Investigation of Synthetic Jet Actuator Design Parameters

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ABSTRACT

The vital attention of this project is directed to active flow control over micro aerial vehicles using synthetic jet actuators. Previous research has demonstrated that oscillating micro-jets have the potential to influence the flow characteristics and change the aerodynamic performance of the airfoils. The aspiration of this effort is to build on the previous work and support the idea of using synthetic jet actuators to improve the deteriorated aerodynamic characteristics of the low Reynolds number flow regimes and potentially use the same structure as a maneuvering device. The main idea is to actively control the pressure distribution over an aerodynamic surface which could lead to elimination of flow separation, lift increase and drag losses. To understand the efficiency of the synthetic jet actuators and the potential for such applications, it was necessary to investigate the nature and the variety of their performance with different design configurations. This paper covers the characterization of synthetic jets, starting with the analysis of different types of diaphragms, diverse size and shape cavities and different size and shape of the exit nozzles. The diaphragm with the thickness/diameter ratio of 0.17 made out of 0.01 inch thick brass shim was found to be the most effective of those studied. The volume and the shape of the cavity were related and it was noticed that the performance of the synthetic jet actuator increased when the device was tuned such that the resonant frequency of the diaphragm and that of the cavity were close to matching. A square diaphragm supplied better displacement characteristics than the circular diaphragms studied and also showed better results when integrated with the enclosed cavity forming the final device.

Keywords: synthetic jet actuator, piezoelectric diaphragm, active flow control, MAV

1. INTRODUCTION

1.1. Aerodynamic Considerations

In view of the size and the operational velocity of MAVs, the range of Reynolds number that have to be managed is one to two orders of magnitude lower than what has been encountered to date. The difficulty of this flow regime range has already been recognized: the viscous forces dominate the inertial forces causing the susceptibility of lifting surfaces to flow separation and lower efficiency. Adverse pressure gradients are most likely to occur when the boundary layer is still laminar so the flow over the airfoil has a reduced resistance and is more prone to separation. The flow separates, transitions to turbulence, reattaches to form a turbulent boundary layer resulting in a laminar separation bubble. As the Reynolds number decreases, this bubble becomes larger, substantially decreasing lift and increasing the
airfoil pressure and profile drag. Consequently, there is a need to avoid these negative effects in order to improve the MAV’s in-flight capabilities, their endurance and versatility.

1.2. Active Flow Control

In the past, active control efforts have employed external and internal acoustic excitation, vibrating wires and flaps, steady and unsteady blowing/bleed and synthetic jets. The recent trend in active separation control is away from steady inputs and towards harmonic inputs. Studies of external acoustic excitation were questionable since strong coupling existed between the sound and the wind tunnel which led to resonances in the wind tunnel test section. Internal acoustic excitation revealed beneficial effects at low angles of attack but unfortunately failed to reveal the same effects at higher angles of attack. Vibrating wires and flaps were used in an endeavor to introduce small amplitude velocity oscillations into the separating laminar boundary layer on the airfoil. The separated shear layer is unstable in the presence of these oscillations, amplifies them and the resultant rapid growth of the shear layer leads to reattachment. The major drawback of this method was that the forcing amplitudes required to realize any improvement in drag were significantly higher than the amplitudes that produced lift increases and, being so high, were not attainable at all frequencies. Unsteady blowing tangential to the surface has been found to effect separation control on airfoils just as did the steady blowing. The major advantage of the unsteady blowing over the steady case was that less power was required for the same effect. A control combination using oscillatory blowing with a small amount of steady blowing proved to be the most efficient method.

1.3. Synthetic Jet Actuators State-of-the-Art

The current contribution to the active flow separation uses synthetic jets. The most influential work on synthetic jets has been performed at Georgia Tech by Glezer et al. They identified the basic performance of the synthetic jets and their ability to affect the flow over aerodynamic surfaces. Bryant et al. at NASA Langley Research Center have investigated the benefits of using high displacement piezoelectric actuators as the active component in synthetic jets. The primary purpose of the piezoelectric diaphragm was to produce large volume displacement in order to draw fluid into and out of the cavity. Next, investigation into characterizing synthetic jets was done by Lachowicz et al. in an attempt to theoretically and experimentally determine the importance of various factors such as the actuation frequency on the performance of the jets. A series of comprehensive numerical studies on characterizing synthetic jets has been performed to model a synthetic jet under a variety of conditions. Lee and Goldstein showed that the increased thickness of the orifice changes the profile of the jet but not the peak velocities. In addition to numerical simulations several attempts have been made to analytically model the performance of a synthetic jet. Rathnasingam and Breuer proposed one of the first synthetic jets models. They modeled the jet as an oscillating flow through an orifice and arrived with the expression for the optimal orifice area. Motivated by the promising results, Hassan and JanakiRam used a version of the Navier Stokes solver and were the first to investigate the effects of the synthetic jets on the aerodynamics of a NACA 0012.

2. SYNTHETIC JET ACTUATOR DESIGN

2.1. Introduction

The actuators used in this work for artificially controlling the boundary layer are piezoelectrically driven synthetic jets. The nature of the actuator excitation is unsteady and as such would induce the mixing of the low momentum flow near the surface with the external flow that has a high momentum. As already mentioned, the idea is to energize the flow by exciting instability and consequently promoting the development of the natural instability of the boundary layer. Previous work has demonstrated that the actuator creates flow structures that displace the cross flow fluid, producing obstruction adjacent to the surface and a locally favorable pressure gradient. Accelerating the cross flow using synthetic jets results in a boundary layer that
is capable of overcoming stronger adverse pressure gradients and ultimately delaying or suppressing flow separation. 14

2.2. Synthetic Jet Actuator Configurations

The entire device consists of a cavity covered with a plate containing a slit flush to the ambient fluid. Opposite this, at the back of the cavity, is the unimorph itself that produced oscillatory vertical displacement when subjected to an alternating voltage of 65V. This is 10V lower than the maximum operating AC field that the piezoceramic of this thickness can normally withstand to avoid depoling. Fluid from above enters and exits the cavity through the jet orifice. By definition, the net mass flux across the cavity orifice is zero while the momentum of the vortices produced by motion of the unimorph is nonzero. The result is a train of vortex pairs injected into the ambient fluid.

Each piezoceramic, either a Navy type VI (PKI-552), 0.5- inch diameter 0.015- inch thick disc or a PZT-5H, 0.5- inch x 0.5- inch x 0.0075- inch square was bonded to a metal shim. The diaphragm was clamped between two aluminum plates as shown in Figure 1. The holes around the cavity are for the screws to hold different pieces of the actuator together and provide uniform clamped boundary conditions all around the cavity. This also provided a simple way of disassembling and assembling the actuator and it provided the flexibility desired for changing its configuration. These clamping screws were important for realizing proper boundary conditions, as using only glue to attach the shim to the actuator cavity resulted in only minimal actuation capability.

Figure 1. Disc and Square Unimorphs as part of the Synthetic Jet Actuator

The base plate had a thickness of 0.0625 inches. One or more plates of the same size could be stacked on top of the existing one, providing a simple way to change the volume of the cavity (Figure 2).

Figure 2. Stacking Aluminum Plates/Changing the Volume
In these trials only one additional plate was added, providing two different volumes that were tested by doubling the height of the cavity. The cavity was closed with aluminum top plates having varied thickness and orifice dimensions. Two different shapes of exit nozzles were used: circular and rectangular (Figure 3).

![Figure 3. Two Different Orifice Shapes](image)

The circular nozzle diameters were 0.04”, 0.08” and 0.12”. The rectangular nozzles were all 9/16” long and the widths were 0.02”, 0.04” and 0.06”. The length of the nozzle was changed from 0.01” to 0.02” and finally 0.06”.

### 2.3. Synthetic Jet Actuator Frequencies

A synthetic jet has two fundamental frequencies: the natural or mechanical frequency of the unimorph and the Helmholtz or acoustic frequency of the actuator cavity. The performance of the synthetic jet is determined by the interaction between these two fundamental mechanisms. The maximum result is achieved by tuning the two frequencies until they equal.\(^{15}\) It is known that the maximum displacement of the unimorph occurs at the resonant frequency, so the idea is to excite the synthetic jet actuators at the resonant frequency of the diaphragm to get the highest performance. However, as already mentioned, we also have to account for the Helmholtz frequency since the performance of the jet increases if the two frequencies are close, if not the same. Knowing that the device has two frequencies that we need to take into consideration we have represented the synthetic jet actuator with a two degree of freedom lumped parameter model, Figure 4.

![Figure 4. Two Degree of Freedom Model of the Synthetic Jet Actuator](image)
The diaphragm has its own mass, stiffness and damping coefficient which are coupled with the mass, stiffness and damping coefficient of the air enclosed in the cavity. For these preliminary tests we were observing only the trends and obtaining qualitative results. The mass of the air was assumed to be negligible and so were the damping coefficients of both the diaphragm and the air. Finally, we were left with Equation (1) for the natural frequency of the diaphragm in which the stiffness of the air is a variable that is controlled by several actuator parameters that can be selectively altered for tuning the natural frequency of the diaphragm.

\[
    f_{Diaphragm} = \sqrt{\frac{k_{diaphragm} + k_{air}}{m_{diaphragm}}}
\]  

(1)

Analysis of both the isolated diaphragms and the synthetic jet actuators was done using a condenser microphone and a Polytec Scanning Vibrometer. The frequency response of the unimorphs was measured using the microphone (Figure 5) in conjunction with siglab (virtual sine sweep program). The microphone had a flat frequency response and as such didn’t affect the final response. It was calibrated and was indicating 12 mV/Pa. In all the tests the microphone was placed at a constant distance of 3 mm from the diaphragm or the exit nozzle.

Figure 5a. Measurement of the Frequency Response of the Diaphragms

Figure 5b. Measurement of the Frequency Response of the actuator

As mentioned, another tool that was used to follow the dynamic behavior of the diaphragm was a laser vibrometer. The advantage of using this instrument was its visual aids, graphics and animations that showed diaphragm displacement at different frequencies and the different modes that were excited. Below is a picture of the setup for the laser vibrometer measurements for both the round and square diaphragms.

Figure 6. Laser Vibrometer Scan of the Disc Diaphragm

Figure 7. Laser Vibrometer Scan of the Square Diaphragm
3. RESULTS AND DISCUSSION

3.1. Testing the Different Unimorphs

The frequency response of both the isolated diaphragms and then the synthetic jet actuator as a complete unit were measured at frequencies ranging from 100Hz-12000Hz. Below is a figure that compares the frequency response, measured using the condenser microphone, for the brass diaphragms of different thicknesses. Magnitude in the y axis is an output to input ratio. These tests were mainly oriented to observe the quality of the results and the corresponding velocity value is to be determined. As it can be seen from the plots the 0.01 thick brass shim gave the highest performance and as such was used in the production of the unimorphs. This agrees with the previous study of electromechanical behavior of unimorphs in which case it was observed that there is a close relation with the diameter of the piezoceramic and the diameter of the metal shim. It turns out that the closer the two diameters are the better. The next parameter that was important was the thickness to diameter ratio of the brass shim. Previous resources and a simple test have shown that this ratio should be in the range of 0.1-0.2. For the piezoceramic that we used, this ratio could be set in that range with a 0.01 inch thick metal shim. This was validated with the tests and it can be seen in Figure 7 that the 0.01 inch brass shim performed the best.

![Figure 7. Frequency Response for Different Thickness Brass Shims](image)

We also wanted to compare the performance of the circular and square diaphragms and observe which one would give a better base for the synthetic jet actuator. In Figure 8 and in other tests, to be discussed next, it appeared that the square diaphragm would be a much better choice to obtain a stronger jet.

![Figure 8. Frequency Response for Different Shape Unimorphs](image)
The results were validated using the laser vibrometer. Figures 9-11 show the graphics that helped visualize the behavior of different diaphragms. These were accompanied with the magnitude values for the velocity and displacement at each frequency that the diaphragm was excited at (darker shade indicates the highest velocity/displacement and lighter shade the lowest).

Figure 9. Dynamic Behavior of the Circular Diaphragm          Figure 10. Dynamic Behavior of the Square Diaphragm

The graphics could be animated and below is the capture of the diaphragm’s lowest and highest points.

Figure 11. Capture of the Square Diaphragm Animation at its lowest and highest points

The two different diaphragms, circular and square, made out of 0.01 inch brass shim were excited at different frequencies ranging from 175 Hz to 10 kHz. The different velocities and displacement of the diaphragms were collected from the laser vibrometer measurements and are shown in the two graphs in Figure 12.

Figure 12. Displacement and Velocity Plots of the Three Diaphragms at Different Frequencies
It can be seen that the shape of the figures and output per input trends obtained using the laser vibrometer were the same as when using the microphone. These tests made the choice of the type and shape of the diaphragm fairly clear. Rudimentary conclusion is that the performance of the PZT diaphragm is the best when the thickness to diameter ratio of the diaphragm is in the range of 0.1-0.2.\textsuperscript{17} We have tested a couple of combinations and the one whose ratio was 0.17 has shown to upper limit performance. Square diaphragm has shown to be a better choice for the synthetic jet actuator active part.

3.2 Testing the Different Synthetic Jet Configurations

The next step was to embed the diaphragm as part of the enclosed cavity and witness how it behaves in such conditions. It is intuitive that the effective mass of the actuator is significantly greater than that of the diaphragm and thus causes the lower natural frequency of the synthetic jet. The Helmholtz frequency of the cavity was estimated using a very simplified equation\textsuperscript{18}:

\[ f = \frac{c}{2\pi} \left( \frac{A}{VL} \right) \frac{1}{2} \]  

(2)

where \( c \) is the speed of sound, \( A \) is the area of the orifice, \( V \) is the volume of the cavity and \( L \) is the length of the nozzle.

From the experiments it was observed that the maximum displacement of the unimorph was achieved when using the 0.01” brass shim. For comparison purposes and proof of concept reasons, different synthetic jet design configurations were made and tested. The acoustic responses of these actuators were measured again using the VSS program mentioned earlier. From the sine sweep we could observe the change of the amplitude of the frequency response as well as the shift in the resonant frequency of the system as we tested different configurations of the synthetic jets.

Two main synthetic jet designs were studied. One was with a circular cavity and the disc unimorph and the other a square cavity and the square unimorph.

3.2.1 Changing the Diameter of the Circular Orifice

First we tested two types of actuators with the circular orifice. We investigated how the different size of the orifice would change the performance of the actuator. The nozzle length was 1/16”. A first glance at the figures justifies our assumption of a two degree of freedom model. We observe two peaks, the first one represents the acoustic resonance and the second the mechanical frequency of the diaphragm. The goal was to change the configuration of the actuator such that the two frequencies meet at one point where their magnitudes will combine and result in the maximum performance. We will observe how changing the different parameters affects the magnitude and the shifting of the two frequencies.

As seen in Figure 13, the performance increased with the increase of the diameter of the orifice. According to equation (2) the Helmholtz/acoustic frequency of the cavity increases as we increase the diameter/area of the orifice. This matches acoustic peak trends found in the Figures 13. On the other hand, considering the device is a coupled system the enclosed cavity will now have an effect on the resonant frequency of the diaphragm. It is assumed that enclosing the diaphragm in a cavity would add extra stiffness. Making the orifice area bigger would decrease that stiffness and, therefore, decrease the resonant frequency of the diaphragm. The shift of the second peak towards left is the indication that this assumption is reasonable.
We can also observe that the two frequencies are shifting towards each other hinting that there should be a crossover of these two frequencies where the output will combine and provide the maximum performance.

### 3.2.2. Changing the Length of the Nozzle

Next, we tested the effect of the length of the nozzle on the final output. It was noticed that thinner exit nozzles resulted in a larger response. Going back to Equation (2), a smaller nozzle length would mean a higher acoustic frequency. Since increasing the nozzle decreases the acoustic frequency it would imply that additional stiffness is being added to the system, resulting in a higher unimorph resonant frequency. This trend is found in Figure 14. In addition, lower performance with the increase of nozzle length may also be related with the increase of the flow resistance as the nozzle length increased. So the two frequencies were shifting away from each other, implying that increase of the length for this particular setup was not efficient.

### 3.2.3. Changing the Volume of the Cavity

Another thing that we were interested in looking into was the change of the performance with the change of the volume of the cavity. It was noticed that for this strength of the piezoceramic it was better to embed the unimorph in a smaller volume cavity. We can back this conclusion up by, again, going back to Equation (2).
Resonant frequency is inversely proportional to the square root of the value of the volume. As volume is increased, resonant frequency of the cavity decreases. Higher volume, however, also implies less, enclosed, air effect so the unimorph frequency naturally went down. Figure 15 shows the differences in results for two different volumes with the same exit areas and exit nozzles.

![Figure 15. Change of the Response with the Volume (Circular Cavity)](image)

Even though we concluded earlier that a square diaphragm would be a better choice for the synthetic jets, we have still embedded the circular unimorphs in the actuator and tested their performance. This would allow us to compare these results with the results of the square diaphragms and make sure that the conclusions were correct.

### 3.2.4. Changing the Shape of the Nozzle

Another thing that we were interested in analyzing was the shape of the nozzle. We have chosen a circular shape and a rectangular shape of the same area and same exit nozzle lengths to isolate the shape and distinguish the effects of the response of the device. As seen in Figure 16, it can be concluded that the rectangular orifice was more effective. This could be explained using the theory of sound or the theory of resonators. According to the theory each channel has a constant conductivity which is inversely proportional to resistance. Circular channels are known to be the ones with lowest conductivity. This means that any shape other than circular would give a better performance than the circular shape channel would. This trend can be observed in the figure below. Again, the two frequencies came closer together and their amplitudes changed, almost doubled for the square cavity implying that the rectangular orifice would be a much better choice for the final actuator design.

![Figure 16. Change of the Response of the Actuator with Different Nozzle Shapes for the Circular and Square Shape Cavity](image)
3.2.5. Changing the Size of the Rectangular Nozzle

The final tuning of the device was done by changing the width of the slit as well as the thickness of the lid or the length of the nozzle. We only looked into the square shape cavity since it was observed in the previous tests that it was more effective than the circular cavity. It can be observed for this geometry a wider slit, or a bigger exit area resulted in a better final outcome and again shorter nozzle length outperformed the larger ones. The trend was the same as changing the size of the circular orifice. In this case, however, results came out better. It can be seen in the two figures below that the two peaks were approaching a common point were the magnitude of the curve drastically increased. In the final case, we tuned the device even more and saw that for the smallest length of the nozzle and the biggest orifice width the acoustic peak almost completely blended in with the mechanical resonance frequency.

![Figure 17. Change of the Response of the Actuator with Different Nozzle Widths and Lengths for the Square Cavity](image)

3.3. Summary

From all of the above tests we can say that the best performing jet was the one obtained using a square cavity and a square unimorph in which diaphragm and acoustic resonances are matched. We were interested in finding the synthetic jet actuator with the strongest performance at the frequency desired for impacting the characteristics of the flow. This work indicates the ability to tweak the final actuator characteristics for achieving such a goal. These parameters studied and their effect on acoustic and diaphragm resonance are shown in Table 1.

<table>
<thead>
<tr>
<th>Orifice Size</th>
<th>Nozzle Length</th>
<th>Cavity Volume</th>
<th>Orifice Shape</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Mechanical Frequency</strong></td>
<td>![Decrease]</td>
<td>![Increase]</td>
<td>Circular orifice: higher mechanical frequency than rectangular orifice</td>
</tr>
<tr>
<td><strong>Acoustic Frequency</strong></td>
<td>![Increase]</td>
<td>![Decrease]</td>
<td>Rectangular orifice: higher acoustic frequency than circular</td>
</tr>
</tbody>
</table>

Table 1. Effect of the Different Actuator Parameters on the Mechanical and Acoustic Frequency
4. FUTURE WORK

The above tests were measured in the inert, zero flow conditions. Hot wire anemometry tests and CFDRC program are currently being used to quantify the above results. The next step is to inject the jets in flow, in which case we will need to account for the properties of the flow in our model, since the jet itself is created from the surrounding fluid in which it is embedded in. One of the main concerns when applying synthetic jets in the flow is the sensitivity of their performance to different flow conditions. Because we plan to exploit the instability of the separating shear layer and its receptivity to time periodic actuation, it will be useful to characterize the flow over our particular wing to determine the position of the separation bubble, or the transition point, which would imply the desired position for the synthetic jet actuator. The information about the pressure distribution over the wing will be a valuable asset for computational simulations of the flow character over the wing and it should help with understanding the performance of the wing in different flight regimes and where to influence the flow to get the desired outcomes. Since complete effectiveness of the system is largely determined by the instability of the flow, it is vital to introduce the right types of disturbances at the right places. Previous research indicate that both frequency of actuation and jet to stream velocity ratio play a major part in how effective the technique can be in reducing the pressure levels. There is a lack of reliable information on the behavior of synthetic jets operating at different conditions. We plan to determine the conditions for synthetic jet operation to achieve maximum effectiveness for various flow control applications. We should be able to determine how properties of a synthetic jet in inert conditions relate to those when synthetic jet is operated within a boundary layer and most importantly how to take the given external conditions and design and operate a synthetic jet to achieve the particular goal.

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