY=STRAIN METHOD=SVD NSINGULA=AUTOMATIC,
ECHO=ALL

MATERIAL OGDEN NAME=1 MU1=0 ALPHA1=0, MU2=0 ALPHA2=0, MU3=0 ALPHA3=0,
MU4=0 ALPHA4=0, MU5=0 ALPHA5=0, MU6=0 ALPHA6=0, MU7=0 ALPHA7=0,
MU8=0 ALPHA8=0, MU9=0 ALPHA9=0, KAPPA=$Kappac DENSITY=1070 FITTING=-1,
VISCOELA=0 TEMPERAT=NO TREF=0.00000000000000 RUBBER-T=0,
RUBBER-V=0 RUBBER-M=0 RUBBER-O=0 MDESCRIP='Cover'

CURVE-FITTIN NAME=2 TENSION=-2 SHEAR-CU=0 EQUIBIAX=0 ORDER=6,
WEIGHTIN=NO CURVE-TY=STRAIN METHOD=SVD NSINGULA=AUTOMATIC,
ECHO=ALL

MATERIAL OGDEN NAME=2 MU1=0 ALPHA1=0, MU2=0 ALPHA2=0, MU3=0 ALPHA3=0,
MU4=0 ALPHA4=0, MU5=0 ALPHA5=0, MU6=0 ALPHA6=0, MU7=0 ALPHA7=0,
MU8=0 ALPHA8=0, MU9=0 ALPHA9=0, KAPPA=$Kappab DENSITY=1070 FITTING=-2,
VISCOELA=0 TEMPERAT=NO TREF=0.00000000000000 RUBBER-T=0,
RUBBER-V=0 RUBBER-M=0 RUBBER-O=0 MDESCRIP='Body'

*MATERIAL ELASTIC NAME=1 E=4000 NU=$Nue DENSITY=1000 ALPHA=0 MDESCRIP='Cover'
*CROSS-SECTIO RECTANGULAR NAME=1 WIDTH=1 HEIGHT=5E-05 SC=0 TC=0 TORFAC=1,
* SSHEARF=0 TSHEARF=0 ISHEAR=NO SQUARE=NO
*
*MATERIAL ELASTIC NAME=2 E=13000 NU=$Nue DENSITY=1000 ALPHA=0 MDESCRIP='Body'
*CROSS-SECTIO RECTANGULAR NAME=1 WIDTH=1 HEIGHT=5E-05 SC=0 TC=0 TORFAC=1,
* SSHEARF=0 TSHEARF=0 ISHEAR=NO SQUARE=NO
*
*  
PROCESS NPROC=1 MINEL=0 MAXEL=999999  
*  
EGCONTROL MAXELG=999999  
*  
ELEMSAVE-STE NODESAVE=NO  
@CLEAR  
 1 $NSteps $ElementStepSkip  
@  
NODESAVE-STE ELEMSAVE=NO  
@CLEAR  
 1 $NSteps $NodeStepSkip  
@  
*  
RAYLEIGH-DAM  
@CLEAR  
 1 $ALPHA $BETA  
 2 $ALPHA $BETA  
 3 $ALPHA $BETA  
@  
CGROUP CONTACT2 NAME=1 SUBTYPE=STRAIN FORCES=YES TRACTION=YES,  
NODETONO=NO FRICITION=0.00000000000000 EPSN=1.00000000000000E-12,  
EPST=0.00000000000000 DIRECTIO=NORMAL CONTINUO=YES,  
INITIAL-=ALLOWED PENETRAT=ONE DEPTH=0.00000000000000,  
OFFSET=0.00000000000000 OFFSET-T=CONSTANT CORNER-C=NO,  
TBIRTH=0.00000000000000 TDEATH=0.00000000000000 TIED=NO,  
TIED-OFF=0.00000000000000 HHATTMC=0.00000000000000,  
FCTMC=0.50000000000000 FTMMC=0.50000000000000 RIGID-TA=NO,  
NORMAL-S=1.00000000000000E+11 TANGENTI=0.00000000000000,  
PTOLERAN=1.00000000000000-08 RESIDUAL=0.00100000000000000,  
LIMIT-FO=1.00000000000000 ITERATIO=2 TIME-PEN=0.00000000000000,  
CONSISTE=DEFAULT USER-FRI=NO DESCRIPT='NONE',  
CFATOR1=0.00000000000000 CS-EXTEN=0.00100000000000000,  
ALGORITHM=DEFAULT RTP-CHEC=NO RTP-MAX=0.00100000000000000,  
XDAMP=NO XNANDAMP=0.10000000000000000 DISPLACE=DEFAULT FRIC-DEL=NO,  
GAP-VALU=0.00000000000000 EKTMC=0.00000000000000  
*  
CONTACTSURFA NAME=1 PRINT=DEFAULT SAVE=DEFAULT SOLID=YES BODY=1,  
ORIENTAT=AUTOMATIC MARQUEEB=0 DESCRIPT='NONE'  
@CLEAR  
 2 1 0  
 3 1 0  
 4 1 0  
@
CONTACTSURFA NAME=2 PRINT=DEFAULT SAVE=DEFAULT SOLID=NO BODY=1, ORIENTAT=AUTOMATIC MARQUEEB=0 DESCRIPT='NONE'
@CLEAR
14 1 0
*
CONTACTPAIR NAME=1 TARGET=2 CONTACTO=1 FRICTION=0.000000000000000, TBBIRTH=0.000000000000000 TDEATH=0.000000000000000, HHATTMC=0.000000000000000 FCTMC=0.000000000000000, FTTMC=0.000000000000000 NX=0 NY=0 NZ=0 OFFSETCO=BOTH, EKTMC=0.000000000000000
*
SUBDIVIDE LINE NAME=14 MODE=DIVISIONS NDIV=32 RATIO=1, PROGRESS=GEOMETRIC CBIAS=NO
*
CSURFACE NAME=2 NODES=2 NCOINCID=SURFACE, NCTOLERA=1.000000000000000E-05 SUBSTRUC=0 GROUP=1
****
ADINA OPTIMIZE=SOLVER FILE='s.dat', FIXBOUND=YES MIDNODE=NO OVERWRIT=YES DATABASE SAVE PERMFILE='s.idb' PROMPT=NO *END SAVE=NO IMMEDIATE = NO
*
CSDELETE LINE GROUP=1 CONTACTS=2 NODE-DEL=YES BODY=0
@CLEAR
14 @
COORDINATES POINT SYSTEM=0
17 0.0 $y17 0.009 0
18 0.0 $y18 0.009 0
@
CSURFACE NAME=2 NODES=2 NCOINCID=SURFACE, NCTOLERA=1.000000000000000E-05 SUBSTRUC=0 GROUP=1
MASTER ANALYSIS=FREQUENCIES MODEX=EXECUTE TSTART=0.000000000000000, IDOF=10011 OVALIZAT=NONE FLUIDPOT=AUTOMATIC CYCLICPA=1, IPPOSIT=STOP REACTION=YES INITALS=NO FSINTERA=NO IRINT=DEFAULT, CMASS=NO SHELLNDO=AUTOMATIC AUTOMATI=ATS SOLVER=SPARSE, CONTACT-=CONSTRAINT-FUNCTION TRELEASE=0.000000000000000, RESTART-=NO FRACTURE=NO LOAD-CAS=NO LOAD-PEN=NO MAXSOLME=0, MTOTM=2 RECL=3000 SINGULAR=YES STIFFNES=1.000000000000000E-09, MAP-OUTP=NONE MAP-FORM=NO NODAL-DE='' POROUS-C=NO ADAPTIVE=0, ZOOM-LAB=1 AXIS-CYC=0 PERIODIC=NO VECTOR-S=GEOMETRY EPSI-FIR=NO, STABILIZ=NO STABFACT=1.000000000000000E-12 RESULTS=PORTHOLE, FEFCORR=NO BOLTSTEP=1
*  
FREQUENCIES METHOD=SUBSPACE-ITERATION NEIGEN=6 NMODE=3 IPRINT=NO,
  RIGID-BO=NO RSHIFT=0.00000000000000 CUTOFF=1.00000000000000E+08,
  NITEMM=DEFAULT NVVECTOR=DEFAULT STURM-CH=NO ACCELERA=NO,
  TOLERANC=DEFAULT STARTTYP=LANCZOS NSTVECTO=0 INTERVAL=NO,
  FMIN=0.00000000000000 FMAX=DEFAULT MODALSTR=NO STATIC=NO,
  NSHIFT=AUTO NSHIFT-B=50
ADINA OPTIMIZE=SOLVER FILE='sMod.dat',
  FIXBOUND=YES MIDNODE=NO OVERWRT=YES
DATABASE SAVE PERMFILE='sMod.idb' PROMPT=NO
A.0.5 Iterate_Ensight.py

The iterate_Ensight.py file is a python API that was generated and read by Ensight. The file generates a text file of pressure along the slip wall at a single moment in time. The code then iterates to generate multiple text files over time. Hence the name of the file, iterate_Ensight.py.

```python
# Python API file for Ensight
# Made by Jesse Daily, May 5, 2010 (El cinco de Mayo)
#
# Background - This Python script allows the user to automate postprocessing
# of CFD results. This allows the user to perform most, if not all postprocessing
# within the main submission script. This particular Python script monitors the
# pressure along a line in time.
#
# Methods - This Python script does 4 things: 1) loads a case file (called f.case),
# 2) Changes the perspective of the CFD data (defunct for batch processes), 3) inserts
# a line tool that monitors pressure in the fluid domain, 4) iterates in time and
# writes the pressure results to an output txt file.
#
ensight.sendmesgoptions(version="9.03 (a)")
ensight.part.select_default()
ensight.part.modify_begin()
ensight.part.elt_representation("3D_feature_2D_full")
ensight.part.modify_end()
ensight.data.binary_files_are("big_endian")
ensight.data.format("case")
ensight.data.shift_time(1.000000,0.000000,0.000000)

ensight.data.replace("f.case")
ensight.view_transf.view_recall("+X")
ensight.tools.line("ON")
ensight.view_transf.function("line")
ensight.view_transf.line(1,0.000000e+00,-21.000000e-01,8.490000e-03)
ensight.view_transf.line(2,0.000000e+00,1.000000e-01,8.490000e-03)

for i in range(800,1495,5):
    ensight.solution_time.current_step(i)
    ensight.solution_time.update_to_current()
```
ensight.variables.activate("pressure")
ensight.part.select_begin(1)
ensight.query_ent_var.begin()
ensight.query_ent_var.description(""")
ensight.query_ent_var.query_type("generated")
ensight.query_ent_var.number_of_sample_pts(500)
ensight.query_ent_var.constrain("line_tool")
ensight.query_ent_var.line_loc(1,0.000000,-.900000,0.008490)
ensight.query_ent_var.line_loc(2,0.000000,0.100000,0.008490)
ensight.query_ent_var.distance("arc_length")
ensight.query_ent_var.variable_1("pressure")
ensight.query_ent_var.generate_over("distance")
ensight.query_ent_var.variable_2("DISTANCE")
ensight.query_ent_var.end()
ensight.query_ent_var.query()
ensight.curve.select_begin(0)
ensight.curve.save("formatted",str(i)+"_output.txt")
ensight.sendmesgoptions(version=0)

# Results - The second to last line writes a text file for each time step.
# Files are named TimeStep_output.txt with 'TimeStep' changing to be the
# time step of the loop
A.0.6  Glottal Gap.enc

Glottal Gap.enc is an Ensight command file that was generated by Ensight. The file determines the minimum glottal gap by measuring the maximum height of the FSI surface (Coordinates[Z]). The maximum height is subtracted from the height of the glottal tract (0.0085) and multiplied by two to simulate the other vocal fold. The file writes a text file of glottal gap vs time.

VERSION 9.03 (a)
part: select_default
part: modify_begin
part: elt_representation 3D_feature_2D_full
part: modify_end
data: binary_files_are big_endian
data: format case
data: shift_time 1.000000 0.000000 0.000000
data: replace f.case
view_transf: view_recall +X
part: select_begin
  21
part: select_end
variables: evaluate Glottal_Gap =2*(0.0085 -Coordinates[Z])
query_ent_var: begin
query_ent_var: description
query_ent_var: query_type generated
query_ent_var: #_of_sample_pts 1500
query_ent_var: begin_simtime 0.000000e+00
query_ent_var: end_simtime 1.875
query_ent_var: constrain min
query_ent_var: sample_by value
query_ent_var: variable_1 Glottal_Gap
query_ent_var: generate_over time
query_ent_var: variable_2 TIME
query_ent_var: end
query_ent_var: query
curve: select_begin
  0
curve: select_end
curve: save formatted Glottal_Gap.txt
APPENDIX B. CAMERA CALIBRATION - AUTO POINT FINDING

B.1 Introduction

Experimental methods are often used to better understand the fluid-structure interactions of the vibrating vocal folds. Of particular interest is the jet that is formed in the glottis (glottal jet) during voiced speech. It is thought the formation of this jet affects the quality of speech (see Chapters 3 & 4).

One of the primary methods for examining the glottal jet is using particle image velocimetry (PIV). PIV uses a digital camera to track particles in a two-dimensional plane in a given fluid flow. However, previous research suggests a highly three-dimensional flow nature of the glottal jet [28], making 2D imaging techniques useful, but inadequate for full characterization of the glottal jet velocity field (see references in Chapters 3 and 4). Synthetic aperture particle image velocimetry (SAPIV) expands on the concept of traditional PIV to include multiple cameras that can track tracer particles in three dimensions [32].

As with PIV, the cameras used in SAPIV all need to be calibrated. Typically, camera calibration is done by imaging a known calibration target. The camera is calibrated to relate image data to real world coordinates. The calibration image gives the researcher necessary information such as length scale (pixel/mm) and lens distortion. Belden et al. [32] created a calibration code that would find the corners of a checkerboard target for each calibration image with seven user clicks per calibration image. Typical SAPIV calibration data can have as many as 60 calibration images, thus requiring more than 300 user clicks to calibrate all cameras. This calibration process is time consuming, user intensive, and prone to user error.

Several methods already exist for calibrating cameras. The basic concept behind each of these camera calibration methods is to image an object or shape of known size to determine the size of other objects of unknown size. This is typically done using a fiducial target. The fiducial markers can be checkerboard squares, circles, binary shapes and/or numbers [69] [70] [71].
Figure B.1: A checkerboard camera calibration target. The checkerboard was setup to be a $10 \times 10$ grid with a 4 mm grid spacing.

OpenCV [72] is a popular open-source computer vision package that can calibrate a camera using a checkerboard target. The OpenCV package will find all of the interior corners of a checkerboard target. Unfortunately, the OpenCV package was not written to calibrate multiple cameras simultaneously which does not lend itself to calibrating for SAPIV. Furthermore, the calibration images for SAPIV were typically low resolution images taken in low light and subsequently had very high image noise. The noise and resolution issues with the calibration images prevented the use of these built-in calibration packages.

A new method was developed to locate the fiducial markers of a checkerboard target with minimal user input. This new method uses a checkerboard calibration target and is capable of calibrating multiple cameras simultaneously even in low-light high noise. This code represents an improvement on the calibration code developed by Belden et al. [32]. In the following sections, the theory and algorithm for faster camera calibration method are explained and compared with the previous calibration method written by Belden et al. [32].

B.2 Calibration Method

A short explanation for obtaining calibration data is given to better understand what the new calibration algorithm needs to accomplish in order to improve the SAPIV calibration process.

Appropriate calibration targets are critical for making any calibration code work. Premade calibration targets are included with the SAPIV code release in a folder entitled Calibration_Targets.zip. All calibration targets are .png files and can be resized for printing to fit any need. Calibration targets come in grid sizes from $2 \times 2$ to $20 \times 20$. The targets can be printed at any size
to suit any calibration volume. If the calibration target is printed on paper, the target needs to be adhered to a flat surface so the target does not bend, flex or wrinkle.

A sample 10 × 10 calibration target with 4 mm grid spacing is shown in Fig. B.1. The new calibration algorithm relies on the repetitive nature of the checkerboard target to determine the location of the checkerboard squares. Only calibration targets with an even number of squares can be used (e.g. 8 × 6 grid, 10 × 10 grid, etc., see Section B.3.3). If a calibration target with an odd number of squares is used then the center of the target will be in between squares rather than at an intersection of calibration squares.

Figure B.2: Schematic of SAPIV experimental setup. The cameras were arranged to image a jet of air that emanates from excised human vocal folds. The cameras were set up in two rows of four.

Eight cameras were positioned so that all cameras could see the entire volume of interest (see Fig. B.2). The cameras were arranged in two rows of four with the volume of interest being a 15 mm³ volume just above the vocal folds. The checkerboard calibration target was placed at
Figure B.3: Calibration images and calibration kernels for all eight cameras. Parts of the calibration images were cropped to a single repeating feature in the image called a fiducial kernel. In this case, the repeating feature was an intersection where four squares intersect. The fiducial kernel for each camera was then autocorrelated with the calibration image for the corresponding camera at any calibration plane.

multiple depths within the volume of interest. Each calibration depth is referred to as a calibration plane. Technically, SAPIV only needs calibration planes at the front and back of the volume of interest; however, having several intermediate planes increases the accuracy of the volume reconstruction algorithms (see Section 3.2.3). It is also important that the calibration target not be rotated in the camera image because this will cause the algorithm to incorrectly identify corner points in the calibration target (see discussion in Section B.3.3). All cameras need to image the calibration target at each calibration plane to complete the calibration process for SAPIV. It is important to note that for the calibration code to work, all of the interior corners of the calibration targets must be visible by all cameras at each calibration depth. A simple way to check for this is to place the target in the extremes of the volume of interest. If the target is visible at the extremes, it should be visible throughout the entire volume.

B.3 Algorithm

The SA_2_calibrate.m file is a semi-automatic calibration algorithm that was written in MATLAB to make camera calibration 1) easier, 2) faster, 3) more robust, and 4) more user friendly.
B.3.1 Autocorrelation

The corners of the calibration target were located using autocorrelation. Autocorrelation is the correlation of a signal with itself which can be used to find repetitive parts of a signal. If \( f(x,y) \) is an image of dimensions \( m \times n \) pixels and \( w(x,y) \) is a subset image of \( f \), the autocorrelation \( c \) of \( w(x,y) \) with \( f(x,y) \) can be defined as

\[
c(x,y) = \sum_{s=1}^{m} \sum_{t=1}^{n} w(s,t) f(x+s,y+t).
\] (B.1)

The autocorrelation will be highest when the subset image \( w \) has similar pixel intensities to image \( f \). This fact is used to simplify the calibration process of SAPIV.

The SA_2_calibrate.m was written to work in either a ‘user’ or ‘auto’ mode. In ‘user’ mode, the user is prompted by MATLAB to crop a single fiducial marker in the image of each camera. The cropped fiducial marker will be referred to as a fiducial kernel. In the case of a checkerboard target, this would be the area where four checkerboard squares meet (see Fig. B.3). Assuming the other calibration planes varied only in translation and not rotation or projection, the fiducial kernel for each camera can be used for autocorrelation at any calibration plane. The fiducial kernels are written to an image file for each camera. The ‘auto’ mode simply reads the fiducial kernel images for autocorrelation. This means the ‘auto’ mode will not work unless the fiducial kernel images have first been created in the ‘user’ mode.

B.3.2 Peak Finding

The cropped calibration is then autocorrelated with the calibration image. The autocorrelation yields peaks of high correlation for half of the corners where the black and white squares align and low negative correlation where the black and white squares are opposite of the cropped image (see Fig. B.4). A zoomed-in view of the autocorrelation shows the peaks give a smooth peak (or valley) with a roughly circular cross section (see Fig. B.5).

The 3-D surface plot of the autocorrelation was then converted into an image (see Fig. B.6). This was done because of the ease of manipulating 2-D data using image processing techniques. The autocorrelation images were positive and negative thresholded with values of \( \pm 0.8 \) to find the approximate area where a corner might be located in the calibration image. These areas were then
Figure B.4: Autocorrelation for camera 1. The figure shows the autocorrelation with the positive and negative correlation peaks corresponding to areas of high and low autocorrelation between the calibration image and the fiducial kernel.

grouped using a connected components algorithm [73]. The connected component areas were then analyzed to determine their centroid using the equation

\[
\text{Centroid} = \frac{\sum_{i=1}^{n} \text{pixel}_i}{n},
\]  

where \( \text{pixel}_i \) is a pixel that is part of the connected component area. This was done for both the positive and negative autocorrelation peaks (see Fig. B.5).

**B.3.3 Finding the Corners and Center**

The SAPIV codes written by Belden et al. [32] require five calibration points from the calibration image as reference points: the four corners and center of the target. For the purpose of clarification, the top left, bottom right, bottom left, and top right calibration points will be designated as A, A’, B and B’ respectively (see Fig. B.7). The top left calibration point (A) is
Figure B.5: Close-up of a positive and negative autocorrelation peaks. The 3-D surface is shown as a 2-D image projected below the surface. The 2-D projection was thresholded to produce an area (shown in black) that contains a single autocorrelation maximum or minimum. Each area was investigated using connected component techniques to find the centroids of each area. The location of each centroid was assumed to be the location of each autocorrelation maximum or minimum.

found by determining the minimum euclidean distance between the top left corner of the image (pixel location (0,0)) and each calibration point and is calculated by

$$\text{Top left point} = \text{Min} \left( \sqrt{(x_i - 0)^2 + (y_i - 0)^2} \right), \quad (B.3)$$

where $x_i$ and $y_i$ are the $(x,y)$ coordinates of the $n$th calibration point. The bottom right (A'), bottom left (B), and top right (B') calibration points were found by finding the minimum euclidean distance between the bottom right, top right and top left of the image and the calibration points respectively.
Figure B.6: Cropped calibration images autocorrelated with the corresponding calibration image. The autocorrelation resulted in areas of high correlation (shown as red spots) and low correlation (dark green spots). Both the high and low correlation areas represented parts of the image that are used for calibration.

Figure B.7: Calibration points and corners for corners for each calibration image. The autocorrelation of the calibration image with the cropped images from Fig. B.3 were thresholded to yield their maxima and minima which effectively found all of the interior corners of the calibration target. The results of thresholding are shown for all eight cameras as green dots superimposed on the calibration target images.
by

Bottom right point = \text{Min} \left( \sqrt{(x_i - \text{image width})^2 + (y_i - \text{image height})^2} \right), \quad (B.4)

Bottom left point = \text{Min} \left( \sqrt{(x_i - 0)^2 + (y_i - \text{image height})^2} \right), \quad (B.5)

Top right point = \text{Min} \left( \sqrt{(x_i - \text{image width})^2 + (y_i - 0)^2} \right). \quad (B.6)

The center calibration was identified using the four corner calibration points. This was done by solving for the intersection of the lines that passes through calibration points in opposing corners (A-A', B-B'). The slopes of the two lines were determined \((m_{AA'}, m_{BB'})\) by using

\[
m_{AA'} = \frac{y_A - y_{A'}}{x_A - x_{A'}}, \quad m_{BB'} = \frac{y_B - y_{B'}}{x_B - x_{B'}},
\]

along with the y-intercepts \((b_{AA'}, b_{BB'})\) using,

\[
b_{AA'} = y_A - \frac{y_A - y_{A'}}{x_A - x_{A'}}x_A, \quad b_{BB'} = y_B - \frac{y_B - y_{B'}}{x_B - x_{B'}}x_B.
\]

The intersection of A-A' and B-B' was then calculated with

\[
x_C = \frac{b_{BB'} - b_{AA'}}{m_{AA'} - m_{BB'}}, \quad (B.9)
\]

\[
y_C = m_{AA'}x_C + b_{AA'}, \quad (B.10)
\]

where \((x_C, y_C)\) correspond to the theoretical center of the calibration target.

The SA_2_calibrate.m file first prompts the user to select a repetitive part of the image. Note that in Fig. B.3 the cropped images are not perfectly square. This will result in the calibration points being off by a few pixels. This is not a problem because these points are passed into a Harris Corner detector \([34]\) function called ‘corner_finder.m’ that finds the true location of the corners with sub-pixel accuracy. The autocorrelation for all eight cameras is shown in Fig. B.6. The maximum of the autocorrelation would only find half of the corners in the checkerboard since the pattern of any corner can be reversed to find the other half of the corners. To find the other half of the corners, the minimum of the autocorrelation would find corners that were the exact opposite of the corner that was cropped by the user (see Fig. B.4). The result is that all interior corners of the checkerboard target can be found as shown in Fig. B.7.
Figure B.8: Method for finding the corners and center calibration points. The four outermost corners are identified by searching for the nearest calibration corner to each corner of the image. Lines were drawn between opposing corners to find the center point.

B.4 Results and Conclusions

The purpose of this research was to improve the camera calibration method used in SAPIV to make it easier, faster and more robust.

The new calibration method (SA_2_calibrate.m) was compared to the old calibration method (calib_point_extract.m) to quantify the improvement of the new calibration method (see Table B.1). Two metrics were considered: the time required to perform calibration and the number of user clicks required.

For the SA_2_calibrate.m code, the ‘auto’ and ‘user’ modes were both tested to determine the best and worst case scenarios for the SA_2_calibrate.m code. The SA_2_calibrate.m code was nearly 34 times faster than the previous calibration method in ‘user’ mode and 122 times faster in ‘auto’ mode. The previous calibration code required seven user clicks per calibration image for a total of 336 user clicks for calibration images for eight cameras in six calibration planes. In ‘user’ mode, SA_2_calibrate.m required 21 times fewer user clicks (16 clicks) and in ‘auto’ mode required no user clicks.
Table B.1: Comparison of the old calibration method (calib_point_extract.m) and the new calibration method (SA_2_calibrate.m). The times improvement of the new to the old code is shown in parentheses.

<table>
<thead>
<tr>
<th>Metric</th>
<th>calib_point_extract.m</th>
<th>SA_2_calibrate.m</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>user</td>
<td>auto</td>
</tr>
<tr>
<td>Number of clicks</td>
<td>336</td>
<td>16 (×21)</td>
</tr>
<tr>
<td>Seconds required</td>
<td>1893.4</td>
<td>56.4 (×33.6)</td>
</tr>
</tbody>
</table>

Assuming the user clicked all the points without any mistakes, both calibration methods are equally accurate. Similarly, mistakes in the user input can result in equally bad calibration error for both algorithms. However, for the old calibration method, more than 300 points had to be clicked in the correct order to calibrate, whereas the new algorithm requires less than 20 user clicks. The new algorithm is more robust due to the reduction in opportunities for the user to make a mistake.

The calibration codes main purpose is to find the corners and center of the calibration targets. Given the method for finding the corners outlined above, the code will fail if it encounters the following issues. All of the calibration targets must have an even amount of squares in both the X and Y directions. This is because when the checkerboard has an odd dimension, then the center of the checkerboard will not correspond to an intersection of four squares. This issue can also be encountered if the camera cannot see the entire target.

The calibration target used in the calibration method is a simple checkerboard. If the camera is looking straight at the target, the autocorrelation method can very accurately find all of the corners of the checkerboard target. However, if the camera is looking at the target at a high projection angle, the checkerboard target will appear highly skewed. The higher the projection, the less of the target will be visible by the pixels of the camera. The fewer the pixels, the less likely the autocorrelation will be able to identify the corner points in the calibration target. This will ultimately cause the calibration code to fail.

The autocorrelation method can also fail if the calibration target undergoes rotation. This is because the autocorrelation can detect translation, but not rotation. The algorithm can withstand between 5° to 8° of rotation (depending on how sharp the calibration image is) before the algorithm fails to locate calibration points. Therefore, when moving the calibration target in the volume of
interest, the experimentalist should only move the calibration target in translation. The problem of target rotation could be easily fixed by using a target of dots since the autocorrelation algorithm would still be able to find the dots even if they rotate. Other methods exist such as fiducial calibration targets that could also be explored to further improve camera calibration.
APPENDIX C. AUTO CALIBRATION CODE FOR SAPIV

C.1 Quick Start

1. **Print targets** - Premade calibration targets are included with the SAPIV code release in a folder entitled Calibration_Targs.zip. All calibration targets are .png files and can be resized for printing to fit any need. Calibration targets come in grid sizes from $2 \times 2$ to $20 \times 20$.

2. **Adhere targets to a flat surface** - If the calibration target is printed on paper, the target needs to be adhered to a flat surface so the target does not bend, flex, or wrinkle.

3. **Image calibration target in volume of interest** - The calibration target needs to be imaged at various depths to calibrate for SAPIV. For the calibration code to work, all of the interior corners of the calibration targets must be visible by all cameras at each calibration depth. The best way to check for this is to place the target in the extremes of the volume of interest. If the target is visible at the extremes, it should be visible throughout the entire volume.

4. **Modify/save SA_0_configdata.m** - Several lines of code need to be checked in this file each time calibration is done. The variables ‘paths.code_direc’, ‘paths.calib_direc’ and ‘paths.save_direc’ all need to be modified to the correct paths for retrieving and saving data. The variables ‘calib.data.*’ all need to be checked to ensure they are correct. The variable ‘calib.data.homog_ref_points’ is a tricky variable that needs to be defined accurately. For example, if you are using a $10 \times 10$ calibration grid you will have 81 ($9 \times 9$) interior points. The variable `calib.data.homog_ref_points` defines where the corner points of the calibration target are **in relation to the center of the target**. The units are in terms of calibration points. Returning to our example, if there are $9 \times 9$ interior points, then the top right calibration point is four points to the right and four points up (4,4), the bottom right corner is four points to the right and four points down (4,-4), the bottom left corner is four points to the left and four points down (-4,-4) and
the top left point is four points to the left and four points up (-4,4) such that the variable ‘calib_data.homog_ref_points’ is defined as [4,4;4,-4;-4,-4;-4,4]. Again, all of these points are defined in relation to the center of the calibration target.

5. **Run the SA_1.camera_to_plane.m** - Typically, SAPIV data is arranged by camera instead of image plane. The purpose of this code is rearrange the calibration data by image plane. So long as the SA_0.configdata.m data file has been set up correctly, the only thing that needs to be changed is the variable ‘camera_files’ to ensure that the variables can read all of the calibration images.

6. **Run SA_12.image_preproc.m** - Belden et al. [32] wrote this code to preprocess the image data of SAPIV and is highly effective. This file requires no modification and does not directly affect calibration. When you run this file, it will prompt you to select a directory that contains your images to be preprocessed.

7. **Run SA_2.calibrate.m** - This file finds all of the calibration points in the checkerboard target. In the ‘preliminary commands’ section, there are several variables the user may need to modify.

   The ‘mode’ variable has two options: ‘auto’ and ‘user’. The ‘user’ mode prompts the user to select repetitive parts of the calibration image that will be used for autocorrelation (see Chapter: B for more info). If the user has done this step previously for a given calibration data set, the user can set the ‘mode’ variable to ‘auto’ which has no user prompts and speeds up the calibration process significantly.

   The ‘diagnose’ variable allows the user to troubleshoot the calibration code and has two options: ‘True’ and ‘False’. Setting the ‘diagnose’ variable to ‘True’ displays intermediate plots of the calibration process that allows the user to see what each step of the process is doing. Setting the ‘diagnose’ variable to ‘False’ suppresses all of these intermediate plots and speeds up the process of calibration. The ‘threshold’ variable is typically set to 0.8 but can be adjusted to ensure optimal thresholding for your calibration images.

   The ‘cam_calib_names’ variable needs to be set so that Matlab finds all of the correct calibration images.
8. **Run SA_3_gocal.m** - This file was written by Thomas Svoboda and shouldn’t require any modification to run. This code does most of the math for calculating the camera matrices used in the SAPIV codes.

You should now have successfully calibrated your cameras for SAPIV. The next step is refocusing. The process for refocusing is not covered in this document.

### C.2 Mathematica Code

This Mathematica code is the original code for performing auto calibration. The code does not pass into the cornerfinder/centerfinder.m files used in SAPIV but does the basic algorithm outlined in the calibrate.m file later on. ‘corner’ has been previously defined as eight corner images of the calibration target.

```mathematica
points = Table[
  temp = {}; 
  Do[
    img = Import["~/Research/SAPIV/Auto_Calibration/Calibration_12_14_2011_v1/ plane_" <> ToString@i <> "/cam_" <> ToString[cams] <> ".tif"];
    x = ImageCorrelate[img, corner[[cams]], NormalizedSquaredEuclideanDistance];
    vals = ComponentMeasurements[MorphologicalComponents[ImageAdd[Binarize[x, 0.88], ColorNegate[Binarize[x, 0.12]]], "Centroid"];
    AppendTo[temp, vals[[All, 2]]];
    ,{i, 4}];
  temp, {cams, 8}];
```
C.3  SA_2_calibrate.m

%%% Header

% Made by Jesse Daily
% Nov. 2011

% Purpose:
% This code automatically calibrates the calibration images used for synthetic
% aperture particle image velocimetry. The code uses a simple auto
% correlation method to find key points in the calibration image. This
% method currently can only handle targets that are checkerboards. Please
% read through the Troubleshooting section for help.

% Inputs:
% The inputs to this code are:
% 1) Variables from the configdata file
% 2) Calibration images
% 3) Either user input to crop the calibration images, or precropped images

% Variables the user can/should modify:
% 1) mode - the allows the user to interactively select significant
% structures or to run the code automatically.
% 2) threshold - Thresholds the auto correlated image. The user can adjust
% this variable to achieve the optimal thresholded autocorrelation. I have
% found .9 to be sufficient.
% 3) diagnose - shows intermediate steps in the calibration process to help
% the user find and correct problems.
% 4) img_size_u/v - are the image dimensions of the calibration images
% 5) cam_calib_names - the names of the calibration images. You want to
% use the 'x' operator so the code can find all the calibration images in a
% directory, not just one.

% Outputs:
% The outputs from this code are:
% 1) Auto correlated points in the all_point_corrs.mat file

% Troubleshooting:
% 1) There are other objects in your image that look like a checkerboard
% corner. Sometimes background objects and even reflections of the target
% can throw off the calibration algorithm. Try to eliminate as many
% reflections and background noise as possible.
% 2) The variables 'calib_data.nx' and 'calib_data.ny' are wrong in teh
% configdata.m file. This is a simple fix, just change the values to be
% the appropriate amount of grid points - Note: only count interior grid
% points
% 3) YOU MUST MAKE SURE THAT THE ENTIRE CALIBRATION TARGET IS VISIBLE IN
% EVERY IMAGE. IF IT IS NOT, THE CODE WILL FAIL!!! You need to be EXTRA
% careful when taking the calibration images to ensure that ENTIRE
% calibration image is visible. No exceptions!!

%%% Preliminary commands
clear all;
close all;
clc;
warning off all;

% Options: 'auto' will import already cropped images
% 'user' will prompt the user to crop calibration images
mode = 'auto';
% Running in debug mode shows all of the intermediate plots to help the
% user to diagnose any problems with the auto calibration. Anything other
% than 'True' will cause the calibration code to run without showing the
% intermediate plots.
diagnose = 'True';
% This is the thresholding value used for the auto correlation
threshold = 0.8;
% Image size
img_size_u = 640;
img_size_v = 640;
% What are the names of the calibration images
cam_calib_names = 'Camera*';
umeas = [];

[paths,calib_data,selfcal,SA] = configdata;
addpath('./support_codes/');

%%% Get cropped autocorrelation images
% Read the calibration image names
imnames = dir([paths.calib_direc 'plane1/' cam_calib_names '.tif']);
if isempty(imnames)
    imnames = dir([paths.calib_direc 'plane1/' cam_calib_names '.tiff']);
end

% If mode is set to 'user' this if statement will allow the user to
% manually crop portions of an image to be used in the autocorrelation.
% The cropped images are then written out to the same directory.
if mode == 'user'
    for i=1:calib_data.numcams
        % Read and show the image
img = imread([paths.calib_direc 'plane1/' imnames(i).name]);
warning off;
% This while loop allows the users to redo the cropping
user_continue = 0;
while user_continue == 0,
    imshow(img)
    % Get the coordinates of the structure
    [x,y] = ginput(2);
    % Crop the image
    img_crop = imshow(img(round(y(1)):round(y(2)),round(x(1)):round(x(2))));
    % Round the pixel locations to the nearest pixel
    Icrop(:,:,i) = [round(x(1)) round(x(2));round(y(1)) round(y(2))];
    user_continue = input('Type 0 to redo, 1 to continue: ');
end
% Write out the cropped images
imwrite(img(round(y(1)):round(y(2)),round(x(1)):round(x(2))),
    [paths.calib_direc 'plane1/cam_cropped' num2str(i) '.tiff']);
clf;
close all;
% Clear memory
clear user_continue x y img_crop img i x y
end % End for loop for iterating through plane1 to crop corners
clc;
end % if mode == user

% If the mode is set to 'auto' this bit of code will read the already
% cropped calibration images to be used in the autocorrelation
% Capture names of the cropped calibration images
crpnames = dir([paths.calib_direc 'plane1/cam_cropped*.tif']);
if isempty(crpnames)
    crpnames = dir([paths.calib_direc 'plane1/cam_cropped*.tiff']);
end

%% Perform autocorrelation & find corners

for j=1:calib_data.num_calib_planes % Iterate over all image planes
    for i=1:calib_data.numcams % Iterate over all cameras
        % Read the cropped image in plane1 directory
        crop = imread([paths.calib_direc 'plane1/' crpnames(i).name]);
        % Read calibration image
        img = imread([paths.calib_direc 'plane' num2str(j) '/' imnames(i).name]);
        %
        % Perform autocorrelation to find the corners
        %
        img_corr = normxcorr2(crop,img); % Perform auto correlation
iimg_corr = normxcorr2(crop,imcomplement(img)); % Perform auto correlation
nbw = im2bw(iimg_corr,threshold); % Threshold the auto correlation
ibw = im2bw(iimg_corr,threshold); % Threshold the negative auto correlation
bw = imadd(nbw,ibw);
if strcmp(diagnose,'True') == 1
  imshow(bw);
  title('Paused: thresholded image of the auto-correlation');
  pause;clf;
end
cc = bwconncomp(bw); % Find the connected components
centers = regionprops(cc,'centroid'); % Find the centroids
points = reshape([centers.Centroid],2,length([centers.Centroid])/2);
[cropx, cropy]=size(crop);
points = [points(1,:)-round(cropy/2); points(2,:)-round(cropx/2)];
%
% This finds the Euclidean distance from the corner of the image to % all the calibration points. The calibration point with the % smallest distance will be designated as a corner.
for ii=1:length(points)
  bottom_left(ii) = pdist([0,0;[points(:,ii)]]);
  bottom_right(ii) = pdist([img_size_u,0;[points(:,ii)]]);
  top_right(ii) = pdist([img_size_u,img_size_v;[points(:,ii)]]);
  top_left(ii) = pdist([0,img_size_v;[points(:,ii)]]);
end
% Locate the four corners in the grid by finding the minimum % distance from each corner to each of the calibration points.
bottom_left = points(:,find(bottom_left==min(bottom_left)));
bottom_right = points(:,find(bottom_right==min(bottom_right)));
top_right = points(:,find(top_right==min(top_right)));
top_left = points(:,find(top_left==min(top_left)));
corners = [bottom_left bottom_right top_right top_left]';
%
% Find the center point
%
% Now we calculate the slopes and y-intercepts of the lines that % are defined by connecting opposite corners. We then calculate % the approximate center position and compare that value with all % the calibration points to see which point is closest.
m1 = (corners(3,2)-corners(1,2))/(corners(3,1)-corners(1,1));
m2 = (corners(4,2)-corners(2,2))/(corners(4,1)-corners(2,1));
b1 = corners(1,2) - m1 * corners(1,1);
b2 = corners(2,2) - m2 * corners(2,1);
center = (b2 - b1)/(m1 - m2); % Find approx center location
center(2) = m1 * center + b1; % Find approx center location
for ii=1:length(points) % Compare approx center to calib points
    find_center(ii) = pdist([center(1),center(2);[points(:,ii)']]);
end
% Find the closest point to the approx center
find_center = points(:,find(find_center==min(find_center)));
center = find_center;
if strcmp(diagnose,'True') == 1
    plot(points(1,:),points(2,:),'.');hold on;
    plot(corners(:,1),corners(:,2),'ro','Linewidth',2);
    plot(center(1),center(2),'go','Linewidth',2);
    axis ij;
    title('Paused: these are the points that were automatically found');
    axis([0 img_size_u 0 img_size_v]);pause;clf;
end
%
% Input corners and center into cornerfinder
%
xx = [center(1),center(2);corners(:,1),corners(:,2)'];
[xx(:,i)] = cornerfinder(xx,img,calib_data.corner_win_x,
                 calib_data.corner_win_y);
%
% The rest of this is a bunch of random stuff from Jesse Belden's
% code that is needed to make things run.
%
% Initial homography estimate from the 5 points
ap0p0 = [xx(1,1);xx(2,1);1];
am1p0 = [xx(1,2);xx(2,2);1];
am1p2 = [xx(1,3);xx(2,3);1];
ap1p2 = [xx(1,4);xx(2,4);1];
ap1p0 = [xx(1,5);xx(2,5);1];
% I really have no clue what most of this code does... and frankly
% I don’t care so long as it works :-). What can I say? I don’t
% like reading other peoples code.
img_points = [ap0p0 am1p0 am1p2 ap1p2 ap1p0];
ref_points = [0,0,1,’];
[xgrid,ygrid] = meshgrid(-(calib_data.nx-1)/2:(calib_data.nx-1)/2,
-(calib_data.ny-1)/2:(calib_data.ny-1)/2);
xy_grid = [xgrid(:)';ygrid(:)'];
pts = [xy_grid ; ones(1,length(xy_grid))];
rptemp = [calib_data.homog_ref_points;ones(1,
length(calib_data.homog_ref_points))];
ref_points = [ref_points,rptemp];
% Use the initial homography to estimate the other grid point locations
[XX] = apply_homog(img_points,ref_points,pts);
% Augment matrix
XX = [XX;ones(1,size(XX,2))];
if strcmp(diagnose,'True') == 1
    imshow(img);hold on;
    plot(points(1,:),points(2,:),'r');
    plot(XX(1,:),XX(2,:),'yo');
    title('Paused: the calibration image overlaid with the found points');
    pause;clf;
end
umeas(size(XX,2)*(j-1)+1:(j-1)*size(XX,2)+size(XX,2),:,i) = XX';
end % End image iterator i
end % End directory iterator j

umeas = reshape(umeas,length(umeas),3*calib_data.numcams)';
IdMat = ones(calib_data.numcams,size(umeas,2));
Res = repmat([img_size_u,img_size_v],calib_data.numcams,1);

%save([paths.save_direc 'all_point_corrs.mat'],'umeas','xy_grid','xy_phys')
save ([paths.save_direc 'points.dat'], 'umeas','-ASCII');
save ([paths.save_direc 'IdMat.dat'], 'IdMat','-ASCII');
save ([paths.save_direc 'Res.dat'], 'Res','-ASCII');
APPENDIX D. SAPIV TRIGGER

A new trigger was built to allow phase locking with the vibration of the vocal folds. The new trigger was made on a printed circuit board in the EE department using a software program called ‘Eagle.’ This trigger was initially used because our laser at the time could only fire at 11 Hz. This circuit would allow us to phase average all of our data. However, shortly after this was built, a new laser became available that could fire at 10 kHz making this trigger unnecessary. The circuit diagram and the final cutout are shown below.

Figure D.1: The circuit diagram of the trigger generated using the Eagle software program.
Figure D.2: This is the circuit board printout of the PIV trigger. Note that the LEDs were later removed because they interfered with the operation and performance of the trigger.
APPENDIX E. CAVITATION TRIGGER

Figure E.1: Block diagram of the triggering program in LabVIEW. The program buffered one second of 50 kHz accelerometer data. When a trigger signal was sent to the program, to stop the buffer and write out a file of the acceleration.