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Instantaneous energy separation in a free jet. Part I. Flow measurement and visualization

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Abstract

"Energy separation" is the re-distribution of the total energy in a fluid flow without external work or heat, and has potential to heat or cool a fluid without using a conventional heating or cooling system. However, currently obtainable heating and/or cooling effects are not big enough for practical applications. It is required to understand the mechanism of energy separation and investigate its enhancement methods. In the present study which consists of two parts, energy separation in a free jet is investigated with instantaneous velocity and total temperature measurements. As a method to enhance energy separation, acoustic excitation with various frequencies is examined. In this first part, an experimental study is performed to investigate the motion of the coherent vortical structure and its response to acoustic excitation in free jets whose Reynolds numbers are 8000 and 120,000. For the low Reynolds number jet, spectral analysis of instantaneous velocity and flow visualization by a schlieren system are performed to characterize the motion of the large scale coherent vortical structure. The frequency of dominant fluctuation, which represents the vortex passing frequency at a given axial location, is around $Sr_D \approx 0.65$ at $z/D = 1$ and moves to $Sr_D \approx 0.4$ at $z/D = 4$. When acoustic excitation is applied, the coherent structure develops more rapidly than in the absence of excitation regardless of the excitation frequency, but very regular and strong vortex pairing is observed only when acoustic excitation with $Sr_{ex} = 0.9$. The flow characteristics of the high Reynolds number jet are also investigated with spectral analysis. The result shows that the velocity fluctuation level is generally elevated, but the frequency of dominant fluctuation is still within $0.4 \leqslant Sr_D \leqslant 0.6$. The response to acoustic excitation is also very similar to the low Reynolds number jet.

1. Introduction

"Energy separation" is the re-distribution of the total energy in a fluid flow without external work or heat, so that some portion of the fluid has higher and another portion has lower total energy (temperature) than the remaining fluid. Since this interesting phenomenon was observed in a vortex tube (or Ranque–Hilsch tube) in the 1930s, many researchers have reported energy separation in various flow situations including plane shear layers [1,2], free jets [3,4], impinging jets [5] and flow across a circular cylinder [6,7]. Two physical mechanisms of energy separation were proposed by Eckert [8]. One is the imbalance between the energy transport by viscous shear work and by heat conduction. The other is due to pressure fluctuation within an unsteady flow field. In flow situations with large-scale coherent structure of vortices such as jets and vortex streets behind a cylinder, pressure fluctuation is caused by moving vortices and it is the dominant mechanism of energy separation. Recent studies support the model proposed by Eckert [8], but the difficulty in measuring rapidly fluctuating velocity, pressure and temperature limits the understanding on energy separation by this mechanism.

Even though energy separation phenomena offer the possibility of heating or cooling a fluid without a conventional heating or cooling system, current obtainable

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Nomenclature

D	nozzle exit diameter
f	frequency of velocity fluctuation
f_{ex}	frequency of external acoustic excitation
r	Radial coordinate
Re_D	Reynolds number based on a nozzle diameter, $= U_e D/\nu$
Sr_D	Strouhal number of velocity and temperature fluctuations, $= fD/U_e$
Sr_{ex}	Strouhal number of acoustic excitation, $= f_{ex} D/U_e$
u, U	axial velocity
U_e	mean velocity at the nozzle exit
z	axial coordinate

temperature differences between hotter and colder regions are generally not large enough for practical engineering applications. Enlargement of the temperature difference in a free jet with acoustic excitation was reported by Seol and Goldstein [4]. They applied controlled-monochromic acoustic excitation with loudspeakers, and measured time-averaged total temperature variation using a specially designed total temperature probe. The results showed that the acoustic excitation significantly enhanced energy separation, but the detailed mechanism of the enhancement was not clearly understood. The enhancement was also observed in a flow around a circular cylinder, when the synchronization occurred between intrinsic acoustic waves of the experimental apparatus with vortex shedding [6,7].

Although information on instantaneous flow and thermal fields is essential to understand the mechanism of energy separation and its enhancement by acoustic excitations, most of previous studies are based on time-averaged total and recovery temperature measurements. In the present study, the mechanism of energy separation in a free jet is investigated by obtaining instantaneous velocity and total temperature data. Results from the present study can not only explain the mechanism in the free jet, but also provide useful information in interpreting energy separation and its enhancement in other flows with large-scale coherent vortices. The present study consists of two parts—(1) flow measurement and visualization, and (2) total temperature measurement. In the first part, the motion of the coherent structure and its response to acoustic excitation are measured with a hot-wire anemometer and visualized by schlieren technique. Spectral analysis of the instantaneous velocity data is performed and the results compared with the flow visualization. Corresponding instantaneous total temperature measurement and comparison with instantaneous velocity data are described in a companion paper [9].

Understanding the motion of the coherent structure around a jet and its sensitive response to acoustic excitation has drawn significant researchers' attention. In the 1930s, Brown [10] visualized the vortex structure and its response to acoustic excitation. He observed that the development of vortex structure was strengthened at certain frequency of acoustic excitation. His observations were extended by Crow and Champagne [11]. They investigated the motion of the coherent structure and turbulent characteristics of a circular jet with/without acoustic excitation. They indicated that vortex passing frequency has a certain value at the end of the potential core of the jet, which was expressed in terms of Strouhal number,

$$Sr_D = \frac{fD}{U_e} \approx 0.3 \tag{1}$$

They called this frequency as the "preferred mode". When they applied acoustic excitation at this frequency, a significant increase in turbulent intensity was observed. After Crow and Champagne, studies to identify the preferred mode were performed by many other researchers [12–15]. Even though they agreed that there was a certain frequency corresponding to the preferred mode, their Strouhal numbers did not agree well, varying from 0.25 to 0.5. Lepicovsky et al. [16] also reported that the large scale coherent structure existed at high Reynolds number jets and corresponding Strouhal number is around 0.4. Russ and Strykowski [17] showed that this difference was due to the different initial shear layer thickness at the nozzle exit. Another interesting feature of the response to acoustic excitation was reported by Hussain and Zaman [18,19], who found that very stable and regular vortex pairing could be induced by applying acoustic excitation at certain frequencies. Similar trend was also observed in high speed, high Reynolds number jets by Lepicovsky et al. [20].

In the present study, the motion of the coherent structure and its response to acoustic excitation are experimentally studied in free jets whose Reynolds numbers are 8000 and 120,000. For the low Reynolds number jet, spectral analysis of instantaneous velocity and flow visualization by a schlieren system are performed with/without acoustic excitation to understand the motion of the coherent structure and its response to acoustic excitation. The flow characteristics of the high

Reynolds number jet are also investigated with spectral analysis, since energy separation is more prominent in high speed flows. The results provide useful information on the motion of the coherent structure and its response to acoustic excitation and become building blocks of energy separation mechanism.

2. Experimental apparatus and methods

A schematic diagram of the experimental apparatus is shown in Fig. 1. It consists of three parts—jet generation system, acoustic excitation system and measurement system. The jet generation system provides an air jet whose velocity ranges from 1 to 150 m/s. Compressed air supplied from a building air compressor at a pressure of 830 ± 10 kPa, passes through a sharp-edge orifice (opening ratio $= 0.63$) which meters the flow rate. After the orifice, the air flows through the preliminary and main plenum chamber. The temperature of the air can be adjusted by an electrical heater wrapped around the outside of the preliminary plenum chamber. Before the air enters the main plenum chamber, unwanted disturbances are removed by an acoustic silencer (Burgess-Manning CA-2.5), where the air flows through an annular passage lined with perforated tubes backed by multiple layers of sound absorbing materials. In the main plenum chamber, the air passes through aluminum-packed chip and honeycomb to remove temperature variations in the radial direction and straighten the flow. The air jet issues through a bell-shaped nozzle with an exit diameter (D) of 20 mm. The diameter of the main plenum chamber is large enough (~400 mm) so that the velocity in the chamber can be neglected.

The acoustic excitation system generates monochromatic sound waves and applies them around the jet. Excitation signals are generated from a wave generator (Wavetek model 75) which can generate arbitrary waveforms at a certain frequency. During the experiment, the amplitude of the signal is fixed, but the frequency of the excitation varies to become the excitation Strouhal number (Sr_{ex}) from 0 to 1.3. A sinusoidal waveform is used at all excitation frequencies. The frequency of the input signal is monitored with an oscilloscope. The signals are amplified by a power amplifier (Altec 9444A). The amplified signals drive four loudspeakers (Altec 290–8 K) in unison which are located 90° apart around the main chamber. Acoustic waves from the speakers are delivered around the jet through wave guides.

The schematic of the measurement system is shown in Fig. 2. Temperatures around the setup are monitored with ten T-type thermocouples placed at various locations. Either a single or dual hot-wire probe is connected to an anemometer system (TSI IFA-100) which has two constant temperature modules. In this first part, a single hot-wire probe is used to obtain instantaneous axial velocity. The dual hot-wire probe is used to measure instantaneous velocity and temperature as described in an accompanied paper [9]. A Pitot-tube and micro manometer (Dwyer model 1230) are used to check the nozzle exit velocity (U_e) and calibrate the hot-wire probes. For the flow visualization, a schlieren system using two converging mirrors [21] is used.

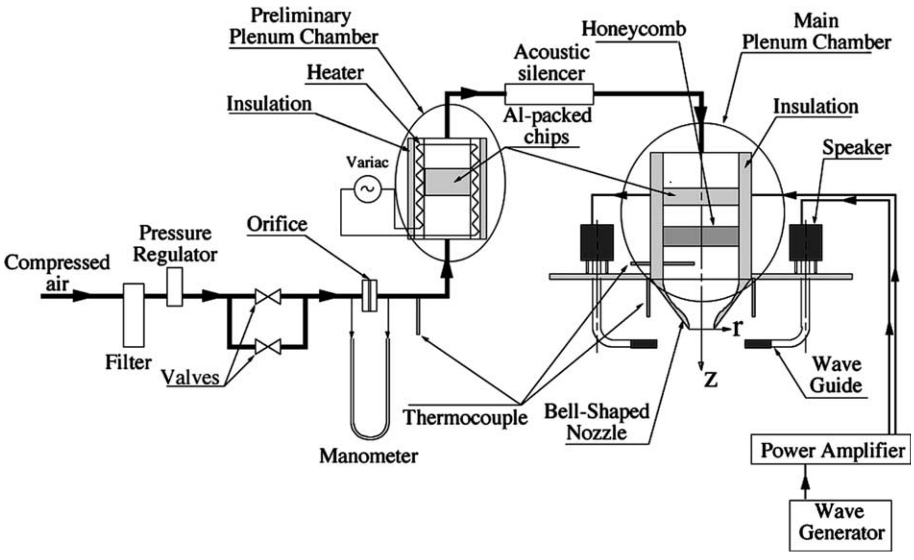

Fig. 1. Schematic diagram of experimental apparatus.

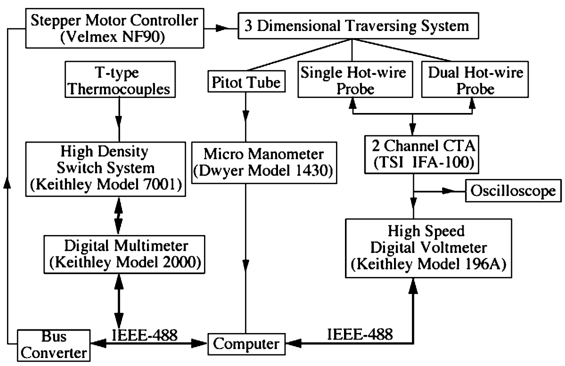

Fig. 2. Schematic diagram of measurement and control system.

The experiments are performed at two different Reynolds numbers. At low Reynolds number case ($Re_D = 8 \times 10^3$), spectral analysis of instantaneous velocity and flow visualization are carried out with varying the excitation Strouhal numbers from 0.1 to 1.3 with 0.2 interval. But for simplicity, the results for $Sr_{ex} = 0$, 0.3 and 0.9 are only shown in the present study. More detailed results can be found in [22,23]. Since the velocity fluctuations within the potential core of the jet are rarely affected by turbulent fluctuation, they are primarily due to the motion of the coherent structure of ring vortices [19]. Spectral analysis of the instantaneous velocity gives information on the velocity fluctuation in frequency domain, which depends on the velocity at which vortices pass across the hot-wire probe and the size of the vortices. Therefore, analysis of the power spectrum of the velocity fluctuation provides information on the characteristics of vortex motion in the flow including the passing frequencies of the vortices and their size.

At high Reynolds number case ($Re_D = 1.2 \times 10^5$), only the hot-wire measurements and corresponding spectral analysis are performed with the three different excitation Strouhal numbers—0, 0.3, and 0.9. Throughout the measurements and visualization, the room temperature is maintained within ±0.05 °C. The temperature of the air at the nozzle inlet, which corresponds to the total temperature at the nozzle exit, is controlled to remain within ±0.05 °C of the room temperature. During the visualization, the jet is heated to approximately 20 °C above the room temperature, but the effect of buoyancy is negligible.

3. Results and discussion

The schlieren image without acoustic excitation is compared with the power spectra at several different axial locations in Fig. 3. For $z/D \leqslant 1$, there is no noticeable ring vortex structure in the schlieren image. In the power spectrum at $z/D = 1$, the dominant frequency is around $Sr_D \approx 0.65$. However, the spectral density at the dominant frequency is relatively small and disturbances at this axial location are not evolving into vortices yet. Noticeable ring vortices are observed around $z/D = 2$, and the power spectrum shows that the spectral density of dominant frequency significantly increases but the frequency still remains around $Sr_D \approx 0.65$. At this location, this frequency represents the vortex passing frequency rather than the frequency of the disturbances. At $z/D = 3$, the size of the vortical structure increases and the corresponding power spectrum shows another dominant frequency of fluctuation around $Sr_D \approx 0.4$ which is expected to be the preferred mode of the present jet. The spectral density at both frequencies are similar, but the density at $Sr_D \approx 0.4$ surpass that at $Sr_D \approx 0.65$ at $z/D = 4$. The lowered dominant frequency indicates that the time interval between two vortex passing events at a

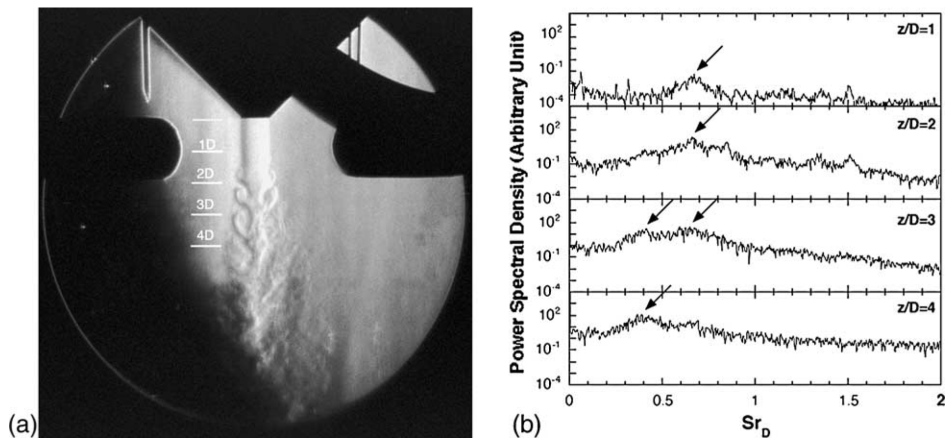

Fig. 3. Comparison between flow visualization by schlieren technique and spectral analysis when $Re_D = 0.8 \times 10^4$ without acoustic excitation: (a) schlieren image, (b) power spectra (filled arrows denote dominant peaks).

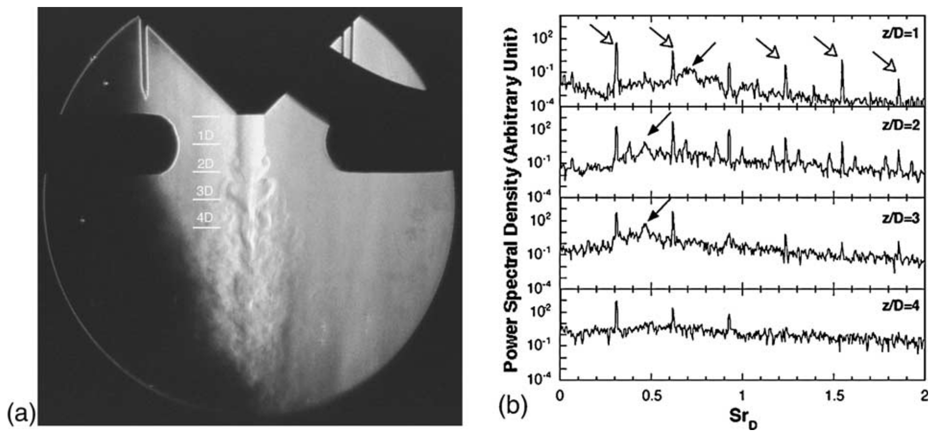

Fig. 4. Comparison between flow visualization by schlieren technique and spectral analysis when $Re_D = 0.8 \times 10^4$ and $Sr_{ex} = 0.3$: (a) schlieren image, (b) power spectra (filled arrows denote dominant peaks and unfilled arrows denote excitation signal).

given axial location increases. This can result from growing of vortices either by viscous diffusion or by vortex-pairing process as described in [19].

The results with acoustic excitation of $Sr_{ex} = 0.3$ are shown in Fig. 4. In general, the shapes of the power spectra are very similar to those without acoustic excitation. However, vortices are initiated at more upstream locations and develop more rapidly. The level of fluctuation, denoted by spectral density, is also elevated. In the power spectra, very sharp peaks (denoted with unfilled arrows in Fig. 4(b)) occur at higher harmonics of $Sr_D = 0.3$ (i.e. $Sr_D = 0.3$, 0.6, 0.9, 1.2, 1.5 and 1.8) which should be originated from acoustic excitation, not from the velocity fluctuations. At $z/D = 1$, very small size vortices are observed in the schlieren image, but the dominant frequency is still around $Sr_D \approx 0.65$ even with acoustic excitation. At $z/D = 2$, the size of vortices increases and the dominant frequency already moves to $Sr_D \approx 0.4$. As the flow goes to $z/D = 3$ where is the downstream of the wave guides, the peaks at higher harmonics of $Sr_D \approx 0.3$ significantly decrease which supports the fact that these peaks are produced by the excitation.

Fig. 5 shows the schlieren image and corresponding power spectra with acoustic excitation of $Sr_{ex} = 0.9$. The vortical structure is observed even at the upstream of $z/D = 1$ as shown in Fig. 5(a). The power spectrum at this axial location also shows very strong peaks at both sub-harmonics of $Sr_D = 0.9$ (i.e. $Sr_D = 0.45$ and 1.35) and higher harmonics of $Sr_D = 0.9$ (i.e. $Sr_D = 0.9$ and 1.8). In addition, these peaks have wider frequency width than the peaks in $Sr_{ex} = 0.3$ which implies that they are contributed by both the excitation and velocity fluctuations. The sub-harmonic frequency of $Sr_D = 0.45$

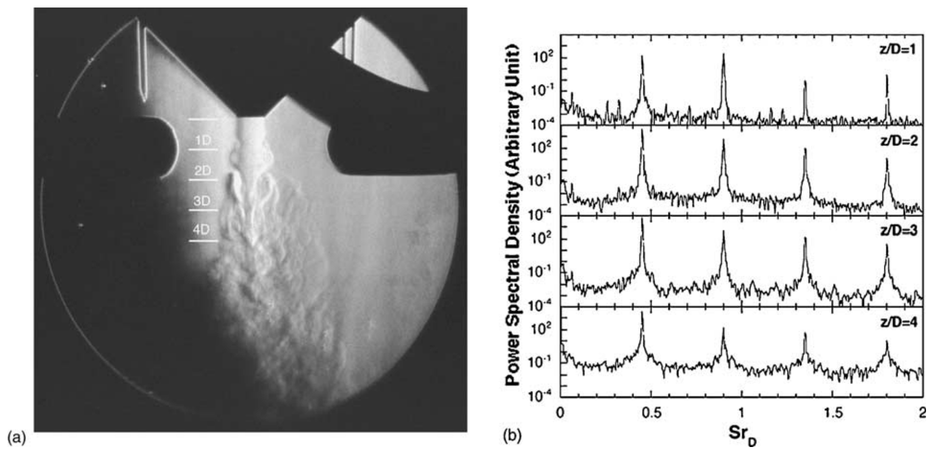

Fig. 5. Comparison between flow visualization by schlieren technique and spectral analysis when $Re_D = 0.8 \times 10^4$ and $Sr_{ex} = 0.9$: (a) schlieren image, (b) power spectra.

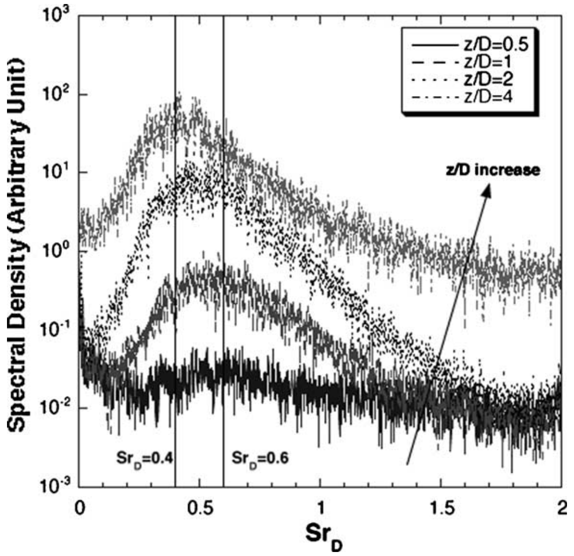

Fig. 6. Velocity power spectra when $Re_D = 1.2 \times 10^5$ without acoustic excitation.

is the dominant frequency at all the axial locations. This sub-harmonic frequency is expected to come from vortex-pairing processes, where a vortex evolved from the excitation with the frequency of $Sr_D = 0.9$ is merging with neighboring one. The resultant vortex has the passing frequency of $Sr_D = 0.45$. Similar vortex-pairing processes by acoustic excitation can be induced when the excitation Strouhal number (Sr_{ex}) ranges from 0.6 to 1.1 [22,23]. The strongest and most regular pairing process is achieved with the excitation of $Sr_{ex} = 0.9$ in which the frequency resulted by the pairing process is close to the preferred mode of the jet.

The power spectra of velocity fluctuation in a higher Reynolds number jet ($Re_D = 1.2 \times 10^5$) without acoustic excitation are shown in Fig. 6. Even though the level of fluctuation is generally raised, no noticeable dominant frequency is observed at $z/D = 0.5$. As z/D increase to 1, the spectral density has a maximum value around $Sr_D \approx 0.6$. At $z/D = 2$, the spectral density around $Sr_D \approx 0.4$ increases and becomes similar magnitude to that around $Sr_D \approx 0.6$. This trend continues to $z/D = 4$, and $Sr_D \approx 0.4$ becomes the dominant frequency. This value of the Strouhal number agrees well with a previous study which showed the large scale coherent structure exist even in a high Reynolds number jet and its Strouhal number is about 0.4 [16]. At this location, spectral density at higher Strouhal number region (>1.5) also increases significantly. This implies the development of small scale eddies which come from breakdown of large scale coherent vortical structure.

The responses of the high Reynolds number jet to acoustic excitation are shown in Fig. 7. When the excitation of $Sr_{ex} = 0.3$ is applied, the overall shapes of power spectra are very similar to those without acoustic excitation. As already shown in the low Reynolds number jet, very sharp peaks at higher harmonics of $Sr_D = 0.3$, which are produced by acoustic excitation itself, are observed until $z/D \leqslant 2$. The effect of acoustic excitation is more evident when the excitation Strouhal number increases to 0.9 (Fig. 7(b)). After excluding higher harmonics of the excitation frequency (i.e.

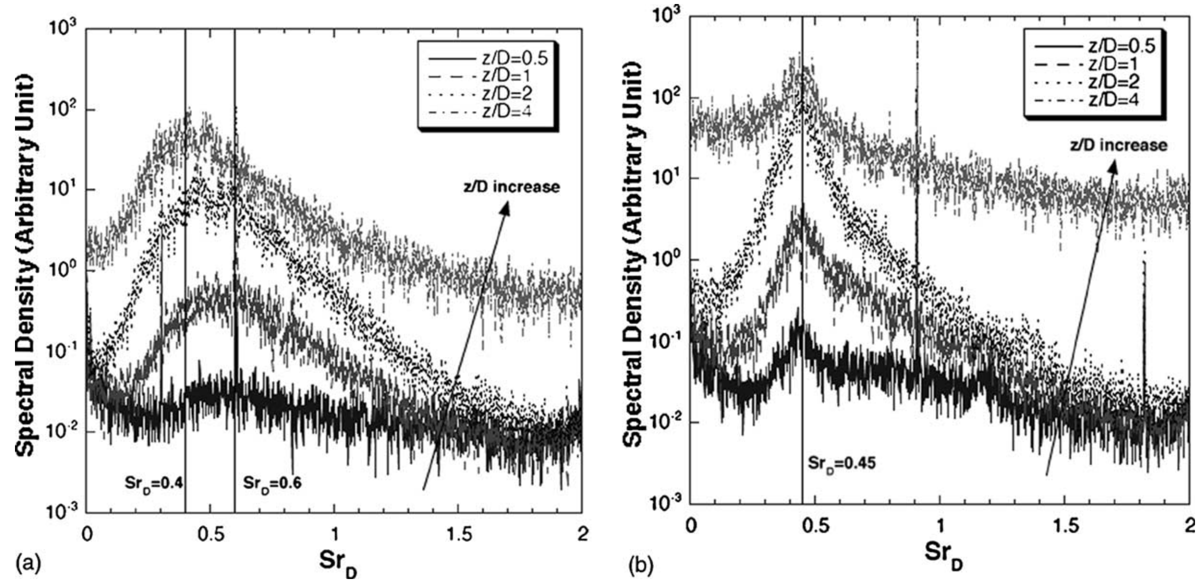

Fig. 7. Velocity power spectra when $Re_D = 1.2 \times 10^5$ with acoustic excitation: (a) $Sr_{ex} = 0.3$, (b) $Sr_{ex} = 0.9$.

$Sr_D = 0.9$ and 1.8), $Sr_D = 0.45$ is already the dominant frequency even at $z/D = 0.5$. Relatively small but local maximum spectral density is also observed around $Sr_D \approx 1.2$. The spectral density at $Sr_D = 0.45$ is getting more predominant as the flow goes downstream, and the value is much higher than the cases of $Sr_{ex} = 0$ and 0.3.

4. Conclusions

To understand the mechanism of energy separation and its enhancement in a free jet, the spectral analysis of instantaneous velocity and the flow visualization are carried out. The results will improve understanding of the motion of the coherent structure and its response to acoustic excitation. Conclusions from the present study can be summarized as below.

1. For the unexcited jet with $Re_D = 8 \times 10^3$, the dominant frequency of the velocity power spectra, which represents the vortex-passing frequency at a given axial location, is around $Sr_D \approx 0.65$ at $z/D = 1$ and moves to $Sr_D \approx 0.4$ as the flow goes downstream. This value falls within the range of the preferred mode of the jet.
2. When acoustic excitation is applied, the vortical structure is initiated at more upstream and grows more rapidly regardless of the excitation Strouhal number (Sr_{ex}). When $Sr_{ex} = 0.3$, however, the dominant frequency of the velocity power spectra remains similar to the case without acoustic excitation. When Sr_{ex} becomes 0.9, very strong and regular vortex-pairing process occurs and the resulting Strouhal number of vortex passing frequencies becomes 0.45.
3. Even when Re_D increases to 1.2×10^5, the observations made in the low Reynolds number jet are still valid with slight changes in the value of the dominant frequency.

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