Numerical analysis of the internal and external dynamics of a fluidic oscillator

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Numerical analysis of the internal and external dynamics of a fluidic oscillator

By

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Thomas Gielda
Peng Wei

The student author, whose presentation of the scholarship herein was approved by the program of study committee, is solely responsible for the content of this thesis. The Graduate College will ensure this thesis is globally accessible and will not permit alterations after a degree is conferred.

Iowa State University

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<td>Feedback Channel</td>
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<td>CFD</td>
<td>Computational Fluid Dynamics</td>
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<td>KPa</td>
<td>Kilo Pascal</td>
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<td>K</td>
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<td>T</td>
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I consider it an honor to have worked under Dr. Richard Wlezien and am grateful for his guidance and encouragement during this work. He has helped me cultivate a more confident demeanor. I would like to also thank my committee members Dr. Thomas Gielda and Dr. Peng Wei for their support throughout this process and constructive input from your areas of expertise. A special thanks to Dr. Gielda for his always sincere advice to never stop striving to improve.

In addition, I would also like to thank my husband and family that have provided unwavering support. As well as my colleagues, the department faculty and staff at Iowa State University for providing an unforgettable adventure.
The purpose of this research is to establish a computational model of the dynamics in a fluidic oscillator to get a better understanding of its key operational characteristics. This research uses readily available CFD software to simulate experiments. A simulation was developed for which parameters could be changed to perform runs under subsonic or supersonic conditions. This method allows for nearly endless data collection possibilities.

With numerical validation being an aspect of this research, studies were done to compare the results with experiments that have been similar conditions. To determine the soundness of a computational space, further analysis was needed to understand the effects that meshes can have on the accuracy of a solution. In addition, a dynamic analysis was done on the main features of the fluidic oscillator. Places of interest include the inlet and outlet, feedback channels, diverter walls, and the external flow field. Correlations made between the different operating conditions provided insight in how to design an oscillator to work more efficiently under higher operating speeds.
CHAPTER I
INTRODUCTION

Innovative designs that are currently being engineered strive to produce a more aerodynamically efficient design (Hassan, McVeigh and Wygnanski). Whether the goal is to enhance the performance capabilities, reduce operational costs, or create a more environmentally friendly aircraft, active flow control provides a simple solution to a plethora of obstacles.

Figure 1.1 Fluidic Oscillator (Raman and Raghu)

The paper *Flow Control for Rotorcraft Application* discusses the results of AFC oscillatory jets for rotorcraft applications. Experiments involving oscillatory jets were conducted to examine instances of advancing and retreating blade lift improvements. When a blade is moving in the same direction as the forward flight speed, the rotor blade tips experience higher velocities than the retreating blade. The tip in particular because of its increasing angular velocity component along the radius of the blade, in part with also being aligned with the forward flight speed. Accompanying the advancing blade is a low pitch angle. This is adjusted to
decrease compressibility affects that occur for any airfoil at high speeds. Even with an angle of attack adjustment, shocks still form at the blade tips and increase the drag of the blade. The introduction of oscillating jets at this location creates a different flow structure without critical conditions. When the blades position aligns so that the angular speed is reverse of the forward flight speed, the velocity at the blade tip is low. Under these conditions the airfoil may experience stall conditions. The pitch is increased to allow greater lift over the airfoil. The introduction of the oscillating jets in this situation would allow for faster flow over the blade and increase lift for when the rotor blade is retreating. The jets create modified characteristics of the airfoil to allow for more desirable aerodynamic characteristics.

Oscillator models were predominately tested in experiments where the external flow field is subsonic. They show validity of using oscillatory jets for active flow control for diverse applications. The author makes several conclusions from the research, one of them being that advanced designs must be modelled to have applicable control authority in transonic and supersonic flow regimes (Hassan, McVeigh and Wygnanski). The use of the oscillating jet in higher velocity fields require greater control authority than demonstrated. For the external jet to have any influence in the high flow regimes the inlet conditions of the model have to increase. By using inlet values that correspond to isentropic supersonic conditions, the external jet is an under expanded jet which exceeds values on Mach 1 in the jet and broadens the operating conditions. Also expressed in this work, is the call to be able to produce accurate forecasts of modified models which aim to optimize the performance and evaluate criteria that define an oscillating jet.

Experiments have progressed by implementing arrays of oscillating jets along a tail rudder of a commercial airplane for wind tunnel testing (Seele, Graff and Lin). The results of this
tested concluded that the same rudder control could be had for a given deflection angle when the jets were turned on and at a smaller deflection angle. The size of the control surface can then be sized down when implemented with the jet array to keep the same control. The research also was initiated as a part of the NASA Environmentally Friendly Aviation project. Because of the promising results of the oscillating jets, it was determined that fuel consumption could be decreased because of the control surface resizing that reduces weight of the airplane.

![Figure 1.2 Mass Flow vs Frequency](S. Gartlein, R. Woszidlo and F. Osermann)

The field active flow control includes a diverse set of actuators. The main types of models, as outlined in *Actuators for active flow control* are fluidic, moving surface and plasma actuators (Cattafest III and Sheplak). Some models discussed in his work require moving parts while others no dot require any fluid inputs at all. The fluidic oscillator is a very well tested actuator that has grown in popularity. This type does require an external fluid source but does not involve any moving parts; making this a robust choice and favorable in real life implementation.
A range of frequencies can be obtained by modifying the inlet conditions or feedback channel geometry. This is based on the well-defined relationship of mass flow through the channel versus the oscillator frequency, Figure 1.2.

The main geometric components of the fluidic oscillator include a mixing chamber, feedback channel, inlet, and outlet. Terminology was borrowed from several resources that examine fluidic oscillators (Figure 1.3). Flow enters through the inlet into the mixing chamber where instabilities cause a jet to form and attach to either internal blocks. The jet is then turned into the feedback channel that diverts part of the flow in the opposite direction, back towards the oscillator inlet. This flow deflects the main jet to the opposite side and feeds into a recirculation bubble that forms opposite the jet in the mixing chamber. This design creates the bi-stable switching property that is unique to oscillating jets. The flow that is not directed back through the feedback channel escapes through the oscillator nozzle. As the internal jet flips back and forth, there is also a jet in the external flow field that oscillates.

![Diagram of fluidic oscillator](Bobusch, Woszildo and Kruger)
CHAPTER II
METHODOLOGY

Research Approach

The aim of this research was to use a computational approach to understand the internal and external dynamics of fluidic oscillators for which research has predominately been done through experimental procedures. By allowing the model to exist in the numerical domain further data acquisition is able to take place inside the model. With meager numerical data available for comparison, this research also produces results to lay further groundwork for this topic. By modelling the fluidic oscillator with both subsonic and supersonic outlet conditions deductions can be made on how to further advance the model to better perform in the higher velocity fields.

CAD Model

The process started out by creating a CAD model of the fluid region of the fluidic oscillator, it is a positive representation of the fluidic oscillator cavity. The model started with a 2D sketch created on an image of a current model that has been popular in research. The sketch was sized based on dimensions from Experimental Investigation of Compressibility Effects in a Fluidic Oscillator by (Gosen, Ostermann and Woszidlo), which proposes an outlet area of 40.32 mm$^2$. Because of the various curvature aspects in the oscillator, the sketch lines were purely based off an original diagram. Once the shape was drawn the form was uniformly scaled up using SolidWorks sketch tools to size the inlet.
radius to the only given dimension. This model is comparable to the model size that would be used for real-life applications, Figure 2.1.

Being that part of the focus of this research is to approach experimental research in the computational domain, the dimensions were kept similar to what a real model would be so results can be directly interpreted as comparable if an experimental procedure was done instead. The actual dimensions are shown in Figure 1 below. Based on the sketch that was originally used, the outlet to inlet nozzle diameters have an aspect ratio slightly above 1, whereas the research claims to use a value equal to 1. After the design of the oscillator was replicated, the sketch was extruded uniformly in the y-direction by 6.25 mm². This creates a square inlet nozzle in the model. Once a model was established, the geometry was imported into Star CCM+ as a parasolid binary file. Because the geometry is relatively simple, the model did not have any issues when being brought into Star CCM+.

![Figure 2.1 Fluidic Oscillator Diagram](image)
StarCCM+ Simulation Set-up

In StarCCM+ there are several variables that must be defined before a simulation can be run. The surfaces of the model must be defined, and physical values have to be set based on the desired flow. Several levels of mesh representations of the model are created. This step creates cells in the region for which the computations to take place in the model. This software then uses a combination of physics model options to create the flow representation to best match what has been captured through experimental research. Solvers must then be selected that will produce the numerical data in the region. Solvers have to be based on the type of flow that is expected otherwise data may not converge or it will be an incorrect portrayal. The simulation can then be run for a specified number of iterations.

A computational domain includes a large freestream region with the oscillator geometry inside. The freestream contains the freestream inlet and outlet and flow is computed in the entire region. The forces are then evaluated on the surfaces to determine aerodynamic characteristics.

As opposed to the problem recently described the current research has physical boundary constraints, as well as, a theoretical boundary used. The theoretical boundary is not physical, but rather creates a region to confine the computational space. This theoretical boundary is larger enough to ensure that the external flow field of the problem can be captured and does not induce computational errors that arise when flow is not allowed to dissipate before the flows exits through the boundary. On the other end of the sizing, the computational boundary should not be too large where it will add unnecessary computational time. These aspects are modelled together to compute flow inside a constrained space that then opens into a large reservoir.
The surface mesh is produced based on the mesh parameters in Table 2.1. A Surface Remesher was used to create the surface mesh from the surface of the imported CAD model. The remesher then takes the original surface mesh and optimizes its characteristics for the intention of volume mesh properties chosen (CD-adapco).

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<thead>
<tr>
<th><strong>Table 2.1 Mesh Parameters</strong></th>
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<tr>
<td>Base Size (m)</td>
<td>0.0015</td>
</tr>
<tr>
<td>Surface Size: Absolute Minimum (m)</td>
<td>1.24E-4</td>
</tr>
<tr>
<td>Surface Size: Target Size (m)</td>
<td>2.1E-4</td>
</tr>
<tr>
<td>Surface Curvature (Pts. / Circle)</td>
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</tr>
<tr>
<td>Surface Growth Rate</td>
<td>1.05</td>
</tr>
<tr>
<td>Number of Prism Layers</td>
<td>11</td>
</tr>
<tr>
<td>Prism Layer Stretching</td>
<td>1.2</td>
</tr>
<tr>
<td>Prism Layer Thickness (% of base)</td>
<td>50.0</td>
</tr>
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The Advancing-Layer Mesher uses prismatic cells along the part surface and forms polyhedral cells to fill the internal space. This model is known to produce cell layers that vary less from each other as they are generated (CD-adapco). Criterion was set by STAR CCM+ to determine the quality of a mesh. Table 2.2 specifies the face validity, skewness angle, and cell quality of the mesh. By a mesh being able to meet these guidelines the mesh has a higher chance for a quality solution.
<table>
<thead>
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<th>Table 2.2 Volume Mesh Characteristics</th>
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<tr>
<td>Number of Cells</td>
</tr>
<tr>
<td>Face Validity</td>
</tr>
<tr>
<td>Skewness Angle</td>
</tr>
<tr>
<td>Cell Quality</td>
</tr>
</tbody>
</table>

The final layout of the computational region can be seen in Figure 2.2 below. For the main region of the fluidic oscillator the flow is fully enclosed. The flow region is modelled as the fluidic oscillator geometry. The flow begins from the left at the inlet feeds into the oscillator the flow goes through the oscillator as described during the Introduction. Flow then exits the oscillator nozzle into the external field. Before the flow exits, a small confined exit where is flow goes through walls before opening to a reservoir. This is modelled so that external jet is allowed to form before entering ambient space. As seen for subsonic inlet condition the external jet is said to oscillate partially due to the jet being able to attach to the exit wall which are set as some angle out from the jet center.
Certain properties of the flow that are wished to be repeated must be known when setting up a basis for boundaries. The inlet surface was characterized by what StarCCM+ calls a Stagnation Inlet. This is defined by the stagnation pressure and temperature value and is ideal to use when the flow is compressible. Isentropic relations were used to calculate these values. The stagnations inlet treats the temperature and pressure values as the values far upstream from a plenum where the flow is perfectly expanded and stationary. The outlet surfaces are defined as a Pressure outlet which is the recommended pairing when using a Stagnation inlet. Ambient pressure is used to define the outlet as the flow exits the nozzle. This is comparable to simulating the actuators model as the external jet oscillates in an external flow field that is in ambient conditions. All remaining surfaces are defined as Wall Boundary and are defined as Star CCM+ as an impermeable surface (CD-adapco). These boundaries make up the final computational space to represent a similar set up as experiments done in the past.
There were three main iterations of simulations that occurred in the process of this research. The first of which started by using similar models to that of a pipe flow example found through StarCCM+. The second set up simulations had an overhaul of the physics models and recreated the meshes. The new mesh model allowed for greater accuracy in the model’s surface and volume representation. The new physics models that were used in the next phase of simulations can also be seen in Table 2.4. The simulation is based on the discretized Navier-Stokes equations computed on the cells of the volume mesh. Further assumptions for the modelling used were three-dimensional, implicit unsteady, and turbulent flow. These supplement the base equations to incorporate attributes of the flow to be expected, based again on what was seen in experiments.
<table>
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<td>Phase 1</td>
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</tr>
<tr>
<td>Steady</td>
</tr>
<tr>
<td>Coupled Flow</td>
</tr>
<tr>
<td>Exact Wall Distance</td>
</tr>
<tr>
<td>Gas</td>
</tr>
<tr>
<td>Gradients</td>
</tr>
<tr>
<td>Constant Density</td>
</tr>
<tr>
<td>Realizable K-Epsilon Two-Layer</td>
</tr>
<tr>
<td>K-Epsilon Turbulence</td>
</tr>
<tr>
<td>Reynolds-Averaged Navier Stokes</td>
</tr>
<tr>
<td>NA</td>
</tr>
<tr>
<td>Three Dimension</td>
</tr>
<tr>
<td>Turbulent</td>
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</table>

The last phase of the simulations developed an important change made to the outlet geometry. The outlet domain was changed from a flat plate to a cube outlet. Initially the outlet geometry did not properly represent the physical experiment. Before the final phase of simulations, the outlet geometry was modelled as a flat plate with the boundaries classified as walls on the large area surfaces and the narrow sides were pressure outlets as previously described. This did not allow the jet to expand as it would in a physical experiment. This error was realized as the outlet pressure was gradually building up caused by backpressure from the walls.
Figure 2.3 Design Changes of Outlet Geometry

Although computational models can be validated with experimental data, this research expanded on the current operating regimes, where sparse data for validation was available. Being that experiments were not all done with the same set up, a generalized validation was confirmed being that the frequency matched up with preliminary trials of the experimental counterpart being tested in other research (Kruger, Bobusch and Woszidlo).

As a harmonic aspect of simulation development, the data collection was also adjusted. A main aspect of this research was flow visualization. Scenes were set up in StarCCM+ that show contoured representation of various flow properties for a given geometry. The surface chosen to visualize the flow was a cross section taken in the x-z plane through the middle of the model. The software uses a volume mesh representation to view data in the cells for the selected area. Scenes chosen to visualize include the pressure
gradient, total pressure, and velocity magnitude. These were used to draw important conclusions about the internal dynamics of the oscillator.

![Diagram showing point data collection]

**Figure 2.4 Data Collection Summary**

Point data was also collected as what StarCCM+ refers to as Data Probes. They are user defined points anywhere inside the computed region where data can be extracted. The location of the data probe was the prime factor when determining what data was taken for that point. Data was taken at points established in previous research as well as other points of interest for this research. Most points were set up symmetrically to verify validity of the computations. Signals at opposite sides could also be used to develop stronger signals. For example, Mach values were collected at the inlet and outlet of the oscillator. These were extracted to verify the operating conditions of the oscillator. For another instance pressure data was visualized in the FBC to determine the flow structure through the channel. An overview of points can be seen in Figure 2.4.
CHAPTER III
RESULTS

During the process of simulation development, initial simulations were run for subsonic conditions. This was in part because most research being done on these fluidic actuators are for inlet and outlet conditions of Mach less than one. Experimental data also tends to use different fluids, water as a popular option. The pressure ratios are more easily obtained in this medium than for air. The only source of validation for the current research being presented is with experimental data and sparse numerical data that has already been produced.

The validity of the model started by looking at visual cues of the internal flow structures. Visual representations were used when determining the progress of a simulation. Once a model was able to present the same flow structures and characteristics of the physical model, the simulation was further tested to obtain data for a comparison to experimental figures. Figure 3.2. Figure 3.1 shows an experimental image of the density gradient using Schlieren Imagery. Both show the mixing chamber with turbulent conditions, and are able to detect the main jet formed and oscillating to either side. Another closeness in the images shows how the flow enters to FBC and part of the main jet is diverted to the inlet, then the channel begins to fill up. The simulation was also able to show how the external jet oscillates in the external flow field. The flow structures are more easily detected and compared using this type of imagery. (Bobusch, Woszidlo and Bergada).
A grid density study is done to determine the effects of the cell count of a mesh on the computational solution. Making the base size larger for the mesh creates a coarser mesh with less cells and can show how the mesh affects the solution. The mesh was changed to double and quadruple the base size. Comparing the same data taken from the coarser mesh simulation show that the coarser mesh gave the same oscillation frequency. The simulation used for the main analysis could have used a coarser mesh to obtain the same results.

Iterating with a gradual larger base size could have been done to determine a maximum size to obtain the same accuracy. However, the residuals of the simulations show that the original base size simulation do not require as many iterations to converge to a stable baseline.

Because the simulation is unsteady the oscillations seen in the residuals are representative of the solvers using sub-steps to iterate for a solution at a particular time (Appendix A). It is because of this that the solution was able to initialize to its unsteady solution faster. But, the coarser mesh was able to produce valid results just as well. To save on computational space, the coarser meshes could be used in place of the simulation chosen.
Other experiments use variable locations in the oscillator to determine the characteristic frequency of the oscillator. For example, in Gosen, Ostermann and Woszidlo it is found by using a difference in signals from central points in the top and bottom feedback channels. They chose this method to create a clearer signal for their analysis. All the locations exhibit the same fundamental frequency while the magnitudes differ. However, in the research being presented here, the data location areas are being directly compared for a better look at the interactions inside the oscillator.

The frequency of a model this size was found to be slightly lower than what the theoretical frequency was predicted at in Figure 3.3. This is believed to occur because of a difference in the covered outlet area of the oscillator. The extended walls create a greater back pressure in the model. When preliminary trials were run with walls on both sides of the oscillator exit, the model had a greater frequency closer to what was expected from the theoretical values. Without any knowledge of the actual model used in this experiment, there was no way of knowing the exact parameters used in the experiment.

![Figure 3.3 Experimental Frequency](Gosen, Ostermann and Woszidlo)
Oscillator Inlet and Outlet

Previous publications consider the internal dynamics of a similar oscillator at subsonic inlet conditions. This research considered supersonic inlet conditions ($T = 205$ K and $P = 371,862$ Pa) while also comparing it to subsonic conditions to get a better baseline comparison with current data. The stagnation inlet at this temperature and pressure, using isentropic relations, is equivalent to a plenum pressure of Mach = 1.5. This corresponds to the outlet of the oscillator fluctuating between Mach = 0.8 and just above Mach = 1, Figure 7. There is an interesting situation where the inlet and outlet of the oscillator have roughly an aspect ratio of about 1 (AR = 1.088 of outlet/inlet). With a supersonic inlet, it shows similar characteristics of a second throat. Although it has smaller area it is still where the flow chokes instead of at the inlet of the oscillator where the area is smaller (this is where it would instinctively choke). But in fact, the inlet throat is slowing down the incoming flow. This allows the inside of the oscillator to remain subsonic which accredits the oscillator to have bi-stable switching properties. If the internal chamber was supersonic the flow would create shocks whenever the flow is turned, but instead it allows for the external flow field to reach values maxing out at about Mach 1.5. These external velocity values correspond to values inside the jet, but not strictly at the center. Given that the jet width fluctuates as the jet deflects back and forth, the data probes would not be able to take data at the same relative location within the jet. The jet also jet does not fully attach to one side or the other, so there would be variable locations at which the jet would be flipped to either side. If it were to have fully attached, the data probe is not positioned where it could reach the center of the jet.
At the inlet and outlet of the oscillator the frequency magnitudes have a more dominating presence of a harmonic frequency. Both cases exhibit a 96-99% total ratio of the harmonic frequency magnitude. While other locations show a 70-90% presence of the fundamental frequency ratio, Figure 3.26 and 3.27. With the large difference in frequency magnitudes at the inlet and outlet location versus every other location.

To directly compare the oscillator performance between the subsonic and supersonic conditions an efficiency parameter of the oscillator was defined. The efficiency is a non-dimensional representation of the pressure change across the oscillator. This parameter is also referred to as the total pressure-loss coefficient. (Lindgren). Although the reference paper discusses the coefficient in the context of wind tunnels, the efficiency is still a representation of the pressure changes when flow undergoes some changes were the outlet is then under different flow conditions when it leaves.

\[
\text{Oscillator Efficiency} \quad \frac{\Delta H_A}{q} = \frac{P_{t0} - P_{t1}}{q_0}
\]
For a system not to accrue losses the inlet and outlet would experience the same total pressure. Losses can occur when a flow is turned or due to frictional losses in the physical system. This parameter does not take into account the frictional losses. The pressure difference then accounts for only the effects from the flow being circulated inside the oscillator. The non-normalized values are comparable by adjusting for the pressure difference by the dynamic pressure at each condition. The subsonic efficiency reaches a maximum value around 3 while the supersonic oscillator reaches a maximum of 10.5. The almost 30% increase from subsonic to supersonic conditions in the pressure drop in the oscillator shows a direct comparison about how the oscillator geometry is affecting the supersonic flow inlet, Figure 3.5.

![Efficiency Comparison](image)

**Figure 3.5 Efficiency Comparison**

The CFD scenes allows a data representation of the oscillators internal happenings. The structure of the jet in the external flow field is able to be seen in many different parameters. Figure 9 shows Mach contours corresponding to the solution time of 0.022 sec. Looking at the external point data for Mach, Figure 3.4, it corresponds to a point in the
solution where the external Mach is at a max. This is most likely due to the oblique shock coming off of the nozzle. Also apparent in the jet are the shock cells. They are a characteristic of the under expanded jets.

![Figure 3.6 Mach Contours](image)

**Feedback Channels**

The FBCs are the cause of the bi-stable switching properties of the oscillator. By part of the internal jet directing mass into the FBC, the oscillations begin. The FBC allows the internal jet to act on itself and in turn also changes its own direction. Moving air fully through the FBC turns the flow in a full circle. When investigating the structure of the flow during a cycle, smaller flow structures form in the channel. When considering the flow going through the FBC, data probes where placed at the inlet and outlet of the channels and several of line probes were along the length of the FBC, Figure 3.7.

![Figure 3.7 Feedback Channel](image)
As previously stated, the flow that goes through the FBC is what merges with the internal jet to divert the main jet to either side. By comparing the differences between the Total and Static pressure, between the inlet and outlet of the FBC, the dynamic pressure is represented at both points in Figure 3.8. The dynamic pressure is greater at the inlet than at the outlet. At the inlet, the dynamic pressure is increased since the flow from the main jet is being diverted to the FBC inlet. The flow has increased velocity coming from the tip of the jet into the FBC inlet, but the flow is also being turned and accelerated in reverse through the FBC. Velocity contours further verify how the flow changes direction. The contours also show how much of the flow has gone into the FBC versus what leaves oscillator. It can is seen how the flow reacts when it hits the cusped edge at the oscillator outlet.

![Figure 3.8 Feedback Channel Pressure Data](image-url)
At the top of the FBC wall there is an area of high velocity that was caused by the flow being redirected into the FBC. It is exactly this reason that the FBC does not seem to be the most efficient design. The probe lines that collect data show how the pressure is distributed along the profiles at the inlet and outlet. The profiles show uneven conditions viewed most predominately at peak values in the oscillations. Comparing the profiles side by side show how the main jet in the FBC shifts. The locations of the stream center were used when developing geometry modifications. Leading to the outlet point, where it was determined that there was an increase in static pressure causing an energy loss just inside the FBC itself. This can lead to lower mass flow through the FBC than originally determined. The mass flow in the FBC is the main factor when determining the frequency of the oscillator. In Figure 3.8 it can be seen that there is a loss in the system as the static pressure. There is significantly less dynamic pressure at the outlet. Since the flow slows down significantly from when it enters the FBC, there is still some dynamic pressure as the flow is turned before the outlet of the FBC.
Figure 3.9 FBC Outlet Top and Bottom
Figure 3.9 shows corresponding total pressure contours relative to the data points taken at the FBC outlet. The pressure contours are instantaneous values for peak values for when the top and bottom FBC have a max peak for the FBC outlet values. This however does not relate to the main jet being attached to the opposite side of the diverter wall. Instead the jet is already in the process of switching. This can seem counter intuitive, where it might seem rather that the maximum outlet FBC would occur when the jet is fully attached to the opposite side.

![Figure 3.9 Feedback Channel Profiles](image)

Also set up in the simulation were line probes along the FBC, Figure 3.10. Data is shown across the inlet, outlet, various position along the straight channel, as well as in the corner. This will provide insight into the data was collected at the data points at the FBC inlet and outlet, where we saw an increase in static pressure from the inlet to the outlet. The line probes show a profile of several data points in the FBC.
Figure 3.11 FBC Inlet Profile Comparison

Inlet Profile t = .0014s

Inlet Profile t = .0028s
Starting with the inlet for an instant in time that aligns with a maximum total pressure of the inlet we can see in Figure 3.11 that the inlet profile is practically uniform \((t = .014\) sec). For example, at a solution time of 0.028 seconds, from one end of the inlet to the other there is a jump of almost 20KPa. The other profiles are taken at the time where the inlet has a max total pressure \((t = .0014\text{sec})\) being that, that is where there is the greatest loss in the FBC.

![Figure 3.12 Subsonic Inlet Profiles](image)

For a subsonic comparison, the time interval selected was at maximum and minimum values for the inlet total pressure values. Peak inlet pressure at the inlet shows a more linear distribution, Figure 3.12. The overall pressures are greater than the subsonic simulation and has nearly double the pressure difference across the profile. This aligns when the internal jet is composed of slower moving air. As flow from the jet is ciphered into the FBC, the internal
jet does not have such an obvious presence in the inlet. The supersonic profile has a global maximum not at the edges of the oscillator showing where the jet was able to extend to the FB inlet.

Moving along the FBC, several of vertical locations in the FBC are examined. Vertical 1 is a profile right after the flow has turned and at the beginning of the horizontal straight channel in the FBC. The profiles show that total pressure is not uniform across this section, Figure 3.14. After examining the inlet profile, we can trace where the FBC flow is being directed towards its outer walls. Flow at this point has gone under a diversion into the FBC and then immediately turned again. This geometry gives rise to the uneven pressure distribution along the z direction. This can be expected from any flow that has been forced to turn with no installations to create a more homogenous flow in the channel.

![Flow Direction](image)

**Figure 3.13 Velocity Contour**
Supersonic (Top), Subsonic (Bottom)
Supersonic Feedback Channel Contours: Total Pressure

For subsonic conditions, the difference across the pressure profile is roughly a 4% drop in pressure across the channel. The supersonic pressure drop is approximately 18%. The data was taken at times when both jets have been considered to attach to one side. This is defined when there is a spike at the external data point in the oscillators external field. At this point the external jet is favoring one side and top feedback channel experiences increased velocity and pressure conditions.

The external point was chosen because the jet has a smoother transition from side to side. The tail of the internal main jet is under the influence of the varied geometry near the outlet of the oscillator. This occurrence creates a less than smooth appearance of the internal jet which can be seen to have an effect of the outlet nozzle. A greater magnitude of its
harmonic frequency is present at this point. Another cause of the internal jets non-uniform appearance is caused because when the flow it being directed through the feedback channel it is going in through the FBC and then begins to deflect the start of the jet. It causes itself to be pushed to the other side only while it is being feed through the FBC at the same time.

Figure 3.15 Supersonic Total Pressure Contour

Further insight can be provided by looking at the velocity profiles, Figure 3.16, and contours and its relations to the pressure data. We see that for the subsonic flow in the FBC, the pressure drop at Vertical 1 shows that when the flow from the main jet is being diverted, it causes a smaller jet through the FBC inlet. Being that the jet does not come through the entire span of the FBC inlet, there is a pressure difference from one side to another.
As the flow proceeds to the second vertical profile we see that the profile is even more exaggerated at the top wall where the total pressure is greater, and the minimum total pressure has moved from the bottom wall of the FBC closer towards the centerline. However, at Vertical 2, the uneven pressure distribution has an additional factor contributing to its profiles characteristics. The smaller jet now going through the FBC has not yet fully filled the channel and flows faster along the top edge of the FBC. Although the total pressure shows a significant drop from the other vertical profile, the velocity magnitude is still in the same range as the other vertical profiles. This can be attributed to a recirculation bubble that has been formed inside the FBC along the lower edge of the channel, Figure 3.16. By looking at the pressure contours or data, it appeared that the flow slowed down significantly. Through further examination it can be seen that flow structures are being developed aside from the main jet such a recirculation bubble forms inside the FBC.

**Figure 3.16: Supersonic Feedback Channel Profiles: Velocity**
As we get to the third vertical line the pressure profile has become more uniform, varying less than 10KPa from side to side. There are no additional flow structures at this point and the flow is all going in the same direction. The flow has redistributed itself to become mostly uniform as it enters the corner of the FBC. The recirculation bubble around the location of the second vertical profile helps pull some of the flow down towards the lower edge of the channel and disperse the smaller jet that was formed at the inlet of the FBC.

For the same conditions, the subsonic vertical profiles can be seen in Figure 3.17. These profiles show a different distribution along the FBC. Whereas for the supersonic profiles the middle of the FBC had the greatest pressure difference across the channel. For the slow moving flow, the first vertical profile shows the greatest difference. In Figure 16 it shows that there is a small recirculation bubble formed at this location. The supersonic condition has a recirculation bubble that forms in the middle of the channel and spans almost the whole length. The remaining channel for the subsonic simulation shows the channel being more uniform than what occurs in the faster moving flow.

![Figure 3.17 Subsonic Feedback Channel Profile](image-url)
The corner position shows that the flow profile becomes more uniform again as the flow is turned, Figure 3.18. Comparing the distribution of pressure along the profile to the first vertical profile, when the flow is first turned in the FBC, there is a smaller difference between max and min. Because the third vertical profile still has some resemblance of a jet in the channel, the fact that there is some irregularity as it goes through the turn should be expected. The jet deflects off the corner into the center of the channel after the turn. The total pressure is greater in the center than at the edges, showing that the jet does not occupy the entire width of the channel.

Excluding the overall pressure values, both simulations show similar profiles. As the flow is turned towards the outlet of the FBC. Pressure has slight tendencies to be more concentrated in the center. From the Star CCM+ User Guide the wall velocities are calculated based on the physics model for all y+ treatment which using a blending function based on a wall distance Reynolds Number (CD-adapco).

Figure 3.18: Corner Profile: Total Pressure
Supersonic (Left) Subsonic (Right)
By the end of the FBC, the outlet shows that the profile is more evenly distributed, Figure 3.19. An exception for this is at the very edge of the wall. Going from the corner profile to this outlet profile, no further flow structures have formed. The channel has finished turning and now has a smoother profile and begins to fill the channel. This more uniform flow then pushes along the jet along the width of the FBC. Figure 3.15 is a good example when the internal jet has begun to flip and the flow coming out of the FBC can be seen as pushing the internal jet. The outlet mass flow then follows along the jet, but the lower pressure area above then allows for the creation of a recirculation region. As the jet continues to flip the less mass flow goes through the upper FBC and the reverse action occurs on the lower FBC. The internal jet no longer has flow coming out the top FBC outlet but the lower FBC is being filled as the jet switches sides.

![Figure 3.19: Supersonic FBC Outlet Profile: Total Pressure](image)

The profiles are mostly consistent with showing constant patterns in the velocity profile in the feedback channel, Figure 3.20. The data was not taken consistent with the
fundamental frequency of the oscillations in the FBC. This is the reason the data does not represent an exact replica of an oscillation that is perfectly periodic. Although the data from Figure 3.9 shows how it takes representation of values at a variety of locations in the oscillations. That being foreseen, the data represents mainly peak and valley values in the oscillations.

Figure 3.2 Subsonic Feedback Channel Profile 3: Time variants of profile
**Diverter Walls**

The data probes set on the diverter walls show that the jet does not attach to the mixing chamber walls. Although in previous studies it is said that the Coanda effect allows this exact thing to happen. The pressure reading at the probes appear unsteady (S. Gartlein, R. Woszidlo and F. Ostermann). Looking at node 4 data at a solution time of $t = .0014$ sec, Figure 24, the presence of a harmonic frequency is more predominate. The minimum static pressure of the nodes corresponds to when the jet is on the opposite side and when the jet does move towards the data probe that static pressure builds, but still fluctuates greatly. Node 6 displays unique physics along the wall. Its location is closest to the FBC and the jet only appears to hit this point shortly before the jet flips to the other side. The node 6 data, in Figure 3.22, shows that there is no real buildup of static pressure, but rather like a switch, in an on or off position. When the static pressure is high, it still shows a similar fluctuation of pressure as node 4 but with another dominate frequency as well. When looking at the time series analysis the data displays two prominent frequencies, Figure 3.21.

Examining the frequency magnitudes at the data points on the diverter wall, it is seen that at location 3 and 4, the harmonic frequency is present in larger magnitudes and this characteristic is amplified from subsonic to supersonic conditions.

The lag displayed between the oscillations from the diverter wall probes and the FBC channel inlet and outlet help identify the time is takes for an oscillation. Based on the external oscillation, which was decided to determine the oscillators fundamental frequency, called the dwelling time (Woszidlo, Ostermann and Nayeri).
Furthering inspecting the frequency magnitude breakdown per locations it shows the same patterns from subsonic to supersonic conditions except for the overall magnitude. While the flow structures remain similar, the geometry is not able to adapt for better efficiency in the supersonic regime.

Figure 3.21 Time Series Analysis
Figure 3.22 Internal Diverter Node Data
**External Flow Field**

Examining the external flow field, and more specifically the external jet, shows perspective of the characteristic of the oscillator at the supersonic conditions. The external jet takes on the same characteristic frequency as the internal jet. This can be seen by the power spectrum of data taken at data points taken inside and outside of the oscillator.

The jet deflection of the external jet was characterized by the angle $\alpha$. The angle was measured at four points along the centerline of the oscillator. The angle was calculated based off the velocity components measured at the data points. The data points do not move along with the jet as it oscillates resulting in data taken at different location in the jet. The resolution of the alpha data allows a consensus that corresponds the characteristic frequency of the oscillator measured at various data points at other location inside and outside the oscillator.

**Figure 3.23 External Jet Deflection**
From the subsonic to the supersonic conditions it can be seen that the maximum jet deflection angle is reduced from a maximum of 41 degrees from center line to 24 degrees, Figure 3.23. This same effect was found in a study done by (Gosen, Ostermann and Woszidlo) and their results can be seen in Figure 3.24.

The higher flow within the jet for supersonic condition can be seen to produce a straighter jet, the subsonic external jet appears to be more affected when the oscillator opens into ambient conditions. When looking into the affects that an array of oscillator can have on the flow over control surfaces, the homogeneity that the jets helps produce in the external flow shows how efficient an oscillator can be to reduce separation. Because of the supersonic conditions the external jet for the corresponding conditions show characteristic of an over-expanded jet. Some of the characteristics of an under expanded jet included shock diamonds inside the external jet. Under expanded jets are caused when the exit pressure is substantially higher than the exit pressure at the final nozzle. The flow conditions must meet the outlet conditions, so the flow expands creating a Prandtl-Meyer flow pattern.
Four points were taken along the centerline of the oscillator. All of which relay the same data. Data points were almost always inside the jet as it was oscillating. There is a slight asymmetrical aspect of the jet deflection angle. This was also seen in experimental data in the paper (S. Gartlein, R. Woszidlo and F. Ostermann). Examining data point located on the outlet wall, still inside the oscillator, these points experience very little effects of the jet. This can be seen by the magnitude of the characteristic frequency of the oscillator. Looking at the same points for the subsonic conditions, the inner points have an overall magnitude increase from $10^e$ to $7^e$, Figure 3.26.

Looking at the ratio of frequency magnitudes for the fundamental and harmonic frequency there are some difference in representation based on location. The locations in the top half of the oscillator all experience slightly more of the harmonic frequency. Same as with the external field for the bottom locations. The fact that the external jet oscillates at the same frequency as the internal jet proves the switching of the external jet is an effect of the oscillator and not just an instability of a jet that is coming out of a nozzle. Even though the

**Figure 3.25 Experimental comparison of jet deflection angle** (S. Gartlein, R. Woszidlo and F. Ostermann)
external jet does not have as much jet deflection as for subsonic conditions, this has been attributed to the compressibility restriction at the outlet (Gosen, Ostermann and Woszidlo). This further leads to show the relationship of how the internal jets affects the external flow field.

**Figure 3.26: Supersonic Frequency Magnitudes**

**Figure 3.27: Subsonic Frequency Magnitudes**
In considering initial deductions about increasing the efficiency of the oscillators, there are several aspects of the fluidic actuators that will be further considered. The main areas of interest were the feedback channels, diverter walls with faces toward the internal/mixing chamber, the inlet and outlet of the oscillator, as well as the external flow field. All these components come together to create the bi-stable jet with no moving parts.

Without much evidence to support the geometric specifications in current fluidic oscillators, this research set out to find areas in the design that can be reconfigured. Other research suggests making revisions on the base geometry that will allow improved performance. The preliminary model of this oscillator drew influence from was angular in all respects. The next version simply smoothed out the edges, as the original model was concluded to produce desirable aerodynamic properties.

To identify further possible changes, Figure 4.1, the main features of the oscillator were laid out with related parameters. With much that can still be optimized with current fluidic oscillators, this research laid out a basis for design decisions in future model iterations.
Some studies have been done that make small scale changes at certain points deemed critical in the oscillator. These are intricate solutions to creating the geometry around the internal and external jet. More drastic changes could recreate the flow dynamics inside the oscillator to create a more improved jet. Once this has been done the design could benefit from more focused improvements in certain areas. (Bobusch, Woszildo and Kruger)

While this model has shown tremendous benefits for subsonic conditions an expansion on the operating regime could prove to be beneficial for aircraft whose control surfaces experience supersonic conditions. The desired outcome would be for the supersonic conditions to provide the same amount of aerodynamic efficiencies. For the current model, the external jet does not influence the same expanse in the flow field. The jet does have a stronger jet which speeds exceed Mach 1. The higher speeds can offer more control authority for when the flow field the actuators are acting in are high speed regions.
Using the results, various points of interest were determined for geometric modification. The predominate points of interest include the FBC, internal wall, and the wall geometry where the main jet is converged to the external jet. All these areas have evidence to support how modifications can allow the oscillator to sweep more efficiently.

![Flow Structures in Oscillator](image)

**Figure 4.2 Flow Structures in Oscillator**

The velocity contour provided in the results section show that a large recirculation bubble is formed alongside the jet in the FBC. In the above Figure 4.2, smaller recirculation structures can be seen forming in other regions of the FBC. The reversed flow sections provide increased resistance to the flow which purpose is the reach the outlet and provide momentum to deflect the main jet in the mixing chamber. The resulting recirculation bubbles can be said to be caused by an excess of space of the FBC. The FBC presented in the results
section, showed how more than just laminar flow is present. Although it may not be realistic to assume that an oscillator could be designed to only have laminar flow through it, changes could be made to reduce such undesired effects.

Figure 4.3 Recirculation Bubble Formation

Reducing the FBC width to a more proportionate size to the diameter of the jet that is going through the channel, there would be less room for the reversed flows to be able to form. Given this modification, the pressure would also increase and would also change the actuator frequency (Cattafest III and Sheplak)

\[ \frac{pv^2}{r} = \frac{dp}{dr} \]

*Euler – N Equation*
An adjustment could be made on the oscillator to revert it back to the original frequency. The FB channel length could be modified to reverse the affects. Overall this modification would allow for mass flow to flow more efficiently through the FBC. Without reverse flow to hinder the flow, it would take less time to deflect the main jet. As a result, this could also make the switching time of the main jet steadier. The steadier main jet will result in a more stabilized external jet. Causing a more homogeneous external flow field which is a property of a more efficient oscillator. (Ostermann, Woszidlo and Nayeri)

The mass flow going through the jet comes out of the FBC and its momentum starts to deflect at the source of the main jet. The jet continues and feeds flow into a recirculation bubble inside the mixing chamber where it grows. This causes the jet to switch sides, a similar structure forms along the other side of the mixing chamber, the process is then repeated (Bobusch, Woszidlo and Bergada). The mass flow out of the FBC and the pressure along the diverter walls oscillate at the same frequency found through a time series analysis done in the raw data. The relation between these two oscillator parameters can be used to deduce similar conclusions about inefficiencies in the rate recirculation bubble is formed and the dwelling time of the main jet.

In the simulation, the jet grazes the edge and diverts a small amount a flow the opposite way through the FBC. The aspect ratio of the model inlet and the length between the tips of the internal diverters can be adjusted to vary the main jet width and allow for a larger span of the jet without being deflected the wrong way through the FBC. Thus, reducing reverse flow through the FBC.

Also effecting the main jet is the mixing chamber geometry. Most research gives credit to the Coanda effect for the oscillators’ bi-stable properties (Cattafest III and Sheplak).
Contradictory to this statement, the data seen from points taken on the internal diverters’ walls, the jet has an unsteady attachment. When the pressure builds up as the jet swings form one side to another, the data shows an increase in static pressure, but with rapid jumps and a difference at times exceeding 60 KPa. It is for this reason that the geometry of the internal diverters should be altered to allow for better jet attachment. The Coanda effect has a certain critical ratio in which the effect takes place as oppose to just local effects. As long as the critical ratio is within the Coanda effect regime, the jet will attach to the internal diverter wall. By streamlining the wall contour a stable attachment could be achieved.

For the expanded operating regime that this research covers, the external jet does not have as great of a deflection angle as for subsonic inlet conditions. So, in order to create the oscillator model more efficient in the external field, the geometry at the second nozzle should be modified (Kirshner and Katz). The current model uses cusped edges to divert the flow. In the flow visualizations from the simulation, it shows the flow hitting the wall without any resemblance of a clean jet being deflected. The knife-edge does not require the flow to be turned so harshly as from a cusped edge. The knife-edge will split the main jets more precisely so that flow goes to the oscillator outlet and the FBC inlet. The point of the edge can then be moved up and down in the z-direction to cut the main jet based on the best location of where the jet may be. It can be beneficial to the jet be cut when it is fully attach to the internal walls. When visualizing how the jet flips from one side to another, it is not a steady rate of change. It may in fact be more beneficial to place the knife-edge where the main jet spends more time, between the deflection angles at which is takes the longest to span. Other parameters it can affect is the frequency being that the placement of the edge will determine the mass flow in to the FBC.
Being that the original model was only used in the subsonic regime, the outlet did not have to be designed to perfectly expand the external jet. It would not be possible to allow the external jet to deflect wider by just changing the exit wall angles. Rather, the switch from cusped-edges to knife-edges can offer a before solution to get a greater deflection angle out of the external jet rather than what could be done for a subsonic jet. Rather than allowing the internal jet to exit based on what the oscillation is deflected at, the edge would set up a wall for the flow to follow out. The idea following entrainment of the jet with the main recirculation bubble in the mixing chamber brought the basis of this idea. By creating an area for the jet to push against a slightly concave wall to turn flow is more effective that allowing the jet to move freely (Kirshner and Katz). Visually inspecting Figure 4.2 and 4.5 the modified geometry shows that that external jet attaches more along the outlet walls. The top edge of the external jet is also angled downward more. Figure 4.2 shows the top edge of the jet instead initially comes out straight before deflecting for the original model.

The efficiency of the oscillator as mentioned in the previous chapter, displays the time-dependent values of the pressure-loss coefficient. It displays the results of how under supersonic conditions the pressure-loss coefficient drops across the oscillations are around 13 whereas the subsonic oscillations are only 1.1. The differences can be attributed to the fact that the supersonic simulation have supersonic outlet conditions. For the supersonic simulation, there will be a greater pressure loss coefficient because the flow is put through a nozzle. The pressure difference in unavoidable because of aerodynamic characteristics of a nozzle. However, there can be changes done to optimize the preferred characteristics of the oscillator.
Table 4.1 Efficiency Comparison

<table>
<thead>
<tr>
<th></th>
<th>Subsonic</th>
<th>Supersonic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max</td>
<td>2.92E+00</td>
<td>1.05E+01</td>
</tr>
<tr>
<td>Min</td>
<td>-6.47E-01</td>
<td>-2.55E+00</td>
</tr>
<tr>
<td>Mean</td>
<td>1.10E+00</td>
<td>4.31E+00</td>
</tr>
<tr>
<td>Difference</td>
<td>3.56E+00</td>
<td>1.31E+01</td>
</tr>
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Primitive simulations were set up to demonstrate the plausible effectiveness of some of these changes. The trials were set up for a steady state, where the feedback channels were not fully modeled. This basic configuration was set-up to be able to get primitive results of what a fully modified oscillator would result in, while saving time and computations. The outlet of the single feedback channel inlet was set to a pressure equivalent in the original oscillator when it was flipped towards one side. The flow would simply exhibit a constant flow in one state of the oscillation. These were to determine if the modified geometry would deflect flow differently.

The main difference seen were that the internal jet flowed over the internal diverters more closely. As seen in Figures 4.4 and 4.5 below, with several modifications made the external jet deflects the flow greater in the external flow field. Also in this observation, more mass flow can be seen diverted to the inlet of the FBC. Another development in the flow occurs at the mixing chamber wall where there is far less separation between the wall and the jet. The original geometry does not have a recirculation bubble on the diverter wall in between the jet. The variation of the model shows a bubble, where the jet could reattach on to the diverter wall before the FBC inlet.
The original model would mainly see greater flow going into the FBC during the switching of the internal jet. The modified model shows that it can continue to divert flow even when the flow is at its maximum external deflection. With a more constant mass flow going through the FBC, this would affect the switching properties with respect to time. It could allow for a more constant rate of change, reducing the dwelling time of the jets oscillation.

**Figure 4.4 Geometry Modifications**  **Figure 4.5 Variation of Model**
CHAPTER V
SUMMARY AND CONCLUSIONS

Summary

The research examined here modelled a fluidic oscillator that has been shown to work with undeniable success for subsonic operating conditions. The computational set up referenced several physical experiments done in attempt to produce equivalent numerical data. Without a complete catalog to any one experiment, an approximate model of the experiments was set up. No perfect method exists that allows computational software to match every physical aspect of experimental flow of the fluidic oscillators with the software parameters. Best practices were put into play with experienced advice to best generate a computational simulation.

Validation was further pursued with the expectation of misconstrued results that must be associated with CFD simulation. Initially visual cues were looked at when starting to set up a base simulation. After simulations were run, signal analysis could be performed and a characteristic frequency of the oscillator was established. The computations proved to perform on target for subsonic operating condition. For supersonic conditions, the frequency was found to be below the expected experimental value for the angular oscillator. Factors that could attribute to this slight discrepancy include: variation of oscillator modelling, misrepresentation of physical flow, or a number of other possible computational aspects. As a computational exercise, further validation was sought to the form a relation between solution and computational set up. Mesh validity proved to be acceptable under basic criteria. Furthermore, a grid density study showed how a coarser mesh affects the iterative start up for
a given simulation. The results were inconclusive in showing how the oscillatory characteristics depend on the computational design. With a foundation established a dynamic analysis was carried out to perform a numerical evaluation of the oscillator.

The approach of this research has led to more accessible data for the model. The fluidic oscillator was broken down piecewise and examined as a series of individual parts. Data collected at the inlet and outlet were used to compare the pressure-loss coefficient of the oscillator for subsonic and supersonic simulations. The FBCs are critical in the operation of fluidic oscillators. The data profiles provide insight into adverse structures that disrupt laminar flow in the channels that more predominately occur under supersonic conditions. Another aspect sensitive to the operating conditions is where the internal jet forms and how it oscillates differently. Results also indicated the impact the jet has on the external flow field. External angle deflections were found to be the equivalent as experimental data for the angular oscillator in both simulations. Certain geometric modification could be made to create a more efficient model at a higher operating regime. These recommendations were put into rudimentary simulations to decide the adequacy of the conclusions.

Conclusions

Using experimental data to assure the computational method was valid, the data collected from simulations were used as most of the support of the conclusions. Subsonic simulations were seen as a best-case scenario for what an oscillator could provide. The supersonic condition simulations were then analyzed to determine how the performance could match that of the lower pressure operations while trying to obtain more control
authority. Conclusions mentioned in the following section are provided to lay ground work for future design changes to better optimize this tool for supersonic operating conditions.

In the discussion about the diverter walls, the topic of the Coanda effect was brought to light. While most research contributes the bi-stable switching properties because of this effect, the data can be seen to show further insight. The spectral data at the nodes on the diverter walls show a more predominate presence of the harmonic frequency than at any other point in the oscillator. The locations along the diverter walls also shows how the jet properties change along the edge itself. At node 4 there is a gradual build up then drop off pressure. Compared to node 6, where there is a longer time of low pressure and then a constant high-pressure section. The data does not show constant pressure values along the internal walls where the jet was thought to be attached. Based on the characteristics found in the data and the same fundamental and harmonic frequencies present through the oscillator, this research concludes that the transportation of mass flow through the feedback channel is the real cause of the internal switching of the jet.

Another characteristic of the oscillator, was that for either operating condition the inside of the oscillator was completely subsonic. In most experiments the aspect ratio of the inlet and outlet was approximately one. The same geometry, when brought into the computational space, ended up being where one nozzle was slightly larger than the other. The inlet nozzle was .53mm smaller, and the outlet nozzle was still the choke location of the oscillator. If the internal dynamics were to have been supersonic the results would have been incomparable being there would have a been shock inside the oscillator. This would not have allowed any oscillations for the actuator.
The external flow field shows a drastic difference between the supersonic and subsonic operating conditions. The external jet deflection angle decreased by 58% from subsonic to supersonic conditions. As a tradeoff, the jet contained higher values (Figure 3.23); whereas values for the subsonic jet stayed the same. In addition, the supersonic jet does not have much effect on the external flow field. The subsonic jet flips around more freely while the supersonic jet stays rigid as it oscillates; being most effective at either side of its oscillations. This shows that under higher operating conditions the oscillator would be able to match the control authority needed for more critical flow fields, but over a more limited expanse.

Efficiencies for both computational models were determined by a pressure loss coefficient value. This value was derived from the turning efficiency coefficient used in wind tunnels. Being both have no moving parts and their main source of pressure loss occurs from flow being turned, this coefficient was used for a non-dimensional comparison across operating conditions. The results in Figure 3.5 and Table 4.1 are used to demonstrate just how differently the fluidic oscillator behaves under changing operating conditions. During operations, the subsonic simulations show a difference between maximum and minimum pressure loss of 3.56 where supersonic conditions there is a difference of 13.1. This drastic contrast gives a clear conclusion of how the fluid reacts to the same physical model under different operating conditions. Even though the jet will still oscillate for supersonic conditions, every aspect examined here shows drastic changes in the data. While the same oscillator does work well under the supersonic operating conditions, it is suggested that a new model be defined deliberately for that regime. The promising data shown in previous
research This model of oscillatory jets would be well worth adjusting to use as active flow control for these additional areas of application.

Some of the most important changes for the oscillator geometry were suggested for the feedback channels. The FBC is the primary factor determining the oscillator frequency. The FBC channel parameters can be adjusted in tandem to achieve different geometries each with varying frequencies. With this recently discussed as the primary source of both internal and external oscillations, the two simulations show how the operating conditions effect the basic dynamics of the actuator. Figure 3.13 was shown to compare how flow structures form inside the feedback channel as a result on non-laminar turning flow. For the supersonic simulation, the recirculation bubble has expanded to half of the channel width. As a result, part of the flow then moves in reverse. With such flow structures to overcome, the internal oscillation properties are not shown to be perfectly symmetric. There is a clear leaning of the oscillations, as described in experimental research as dwelling and switching time. Mass flow through the feedback channels are unsteady because of this and is exaggerated from the lower to higher operating conditions. It is with this result that a geometry should be developed to turn flow more effectively back to start of the internal jet. To improve upon tested designs, the oscillator should be designed with a focus on providing a steadier oscillation to the external flow field.

With a surge of air vehicle designs incorporating active flow control technologies, the current actuator models must be further enhanced to meet diverse requirements. As a result of this research, a popular fluidic oscillator design was brought into a computational domain. Using already developed CFD software the physics of fluidic oscillators can be comparably simulated. With further adjustments, the base simulations can be recreated for fluidic
oscillator of varying geometry and operating conditions. However, there are inherent
differences in the data being compared. Further manipulations on the geometry could prove
beneficial to boost validity of the computational modelling. More rigorous results should be
obtained to match a particular experimental set-up.

The abundance of accessible data allows for further insight into the dynamics of the
model. Being able to use the data to analyze the predominate elements that define a fluidic
oscillator unveils parameters of the internal works. Subsequently, several modifications were
recommended for a model under supersonic operating conditions based on results obtained.
It is with these simulations, that the research can appropriately provide insight into
forthcoming fluidic oscillator designs.
BIBLIOGRAPHY


APPENDIX A

COARSE MESH RESIDUAL COMPARISON

Original Base Size Residuals

Original Double Base Size Residuals
Original Quadruple Base Size Residuals
APPENDIX B

LABVIEW MODEL
Schlieren Function

Inlet Pressure Initializing Function