An Investigation on Fundamental Characteristics of Excited Synthetic Jet Actuator Under Cavity and Diaphragm Resonances

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Abstract

This paper experimentally studies the basic characteristics of an isolated two-dimensional synthetic jet actuator (SJA) and two resonance frequencies found at 40 Hz and 160 Hz, which are respectively corresponding to the resonance of diaphragm and resonance of cavity of SJA. Data indicate that the former is independent of various excitation waveforms, excitation voltages and exit area of the SJA orifice. The latter is only associated with the exit area of the orifice. In addition, the dimensionless stroke length \( L_d \) is proportional to the Reynolds number of the exit velocity for the diaphragm resonance at various excitation voltages. As for the cavity resonance, the important result is that the dimensionless stroke length is proportional to \( Re^{3/2} \) for all four different excitation voltages and the effective neck length \( l' \) doesn’t keep constant with the varying exit area of orifice. That is, the \( l' \) increases linearly with the increasing \( A^{3/2} \). Regarding the relationship among the maximum ejection velocity \( \bar{U}_{max} \), mean ejection velocity \( \bar{U} \) and the resonance frequency of cavity \( f_c \) at various voltages of excitation, both \( \bar{U}_{max} \) and \( \bar{U} \) are inversely proportional to the \( f_c^{3/2} \) in this study. The current experimental results are expected to be useful for designing a synthetic jet actuator for real applications.

Keywords: Synthetic jet, Resonance, Reynolds number, effective neck length, Helmholtz

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1. Introduction

In recent years there have been many researches in the analysis of flow control, which involves the passive and active controls, with some methods for the past decades. The application of flow control at these techniques are often used for the passive control, such as the turbulator and vortex generator [1, 2] use the variation of geometric shape to adjust the gradient pressure on a surface for reducing drag on flow control. Additionally, the active flow control needs to consider the flow physics and the characteristic of the actuator to be achieved the desired flow control by artificial operation, for example, the internal acoustic excitation [3], ejected air by periodic oscillation [4], flapping control [5] and synthetic jet actuator.

Synthetic jet is a synthesized jet at the edge of an orifice (or a slot) by periodic motion of a membrane mounted on one wall of cavity without any leakage. When the membrane moves the orifice forward, the vortex pair appears at the edge of the orifice. While the membrane moves away from the orifice by its own self-induced velocity, a vortex pair keeps moving far enough away and is not influenced by the fluid that is pulled into the cavity. Hence, the synthetic jet is a zero-net-mass-flux jet but it is a nonzero momentum-flux jet [6-8]. A synthetic jet actuator can be made in several ways, such as an oscillating diaphragm [6], a piston-in-cylinder arrangement [9] and acoustic excitation [10, 11]. The synthetic jet actuators (SJAs) have been applied to control flow separation in boundary layer, virtual shaping, enhancing mixing layer, etc, and the piezoelectric-driven SJAs have been extensively applied in many fields for flow control. More recently, there have been studied on the optimal control parameters of synthetic jet actuator for the flow control in many investigations. Some literatures experimentally found that two peak velocities took place as its basic characteristics of synthetic jet with piezoelectric-driven disk [12-15]. The two peak values of velocity are associated with its resonance frequency in itself. This may be the optimal parameters for flow control that velocity output from the actuator is highest as it is excited at its resonance frequency. It is very difficult to demonstrate experimentally that a detailed study of two peak velocities for a synthetic jet actuator at the piezoelectric-driven disk. The major reason has two factors. One considering the orifice of a piezoelectric-driven SJA is too small to be measured accurately with hot-wire probe, the other is the output power of the piezoelectric-driven material too low to produce higher amplitude of diaphragm. Hence, the comparison of two resonance characteristics is still not clearly described in recent studies.

Smith and Glezer [6] and Glezer and Amitay [16] suggested two primary dimensionless parameters of the stroke length ratio \( \frac{L_0}{w} \) and Reynolds number \( \frac{U_0 w}{\nu} \) that dominate the characteristics of the synthetic jet. The stroke length \( L_0 \) stands for the flow travel distance from the exit of slot while the flow is ejected out the cavity, \( L_0=U_0 T \). Here \( T \) is the entire period for the oscillation of actuator and \( U_0 \) is the time-averaged ejected velocity over the whole cycle and the definition of \( U_0 \) is presented in Equation (1)

\[
U_o = \frac{1}{T/2} \int_0^{T/2} u(t) \, dt
\]

where \( u(t) \) is the instantaneous area-averaged streamwise velocity at the slot of exit. Another important dimensionless parameter is the Reynolds number, which is in terms of the time-averaged ejected velocity over the whole cycle. Smith and Glezer [16] investigated extensively the formation and evolution of two-dimensional synthetic jet through Schlieren visualization and velocity measurements. Although a lot of experts have focused on the applications of synthetic jet actuators including flow control [17-19], electronics cooling [20, 21] and fluid...
mixing [22], however, the variation of flow inside the cavity of the synthetic jet actuator at resonance part for experimental data is reported in some literatures, which are still nor clearly explained [23-25]. In order to obtain more meaningful results, the flow inside the cavity of SJA needs to be simulated, but it is often ignored for cavity of SJA at resonant condition in simulation, leading to both experimental study and numerical simulation are restricted in this field.

The cavity of resonance was regarded as the Helmholtz resonator, invented by Hermann von Helmholtz, who had created a formula for calculating the resonance frequency of a cavity with a circular orifice [26]. The equation of Helmholtz resonator was represented as (follows in Equation. (2))

$$f_c = c \left( \frac{A}{U_V l'} \right)^{1/2}$$

where $f_c$ is the resonance frequency, $A$ is the cross-section area in the opening, $c$ is the speed of sound, $l'$ is the effective neck length and $U_V$ is the volume of cavity. The importance of the Helmholtz resonator has attracted the interest of a lot of scholars. Dicky and Selamet [24] studied the effect of the small cavity length-to-diameter ratios. The results pointed out that the most significant effect of wave motion in the resonator volume is to change the location of the primary resonance frequency. Tang [25] studied that relation between Helmholtz resonator and tapered necks. These results showed that the impedance magnitude of the resonator is the weakest near the resonance frequency. Some papers experimentally investigated that the fundamental characteristics of the synthetic jet have two peak velocities with all kinds of excitation frequencies [12-14]. Up to now, Chaudhari et al. [14] designed a novel synthetic jet actuator to investigate two peak velocities. The actuator of driven loudspeaker with 50 mm diameter as the vibrating element takes the place of piezoelectric-driven material, the size of orifice and the depth of cavity can be adjusted in his experimental works. His results showed that the depth in cavity did influence two peak velocities less significant than the size of orifice. Some researchers used more output power of loudspeaker to study the two peak velocities. Unfortunately, those two resonance problems don’t still be resolved. For cavity resonance, the changed exit area of an orifice, no paper also refers to the effective neck length $l'$ whether or not maintain constant the Helmholtz frequency. Therefore the purpose of this paper will resolve those two resonance frequency problems and explore their basic characteristics of the synthetic jet actuator at the two frequencies of resonance.

2. Experimental approach and data analysis

Now, the major structure of this SJA adopts a loudspeaker, 203 mm in diameter, as the driving mechanism for the synthetic jet actuators. Both the cavity and rectangular orifice are made of acrylic material. The dimension of the cavity is 175 mm in depth and 140 mm in diameter with the opening rectangular orifice 280 mm in length and 8 mm in width. The loudspeaker was seamlessly bounded to the outside surface of the diaphragm without any leakage as shown in Fig 1[27]. The 2-D orifice in rectangle is adopted in this experiment for the synthetic jet actuator (SJA). In order to understand further why their experimental results don’t solve two resonance problems, the exit orifice of SJA will be changed at its exit area as experimental parameters in Table 1. In operating the experiments, the synthetic jet actuator is driven either by a sine wave, a sawtooth wave or a square wave from a standard electrical signal generator. The instantaneous streamwise velocities at exit slot of the jet are measured using a cross hot-wire probe of HW-110 anemometric system. The sampling rate and sample number through the employment of the Analog-to-Digital Converter are respectively adjustable according to the forcing frequency used from the signal generator between 10 Hz and 280 Hz. For instance, the sample rate and sample data were respectively set at 1000 Hz and at 2048 points when the forcing frequency is within 100 Hz measured for about 2 seconds. Additionally, a laser displacement sensor is employed to measure the tiny oscillation of the object. Although the structure of instrument is simple, it helps measure the amplitude of the synthetic jet actuator. This instrument is composed of a Fiber Optic Sensor, a Controller and a Power Supply. The sampling cycle of measurements is $2\times10^5$ second in the shortest required time for this laser displacement sensor. The measured error in amplitude of this laser sensor is less than 0.0001 mm.

The card of Analog-to-Digital converter is used for acquiring the data transferring analog voltage to digital codes from some measured sensors. It has few differences in each data set for measuring sensors at the same experimental conditions. Using the 95-percent confidence interval in statistical data analysis of the measurements can be written as $\overline{x} \pm 2\sigma_x$, where $x_i$ is the measurement data, the mean value, the standard deviation and the standard deviation of
the mean can be represented as $\bar{x} = \frac{1}{N} \sum_{i=1}^{N} x_i$, $S = \sqrt{\frac{1}{N-1} \sum_{i=1}^{N} (x_i - \bar{x})^2}$, and $S_\mu = S / \sqrt{N}$, respectively, with the total sample data $N$. In this study, the data errors mainly come from each instrument including Analog-to-digital converter, hot-wire anemometric system and the signal generator, etc. The total errors from each instrument were reasonably small. Taking the 95-percent confidence interval as an example for the data analysis of the maximum velocity, the error of maximum velocity ranges from -0.2 m/sec to 0.2 m/sec.

Table 1. The preliminary models at a small exit area for orifice of the synthetic jet actuator are selected as experimental parameters

<table>
<thead>
<tr>
<th>Dimension of exit orifice for synthetic jet actuator</th>
<th>Length (mm)</th>
<th>Width (mm)</th>
<th>Length-to-width ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model 1</td>
<td>280 mm</td>
<td>8 mm</td>
<td>35</td>
</tr>
<tr>
<td>Model 2</td>
<td>40 mm</td>
<td>2 mm</td>
<td>20</td>
</tr>
<tr>
<td>Model 3</td>
<td>40 mm</td>
<td>4 mm</td>
<td>10</td>
</tr>
<tr>
<td>Model 4</td>
<td>40 mm</td>
<td>6 mm</td>
<td>6.667</td>
</tr>
<tr>
<td>Model 5</td>
<td>40 mm</td>
<td>8 mm</td>
<td>5</td>
</tr>
</tbody>
</table>

Fig. 1 (a) Top view and (b) Side view of an isolated two-dimensional synthetic jet actuator [27]

3. Results and discussion

There is only one peak velocity appeared at the four models (Model 2-5) except for the results of Model 1 in the present experiment that shown in Fig. 2(a). This reason is that two peak velocities cannot still be resolved for the synthetic jet actuator at previous other investigations. An important result was observed from this experimental investigation that is two peak velocities merge into one peak velocity and separate them again. Suppose that one of two peak velocities is directly related to the cavity resonance of Helmholtz equation. In order to resolve these two problems of resonance, the Model 1 of synthetic jet actuator has been designed to separate two peak velocities from merging one peak velocity, as shown in Fig. 1.

![Fig. 2 (a) Except for Model 1 having two peak velocities, other Model 2, Model 3, Model 4 and Model 5 are only one peak velocity appeared. Variation of (b) maximum ejection velocity and (c) mean ejection velocity versus the excitation frequency ($f_e$) for three excitation waveforms on 280 × 8 mm² of exit orifice area](image)

The behavior of the synthetic jet usually depends on some parameters related to the flow control. In order to understand flow characteristics of the synthetic jet, several parameters including effect of excitation waveform, excitation voltage and excitation frequency will be discussed according to the experimental results which will be explained in the following sections.
3.1. Effect of excitation waveform

During the experiment, the loudspeaker is respectively driven by a sine wave, sawtooth wave and square wave from a standard electrical signal generator. Because the cross flow was not considered, the cross-wire probe was used to measure the instantaneous velocity at the center from exit of the jet. Figs. 2(b), 2(c), 3(a) and 3(b) show that two peak values were taken place at 40 Hz and 160 Hz respectively, which are focused on both frequencies of resonance in the current research, and it is known that both frequencies are independent at various excitation waveforms and excitation voltages. Reversely, the velocity response of the SJA depends upon the different excitation waveforms. Figs. 2(b) and 2(c) display that the velocity response of the SJA excited by the square wave is the best for other both. Then the velocity response of the SJA at excitation waveform of the sine wave is the better than those of the sawtooth wave. The responses of maximum and mean ejection velocities reach approximately 12 m/sec and 5 m/sec for 40 Hz of excitation with square wave on 5 V. In contrast to 160 Hz of excitation, the responses of maximum and mean velocities also attain to 9 m/sec and 5 m/sec, respectively. Similarly, the velocity response of sawtooth wave is the lowest in the three cases. The responses of maximum velocity and mean ejection velocity are respective 6 m/sec and 3 m/sec for a sawtooth wave with 40 Hz of excitation on 5 V. In regard to the other frequency of excitation (160 Hz), the responses of maximum velocity and mean ejection velocity are both approximate 3 m/sec. As mentioned above, the changed range of respective maximum and mean ejection velocities are 6 m/sec to 12 m/sec and 3 m/sec to 5 m/sec at 40 Hz of excitation on 5V in Figs. 2(b) and 2(c). From the above results obtained, the two frequencies of excitation still keep constant with various waveforms at the same value of 5 V. The response of velocity also depends on the effect of waveform.

![Graphs showing velocity responses](image)

**Fig.3 Variation of (a) maximum ejected velocity and (b) mean ejection velocity with excitation frequency at the same sine wave and various forcing voltages for 280 × 8 mm² of exit orifice area. Variation of mean ejection velocity with excitation frequency at the same sine wave and various forcing voltages for (c) 220 × 8 mm² and (d) 160 × 8 mm² of exit orifice area.**

3.2. Effect of excitation voltage

The following investigation will be focused on the effect of excitation voltage. In the meanwhile the parameters of excitation voltage are adopted for 5 V, 10 V, 15 V and 20 V, respectively. Two frequencies of excitation are independent with various voltages of excitation at the same sine wave, as shown in Figs. 3(c) and (d). This actuator is excited with the same sine wave at 40 Hz and 160 Hz frequencies of excitation and the variation of excitation voltage from the unsaturated voltage of 5 V to the saturated voltage of 20 V, the response of maximum velocities of the SJA at 40 Hz of excitation are respective 7.5 m/sec, 11.4 m/sec, 14.3 m/sec and 21.4 m/sec, corresponding to four excitation voltages. Similarly, these responses of mean ejection velocities of the SJA are respectively 3.7 m/sec, 5.8 m/sec, 7.5 m/sec and 9.4 m/sec at the same excitation conditions. Another resonance frequency is the cavity resonance of frequency which takes place at 160 Hz. Their maximum velocity responses of the SJA are also respective 7.1 m/sec, 15.8 m/sec, 18.1 m/sec and 22.1 m/sec at the same excitation condition as the resonance frequency of diaphragm. Besides, responses of its mean velocity are 3.4 m/sec, 8.3 m/sec, 10.9 m/sec and 11.7 m/sec, respectively. From the present results obtained, the maximum and mean velocities of the SJA increase with increasing output voltage of excitation. These results show that the changed range of respective maximum and mean ejection velocities of the SJA are 7 m/sec ~ 22.1 m/sec and 3.4 m/sec ~ 11.7 m/sec at 40 Hz of excitation on 20 V.
from 5V of excitation voltage. Besides, the changed range of respective maximum and mean ejection velocities are 7.1 m/sec ~ 22.1 m/sec and 3.4 m/sec ~ 11.7 m/sec at 160 Hz of excitation on 20 V from 5V of excitation voltage. These results confirm again that the effect of excitation voltage rather is directly related to the amplitude of a synthetic jet actuator than the effect of excitation waveform.

3.3. Effect of excitation frequency

Another experimental analysis is carried out the variation of exit area at orifice to study the relation of two frequencies of resonance. Following exit area of the orifice is decreased from 280 mm² to 220 mm². These results indicate that one of two frequencies has been changed from 160 Hz to 150 Hz, as shown in Fig. 3(c). The variation of the exit area can influence one of two frequencies of resonance in the present research. Further the reducing exit area of orifice to 160 mm² from 220 mm², the second frequency of resonance still decreases from 150 Hz to 140 Hz in Fig. 3(d). According to theoretical equation of Helmholtz resonator was represented in Equation (2). It is obvious to know from Equation (2) that the resonance frequency in cavity \( f_r \) decreases with the decreasing exit area of orifice \( A \). The applications of synthetic jets have widely been developed for flow control, it is so pity that nobody knows detailed the fundamental characteristics of the SJA in itself at both resonance conditions in some literatures. The present works is to study experimentally where the cavity resonance and resonance of diaphragm take place. Then it is to keep understanding their basic characteristics for the SJA at both frequencies of resonance.

3.4. Resonance frequencies with diaphragm and cavity of synthetic-jet actuator

3.4.1. Characteristics of resonance with diaphragm of synthetic jet actuator

For the resonance of diaphragm, it can be preliminary obtained from effect of varying exit area of the orifice. The resonance frequency of diaphragm takes place at 40 Hz at this actuator in the present research. The following investigation will be focused on the characteristics of resonance with diaphragm of this actuator. It is very clear to see that formation of the synthetic jet at resonance of diaphragm with 5V sine wave from flow visualization is as shown in Fig. 4. The resonance of diaphragm takes place at 40 Hz. That is, the oscillating cycle of diaphragm in the entire period is 0.025 second. Then using a high-speed camera of MotionPro X4 is to capture images with sampling rate setting at 2000 pictures per second. Therefore, the formed time of the synthetic jet is 0.0125 second as flow ejected out the cavity as shown in Fig. 4. The stroke length \( L_0 \) is defined as the flow travel distance from exit of slot while the flow is ejected out the cavity. The dimensionless stroke length at resonance of diaphragm is calculated as \( L_0/w \) = 5.6 shown in Fig. 4 while the flow is ejected out the cavity. In addition, the flow keeps traveling along downstream of center from exit orifice during the flow sucked into the cavity. So the flow travels distance over \( L_0/w \) = 6.25 for one cycle which includes time of one ejection plus one suction.

Fig. 4 The formation of a synthetic jet for resonance of diaphragm (at 40 Hz) with 5 V sine waveform flow visualization (Total ejected time \( T=0.0125 \) second)

In order to make sure again that 40 Hz of the excitation frequency is the resonance of diaphragm. It is also necessary that using the laser displacement sensor to measure the amplitude of the SJA diaphragm. Fig. 5(a) reveals that the sample data for oscillation of the diaphragm is obtained by the laser displace sensor. The amplitude of the diaphragm is excited with three types of waveforms at the same excitation frequency (40 Hz) and excitation voltage (5 V). The result in Fig. 8 shows that the maximum amplitude of the SJA diaphragm excited with three types of waveforms is through statistic method shown. Figure 5(b) shows the result of the maximum amplitude of the SJA diaphragm with respect to the excitation frequency at sine wave of excitation, the result can be still found that the 40 Hz is the resonance frequency of diaphragm and to be the maximum for all three excitation waveforms at the same
input voltage of 5V. A comparison among these results with different excitation waveforms in Fig. 5(b) shows good agreement. In these experiments have also been confirmed that 40 Hz of excitation frequency is the resonance frequency of diaphragm.

![Graph of amplitude vs. time for different excitation waveforms](image1)

Fig. 5 (a) Sample data of the SJA diaphragm for three types of excitation waveforms at the same excitation conditions. (b) The comparison between amplitude and excitation frequency with sine wave, sawtooth wave and square wave at the same excitation voltage of 5 V.

Once the result of the resonance frequency of diaphragm is obtained, the following step is to investigate the velocity behavior of the SJA by hot-wire measurements. Now, a series of parameters at changed exit area of the orifice are adopted. Though the resonance frequency of diaphragm is not influenced by the adjusting the variation of exit area at the orifice, the responses of maximum ejection and mean ejection velocities increase with the decreasing exit area of the orifice. Another the governing parameters for the synthetic jet according to a synthetic jet of the Reynolds number \( (Re) \) can be defined in terms of the time-averaged orifice velocity \( (\bar{U}_e) \) during the ejection. \( Re = \frac{\bar{U}_e w}{v} \), where \( w \) is the diameter of the orifice (or the width of the slot), \( v \) is the kinematic viscosity of the flow. Both the Reynolds number and the dimensionless stroke length \( (L_d/w) \) are two important parameters used in the present research. It is also clear found that the flow travels distance to be varied with exit velocity of ejection. Therefore, in Fig. 6 (a) indicates that the relation between dimensionless stroke length and the Reynolds number at the same sine wave and various excitation voltages for resonance of diaphragm. The dimensionless stroke length \( (L_d) \) increases linearly the increasing Reynolds number \( (Re) \) at the resonance of diaphragm. Its slope is 0.0114 for the relation between \( L_d \) and \( Re \) at the resonance of diaphragm.

![Graph of dimensionless stroke length vs. Reynolds number](image2)

Fig. 6 The relation between dimensionless stroke length \( (L_d) \) and Reynolds number \( (Re) \) at the same sine wave on various excitation voltages for (a) resonance of diaphragm and (b) resonance of cavity.

It is worthy note that the relation between the maximum ejection velocity \( (\bar{U}_{e,max}) \) and the resonance frequency of cavity \( (f_c) \) is at various excitation voltages for the resonance of cavity. Both \( \bar{U}_{e,max} \) and \( \bar{U}_d \) are inversely proportional to the \( f_c^{1/2} \). It is important though, to understand the Reynolds number and dimensionless stroke length \( (L_d/w) \) are both important parameters used in the present research. It is clear found that the flow travels distance to be varied with exit velocity of ejection. Therefore, in Fig. 6 (b) indicates that the relation between dimensionless...
stroke length and the Reynolds number at the same sine wave and various excitation voltages for the cavity resonance. From these results in Fig. 6(b) obtained, the $L_d$ is proportional to $Re^{3/2}$ at all four different excitation voltages. Both $Re$ and $L_d$ are respectively expressed as exit velocity of the SJA orifice and the flow traveling distance. From the present research obtained, the flow travels distance at resonance of diaphragm is farther than that of the cavity resonance. Hence, the result shows that the SJA application at both frequencies of resonance can be respectively used for flow control.

3.4.2. Characteristics of resonance with cavity of synthetic jet actuator

As for the second frequency of resonance, it takes place at 160 Hz in the present investigation. This result needs to discuss further. In particular, it is interesting to know more the characteristics of the SJA at cavity resonance. After all, the characteristics of resonance with the SJA cavity has been done in some literatures, but these results aren’t still described clear about the fundamental characteristics of the SJA at cavity resonance.

The resonance frequency in cavity takes place at 160 Hz, then using a high-speed camera of MotionPro X4 is to capture images with sampling rate setting at 2000 pictures per second, the oscillating cycle of its diaphragm in the periodic time is 0.00625 second. These pictures shown in Fig. 7 display formation of the synthetic jet at cavity resonance with 5V sine wave from flow visualization. It is obvious that the amplitude of oscillating diaphragm at cavity resonance is less much than that of resonance of diaphragm as indicated in Fig. 8. The dimensionless stroke length at resonance of cavity is calculated as $L_0/w = 1.4$ shown in Fig. 7 while the flow is ejected out the cavity. Apparently, the flow stops traveling along downstream from exit orifice and the flow begins to travel into the cavity when the diaphragm of the SJA moving forward inside the cavity. To this point, it makes a difference between the resonance of diaphragm and the cavity resonance. From inspection of these pictures in Fig. 7, it needs to obtain also exit velocity of the SJA orifice with the hot-wire measurements. Then it is to compare some differences between the resonance of diaphragm and the cavity resonance.

![Fig. 7 The formation of a synthetic jet for cavity resonance with 5 V sine wave from flow visualization (Total ejected period T= 0.03125 second)](image)

Formation of the synthetic jet at cavity resonance from flow visualization has been found that its dimensionless stroke length is less than that of the resonance of diaphragm. Similarly, the response of its exit velocity at the SJA orifice is strong better than other excitation frequencies except the resonance of diaphragm. In general, Designing the exit area of the SJA orifice is too small or the height inside cavity is enough deep, there will be difficult to be found the two frequencies of resonance in our previous studies. Both frequencies of resonance have been emerged into together, in order to separate them again with the bigger exit area of orifice in the present investigations. These two frequencies of resonance for the SJA application will be used respectively to flow control. Once the result of the resonance frequency in cavity is obtained, the next step is to investigate the velocity behavior of the synthetic jet by hot-wire measurements. Then a series of experimental parameters by changed exit area of the SJA orifice are conducted with the hot-wire measurements. Surprisingly, the frequency of resonance in cavity depends on the variation of exit area of the SJA orifice. The resonance frequency of cavity reduces with a decrease in the exit area of the SJA orifice. Therefore, the relation of both frequencies of resonance by varying exit area of the SJA orifice at the same 5 V sine wave is shown in Fig. 8(a).

3.4.3. Parametric analysis for Helmholtz resonance

The cavity of resonance was regarded as the Helmholtz resonator, whose theoretical formula for calculating the resonance frequency of a cavity with a circular orifice. Equation of Helmholtz resonator was represented as in Equation (2). Here $l'$ is a theoretical value represents the effective neck length, so far, nobody knows that it is a
constant or variable can be described detailed in some literatures. Suppose that the problem of $I'$ can be resolved via the present research. The cavity resonance of the SJA will be designed easy when the user wants to use it. As already explained, the given parameters for the exit area of the orifice ($A$) and resonance frequency of cavity ($f_r$) are substituted into the Equation (2), the $I'$ can be easily calculated. Shown in Fig. 8(b) indicates that the relation between the effective neck length and the variation of exit area of the orifice is at the same 5 V sine wave. The interesting or important result here is that the effective neck length doesn’t keep constant with the varying exit area of the SJA orifice. That is, the $I'$ increases linearly with the increasing $A^{2/3}$.

Moreover, a series of experimental parameters by changed exit area of the SJA orifice is conducted with hot-wire measurements. Though the resonance frequency in cavity can be influenced with respect to adjust the variation of exit area of the SJA orifice, the response of maximum ejection and mean ejection velocity increase with the decreasing exit area of the SJA orifice. According to the results of the present experiment, taking logarithm of the resonance frequency in cavity, maximum ejection velocity and mean ejection velocity are also plotted in Fig. 9.

![Fig. 8](image_url) (a) The relation between two resonance frequencies and exit area at the same excitation conditions (b) The effective neck length versus area of exit slot for cavity resonance

![Fig. 9](image_url) The relation between the velocity and the resonance frequency in cavity at (a) 5V and (b) 10 V (c) 15V and (d) 20 V of excitation voltages


This paper verifies experimentally that, after studying 5 different-sized synthetic jet actuators, it is able to differentiate that either one peak resonance frequency or two peak resonance frequencies can be found. For the small piezoelectric SJAs, basically one can only find one peak at 160 Hz, which is related to the Helmholtz resonance. While for larger sized diaphragm type SJA, so called Model 1, two significant resonance frequencies (40 Hz and 160 Hz) are found, that will be used as studying the fundamental characteristics of resonance conditions in this study. The experimental results indicate that two peak values take place at 40 Hz and 160 Hz in our present study. Through a series of experimental parameters, the 40 Hz and 160 Hz resonance frequencies in the actuator are respectively corresponding to the diaphragm resonance and the cavity resonance. The value of diaphragm resonance frequency keeps constant with the variation of excitation waveform, excitation voltage and the area of exit orifice, but it has an important relation between the Reynolds number ($Re$) and dimensionless stroke length. That is, the Reynolds number is proportional to the dimensionless stroke length ($L_d$). Another 160 Hz resonance frequency is the cavity...
resonance, which is only associated with the area of exit orifice. These results have shown that the Helmholtz resonator resonance of cavity of the SJA is also verified, but its effective neck length doesn’t keep constant with the varying exit area of orifice. That is, the $l'$ increases linearly with the increase of $A^{2/3}$. The $L_d$ is proportional to $Re^{3/2}$ at all four different voltages of excitation. Similarly, Both $\bar{U}_{e\text{,max}}$ and $\bar{U}_e$ are inversely proportional to the $l'^{3/2}$. From above experimental results obtained, the information provided in this paper will be more useful for design of a synthetic jet actuator in the future.

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