Passing Frequency of Vortical Structures in the Near Field of an Axisymmetric Turbulent Jet

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Abstract

This paper presents the results from an experimental study of an axisymmetric jet exiting a circular tube. The exiting flow was fully developed and turbulent with a Reynolds number of 7,500 based on the jet diameter. Utilizing both constant temperature anemometry and flow visualization, the passing frequency of the vortical structures was measured at four streamwise locations downstream of the jet exit (i.e. 1D, 2D, 3D, and 4D). The results show a decrease in passing frequency with increasing distance downstream of the jet exit. The results were compared to the 'preferred mode' of an axisymmetric jet found in previous studies.

Keywords — *Axisymmetric Turbulent Jet, 'Preferred Mode', Flow Visualization, Shedding Frequency*

I. INTRODUCTION

As a moving fluid separates from a surface of a body, vortical structures are formed by the Kelvin-Helmholtz instability resulting in the rolling-up of vortices. At low speeds these vortices roll up into spirals and continue to develop as they move downstream. These vortical structures move away and convect downstream of the jet exit at a fixed frequency. In non-dimensional form this frequency is represented by the Strouhal number and depends on the flow velocity and a characteristic length:

$$St_D = \frac{fD}{U_c} \tag{1}$$

where D, exit diameter of the tube is the characteristic length, f is the frequency which the vortical structures are formed and convect downstream and U_c is the centerline velocity at the exit of the jet.

Previous research has shown that axisymmetric jets have a preferred frequency or 'preferred mode' at which a vortical structure undergoes maximum amplification. Crow and Champagne [1] showed that an axisymmetric jet at a Reynolds number of 106,000 had a 'preferred mode' located at 4D (diameters) downstream of the exit corresponding to a St_D=0.3.

As turbulence is still not completely understood, there is much debate about the location where the preferred mode develops, the frequency and corresponding Strouhal number associated with the 'preferred mode', and what affect the Reynolds number has on this mode.

Ko and Davies [3] showed that for Reynolds numbers of 124,000 and 248,000 the 'preferred mode' occurred at 3D downstream with a frequency corresponding to a St_D=0.43. Fuchs [4], who tested a Reynolds number (267,000) similar to that of Ko and Davies found the 'preferred mode' was also located at 3D downstream of the jet exit but had a Strouhal number of 0.46. However, Chan [5] performed a study with a similar Reynolds number (260,000) but resulted in the 'preferred mode' being located 3.5D downstream and having a frequency corresponding to a Strouhal number of 0.35.

Chih-Ming and Hsiao [2] have shown that the preferred frequency and corresponding Strouhal numbers are dependent upon Reynolds number. The frequency and Strouhal numbers were determined to be relatively uniform at moderate to high Reynolds numbers but vary at lower Reynolds numbers. They also showed that the Strouhal number typically increases at lower Reynolds numbers. However, Yule [6] performed a study that showed that the Strouhal number increases as the Reynolds number increases. Yule also showed that the 'preferred mode' occurred at the same location despite the change in Reynolds number. His study was conducted at three Reynolds numbers (9,100, 21,000, and 200,000) with corresponding Strouhal numbers (0.29, 0.33, and 0.43). Finally, Drubka [7] found that the 'preferred mode' was constant at 0.42 over one decade change of Reynolds numbers.

In the current study, air was discharged from a circular pipe and formed an axisymmetric jet at a Reynolds number of 7,500. The evolution of the instabilities was characterized from the pipe exit down to the location where these vortical structures break down. Using flow visualization and thermal anemometry (i.e. hotwire), the passing frequency of the vortical structures was determined to provide a better understanding of the development of Kelvin-Helmholtz instabilities.

II. EXPERIMENTAL STRATEGY

In the current study, the flow system consisted of an air supply reservoir, a flow regulator, an illumination source, a smoke generator, a thermal anemometer with a miniature hotwire probe and a fully developed turbulent pipe flow forming an axisymmetric jet. The flow regulator was set to maintain a Reynolds number of 7,500 with an exit velocity of 5.6 m/s. The jet was produced using a black iron pipe with an inner diameter(D) of 19.05 mm (0.75 in.), a length (L) of 914.4 mm (36 in.), and a wall thickness of 3.175 mm (0.125 in.). The pipe was sufficiently long to establish a fully developed turbulent flow prior to the pipe exit. The exit profiles were acquired and compared to previously published literature to ensure the flow was completely developed and axisymmetric.

As seen in Fig. 1, compressed air was supplied from an air reservoir and directed to the pipe while smoke was simultaneously drawn into the flow prior to entering the pipe flow. A Lexel 95-3 Argon Ion Laser operating in single line mode (514.5 nm wavelength) producing a green beam 1.5 mm in diameter was used as the light source. The beam was directed through a laser light sheet generator, which produced a thin 0.5mm thick light sheet which illuminated the flow as it exited the pipe.

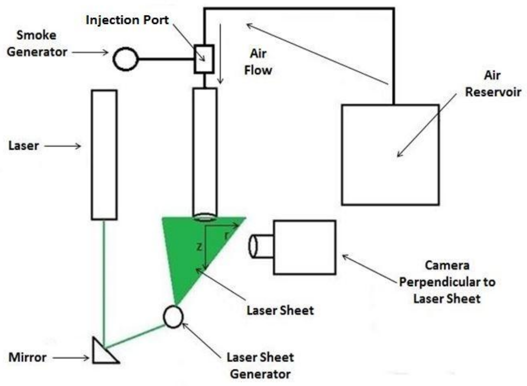

Fig. 1 Flow Visualization Setup

A Photron SA1.1, 1 mega-pixel high-speed camera was used to capture images at 2,000 frames per second (fps). The Photron camera was placed perpendicular to the light sheet in order to capture the two-dimensional images of the axisymmetric jet. Images were viewed with a 20mm F1.8 DG Macro lens with an f-stop of 4.0.

The images were then analyzed to determine the frequency and corresponding Stouhal number of the passing vortical structures. The frequency was calculated by ensemble averaging the time required for the center of 25 structures to pass a pre-specified location. The passing frequency was calculated for the following four downstream distances: 1D, 2D, 3D, and 4D.

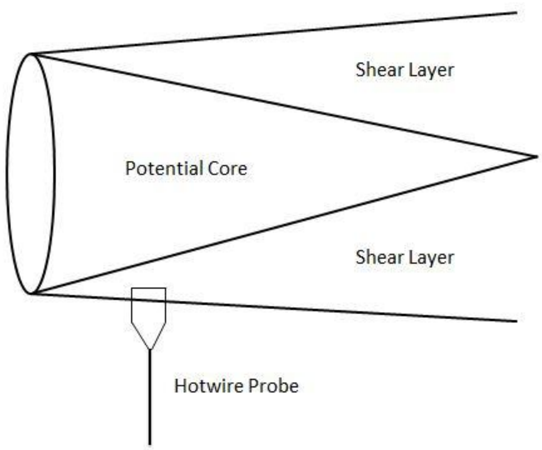

Fig. 2 Position of Hotwire Probe

In order to determine the passing frequency with thermal anemometry, a miniature uncalibrated hotwire probe was used as a reference trigger wire. The probe was positioned just inside the low speed edge of the shear layer (Fig. 2). The hotwire probe was oriented such that the active section of the wire was positioned perpendicular to the flow to ensure reliable detection of the passing of vortical structures.

The hotwire output voltage was then analyzed using a Fast Fourier Transform (FFT) and the dominant frequency of the passing structures were noted (Fig. 3 through Fig. 6).

Passing frequencies and their corresponding Strouhal numbers were obtained for four downstream locations (1D, 2D, 3D, and 4D) with both measurement techniques. This was obtained once the startup transient passed and a fully-developed turbulent flow was established. Flow visualization was also used to visually characterize the vortical structures upon initiation of the jet to determine if their passing frequency was similar to those at steady state.

III.RESULTS AND DISCUSSION

A. Hotwire

Fig. 3 through Fig. 6 shows the Fast Fourier Transforms (FFT) from the data obtained by the hotwire.

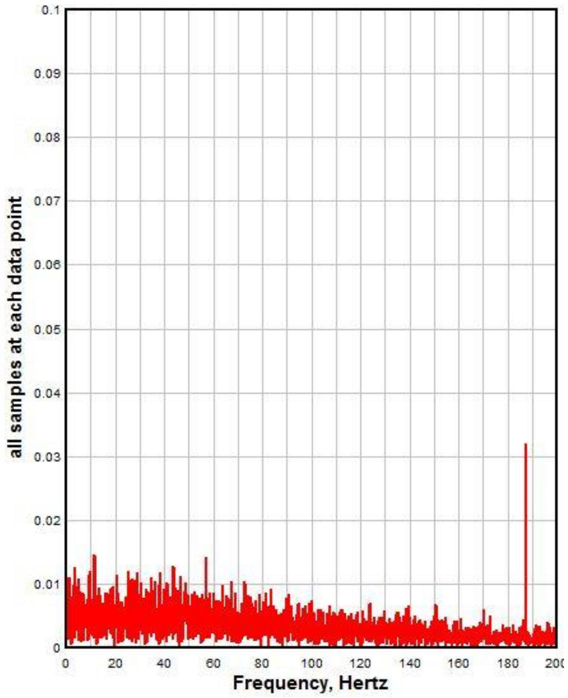

Fig. 3 Fast Fourier Transform (FFT) of the Hotwire Data at 1D Downstream of the Jet Exit

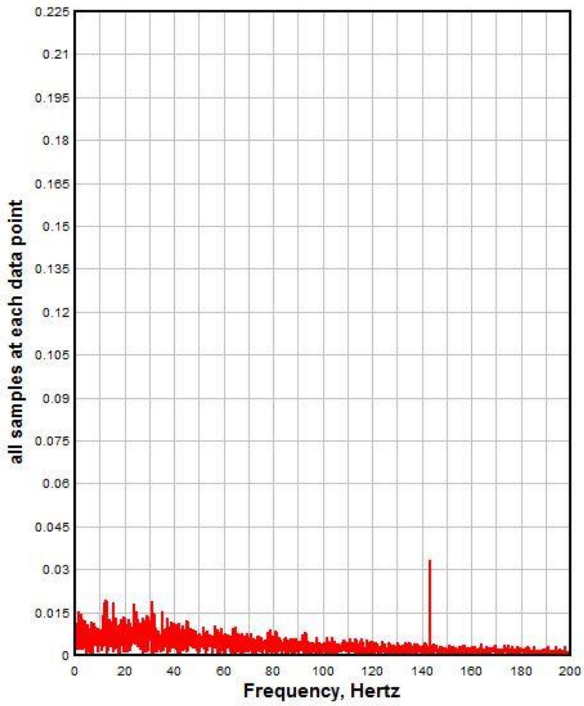

Fig. 5 Fast Fourier Transform (FFT) of the Hotwire Data at 3D Downstream of the Jet Exit

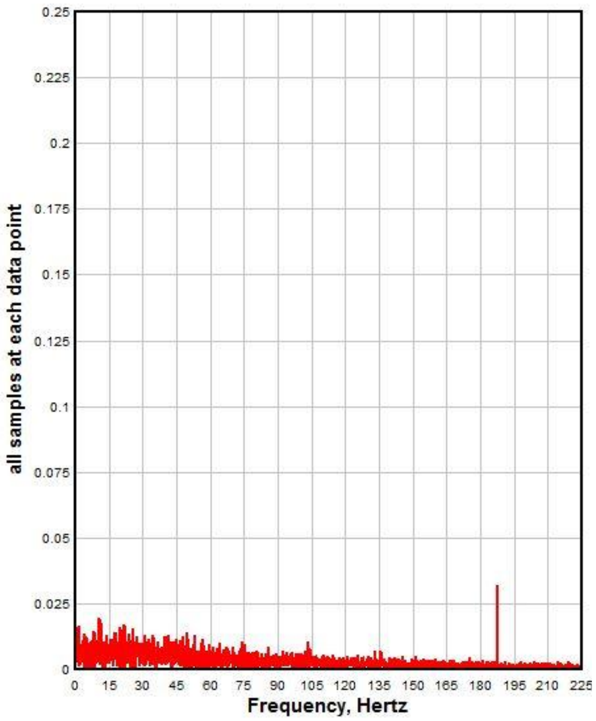

Fig. 4 Fast Fourier Transform (FFT) of the Hotwire Data at 2D Downstream of the Jet Exit

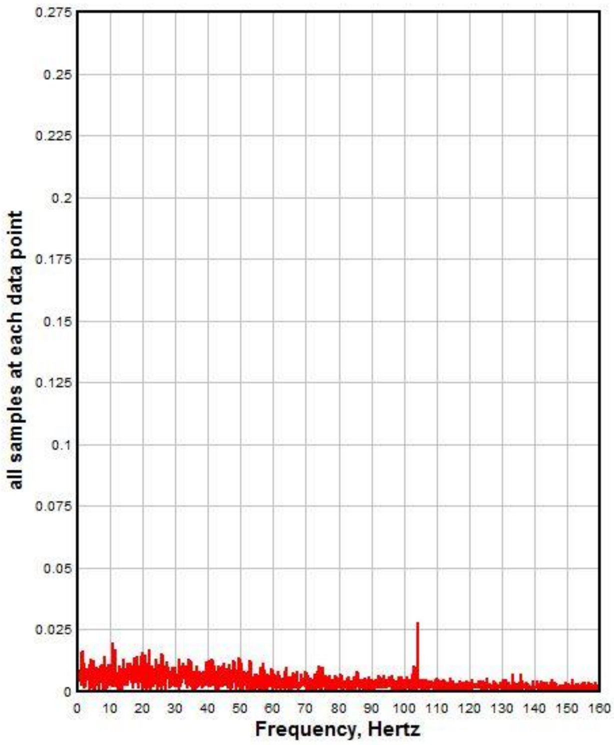

Fig. 6 Fast Fourier Transform (FFT) of the Hotwire Data at 4D Downstream of the Jet Exit

The results show a similar passing frequency at 1D and 2D downstream of the jet exit and a decrease in frequency at 3D and 4D downstream as shown in Table 1.

Table I : Passing Frequency and Corresponding Strouhal Number Measure by Hotwire Technique

Downstream Distance (D)	Frequency (Hertz)	Strouhal Number
1	187.6	0.638
2	187.4	0.637
3	143.4	0.487
4	104.3	0.354

B. *Flow Visualization*

Fig. 7 shows a typical image of the flow visualization used to calculate the passing frequency for the steady state condition. As can be seen in this figure, the vortical structures are much closer near the exit of the jet and undergo an increase in wavelength (become farther apart) as they develop and travel downstream.

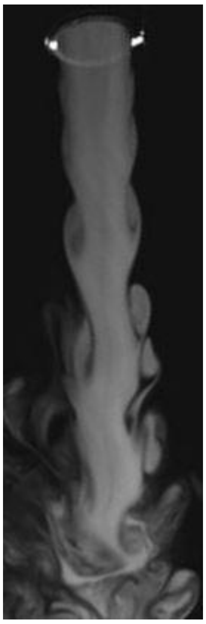

Fig. 7 : Flow Visualization of an Axisymmetric Turbulent Jet at Steady State

As the jet fluid travels downstream, it entrains surrounding fluid causing the spacing between vortices to increase. In addition, the vortex may undergo a pairing process and merge with another vortex causing a decrease in the passing frequency as it travels downstream as shown in Fig. 8.

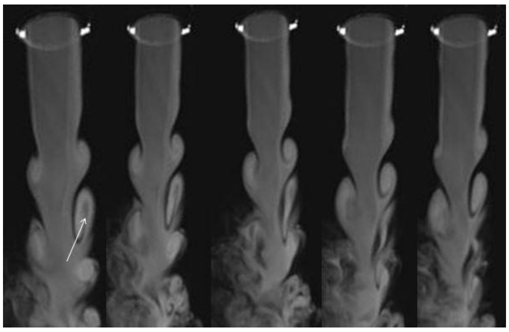

Fig. 8 : Vortex Merging

Visualization of the transient start of the jet was captured in order to determine if the vortical structures that follow the initial vortex display the same 'modes' as when a jet reaches steady-state as described above.

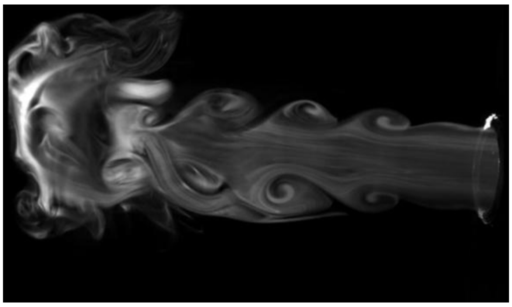

Fig. 9 : Flow Visualization of an Axisymmetric Turbulent Jet at the Transient Start Following the Initial Vortex

As seen in Fig. 9, the vortical structures that follow the initial vortex for the transient start of the jet pass at a uniform frequency at all locations downstream up until they break down.

As previously described, the frequency at four downstream locations was determined using of flow visualization (FV). This was accomplished by measuring the time duration for the center of 25 structures to pass each of the four pre-specified downstream location. The results are presented in Table 2 along with the results from the hotwire (HW) measurements.

Table II : Comparison of the Frequency and Strouhal Comparison Measurements Between Hotwire and Flow Visualization

Distance (D)	HW Freq. (Hz)	HW St #	FV Freq (Hz)	FV St #	St Diff (%)
1	187.6	0.638	191.2	0.650	1.84
2	187.4	0.637	190.7	0.648	1.69
3	143.4	0.487	136.5	0.464	4.72
4	104.3	0.354	98.4	0.334	5.64

Table 2 shows that there is a good agreement between the results measured using both techniques. These results show that as a vortical structure moves downstream, it begins to entrain surrounding fluid causing an increase in separation and a decrease in passing frequency. Also, it was found that as the vortical structure moves downstream the vortex can undergo vortex interaction and merge with a leading vortex. Vortex merging can cause significant frequency jumps. Due to the vortex pairing and the breaking down of the vortical structures, there is a larger discrepancy between the two measurement techniques as measurements are made farther downstream closer to the vortex breakdown position.

Fig. 10 displays the results of the current study and compares this data to that of previously published studies. From this figure, one can see that beyond a downstream distance of 1D the HW and FV data acquired in the current study correlates very well with a slope of -0.1493.

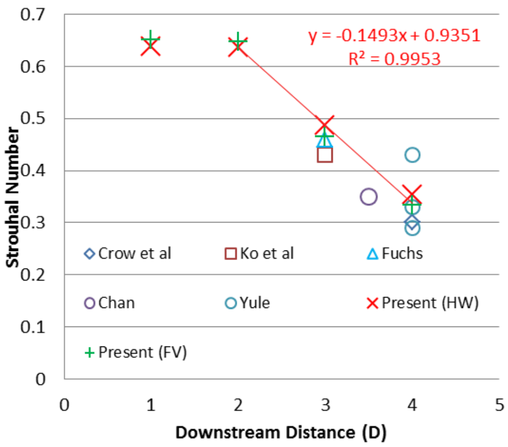

Fig. 10: Current Study Results Compared to Previous Published Studies

As shown by Gutmark and Chih-Ming [8], if the location of the 'preferred mode' is selected to be 4D downstream of the pipe exit, the Strouhal number has been found to vary between 0.275 to 0.5. The results from the current study at 4D agree well with this range but suggest a value of 0.35 is more appropriate. However, as one moves upstream closer to the pipe exit the Stouhal number increases. It is concluded that there is not a universal 'preferred mode' for an axisymmetric jet independent of jet size and speed. Previous published literature has shown that at low Reynolds numbers, there is a wide range in Strouhal numbers and the location at which the 'preferred mode' occurs. The present study shows that this lack of uniformity is probably due to the jumps in frequency caused by vortex merging as shown in Fig. 8.

IV. CONCLUSION

The current study presents the characteristics of the passing frequency of the vortical structures of a turbulent axisymmetric jet at a Reynolds number of 7,500. Both hotwire and flow visualization were used to measure the frequencies of the passing vortices. The largest discrepancy between the two measurement techniques was only 5.64%. These results show that due to the entrainment of surrounding fluid and the merging of vortices, the passing frequency decreases the farther downstream the vortical structure travels. Near the jet, however; the passing frequency is uniform up to 2D downstream. Also, the flow visualization of the transient start of the jet revealed that the passing frequency is uniform from the exit all the way until the structure breaks down. A decrease in passing frequency is not observed until the flow has reached steady-state. Therefore, it is concluded that there is not a universal 'preferred mode' for an axisymmetric jet of various sizes and speeds due to the merging of vortices. However, there seems to be a range of 'preferred modes' as displayed in previous published literature in which the current study is in very good agreement. In fact, this variation in the literature appears to be related to the measurement uncertainty of each study.

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