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VISUALIZATION RESULTS OF AXISYMMETRICAL WAKE FLOW WITH/WITHOUT ACOUSTIC EXCITATION

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Abstract Visualization results demonstrate the evolution of Kelvin-Helmholtz unstable waves into vortex pairing in a separated shear layer of a blunf circular. The results with acoustic excitation are quite different from that without acoustic excitation, and the phenomenon with excitation in a separated shear layer follows the rule of Devil's staircase, which always occurs in a non-linear dynamical system of two coupling vibrators.

Key words K-H unstable wave; separated shear layer; acoustic excitation; turbulent control; non-linear dynamical system

0 Introduction

The swing of two clocks with pendulums, hanging back to back on the wall, will probably be synchronizing their motion. Such a phenomenon is known as frequency locking or lock-in. The coupling of an oscillation wave or vortex shedding to an external periodic acoustic or mechanical oscillator in a shear flow might also dynamically drive the fluid system into synchronization. For weak competition the locking interval of the frequencies are narrow, and the motion in phase space is quasi-periodic, and for most driving frequency the ratio between the two frequencies is more likely irrational. When the competition increases, the system turns into synchronization and the system is re-ordered. If much stronger competition is exerted, the lock-over occurs, i.e., the motion of the system is chaotic again. Theoretical analysis shows that due to the competition between the frequencies of oscillater's and the external excitation, an infinite step will arise, which is termed as Devil's staircase by mathematicians. In general, the evolution of the K-H unstable waves in a shear layer separated from the leading edge of an axisymmetrical bluff body will finally results in the development of helical vortex shedding in its bubbles on the surface of the bluff-body or in the wake behind the bluff-body. Devil's staircase emerges not only in non-linear mechanical systems of vibration, but also in long-range spatially periodic solid structures in the condensed-matter physics, and K-H unstable waves in the shear layer or the frequency of vortex shedding in the wake flow with external acoustic excitation, etc.

In this paper, some experimental results are presented on the competition between the frequ-

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encies of Kelvin-Helmholtz unstable waves in a separated shear layer from the sharp edge of the front flat of an axisymmetrical body with that of external acoustic excitation. Up to now, there is little information related to how the behavior of K-H unstable waves in a shear layer separated from the leading or trailing edge of an axisymmetrical bluff body is affected by an acoustic excitation emitted from a forthward-facing or a backward-facing loudspeaker mounted in it, as well as how the frequency of helical vortex shedding is synchronized on an excited acoustic frequency. Therefore, a project of trying to put some insight into these phenomena about the influence of acoustic excitation on the behavior of K-H unstable waves in a separated shear layer and the helical vortex shedding in an axisymmetrical wake flow has been conducted in our group. The conditions about why Devil's staircase will occur and how to employ non-linear theory of dynamical systems to explain such new phenomena in the turbulent shear flow are emphasized. This paper mainly concerned the behavior of K-H unstable waves in the shear layer separated from the sharp leading edge of an axisymmetrical bluff-body.

1　Experimental Setup

The experiment was done in a low turbulence wind tunnel at Beijing University, whose cross-section and the length of the test section is $0.3\text{m} \times 0.8\text{m}$ and 3.2m respectively. The velocity varies from $0.1 \sim 20\text{m/s}$, and the level of free-stream turbulence is less than 0.08%. The bluff-body was made of plexglass with a sharp leading edge. Model's diameter and length are 80mm and 350mm respectively. A loudspeaker as the source of excitation is embedded into the front of the model. There is a disk before the loudspeaker and acoustic waves are forced to pass through a thin gap between the front edge of the model and the disk. The loudspeaker with power of 4W is driven by an amplifier and its frequencies range from $20 \sim 5000\text{Hz}$. The output of frequency is controlled by a low-frequency signal generator, Model XFD-74A. The coordinates for the measurement are as follows: X axis is along the streamwise, Y axis is vertical to the axis of the bluff-body; the leading edge point is defined as the original point$(0,0)$. TSI-1050 anemometer, a single probe and a X-probe are employed for measurement. Signals are transferred by an A/D convertor and then processed in a personal computer for obtaining turbulent parameters and the spectrum. The sample points of each segment are 1024.

2　Analysis of Experiment Results

We have already revealed some important behaviors related to the transition of vortex shedding from ordered to the chaotic in the wake flow behind a 2-D circular cylinder in the past several years. It is assumed that there could be more interesting chaotic phenomena, especially its behavior related to the transition of helical vortex shedding from order to chaos in an axisymmetrical wake flow. Besides the pure chaos study mentioned above, we also have another practical pursuit, i.e., the application of such a device for reducing noise of vortex shedding and drag of an axisymmetrical bluff body in our project. In our experiments, the amplitude of the induced-oscillation excited by acoustic waves of compressive and rarefied pressure is much smaller than that of mean velocity, but comparable with that of turbulent fluctuation velocity. It is quite interesting that such a very small excitation can change the structure of the main flow greatly, reduce the reattachment length of the separation bubble and even make the bubble vanish. Therefore there exists another approach of reducing the form drag of a bluff-body by means of external sound wave, interacting with K-H unstable waves in the shear layer separated from the leading edge of the bluff-body. On the other hand, we also found that the acoustic excitation can also enhance the chaotic mixing in certain regions, which reveals the potentially engineering application to the combustion in engines and the blending processing in petro-chemical industries.

The visualization of the separated shear layer by the oilsmoke is shown in Fig. 1, which demonstrates the vortex shedding resulted from the evolution of K-H unstable waves.

Fig. 1 The evolution of the separated shear layer from a leading edge

图1 前缘分离剪切层的演化发展过程(流动显示)

When vortices go downstream, two vortices would interact with each other, and finally result in pairing and forming a larger one. As the larger vortex matches with the height of the separation bubble, the vortex will touch the wall of the bluff-body, i. e., the shear layer reattaches to the wall. The motion of the flow in the reattachment region is very complicated and the turbulent energy is higher than that in the other regions.

2.1 Effect of Acoustic Excitation Under Different Frequencies

The effect of acoustic excitation on the behavior of the separation bubble is illustrated in Fig. 2. It's obviously that the effect on the separation bubble with different excitation frequencies is different. At $St < 0.7$, the reattachment length of the separation bubble decreases with the increment of Strouhal number; in the range of $0.7 < St < 1.6$, it approximately remains constant; at $St > 1.6$, it becomes longer and longer till to the length in the natural state. The effect of acoustic excitation is also related to Reynolds number, the lower Reynolds number is, the stronger the effect of acoustic excitation is. However, the region with the most effective acoustic excitation is independent of Reynolds number, and the most effective region of Strouhal number manges from $St = 0.7$ to $St = 1.6$.

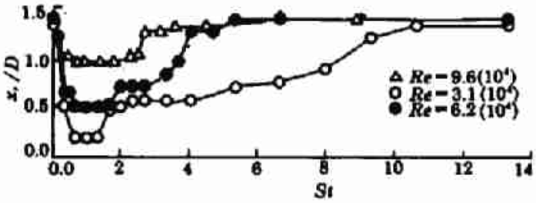

Fig. 2 The effect of acoustic excitation on the reattachment length

图2 声激励对再附长度的影响

2.2 Characteristics of Mean Flow Field with/Without Acoustic Excitation

The difference of mean velocity with/without acoustic excitation is shown as Fig. 3. Under acoustic excitation, the height of the separation bubble is lower than that in natural state. However, the region effected by acoustic excitation is limited, when $x > 3D$, there is little influence on the mean velocity profile. Fig. 4 shows the difference of turbulent energy and Reynolds stress with/without acoustic excitation.

As is known, from the leading edge to the reattachment region, the turbulent energy and

Reynolds stress gradually increase, and reach the maximum at the reattachment region. Under acoustic excitation, the separation bubble reduces, and the position of the maximum of turbulent energy and Reynolds stress is nearer to the leading edge. So, at the position of $x = 0.31D$, the turbulent energy and Reynolds stress with acoustic excitation are bigger than those in natural state respectively; at the position of $x = 1.25D$, they are nearly equal; and at the position of $x = 3.75D$, the turbulent energy and Reynolds stress with excitation are smaller than those in natural state.

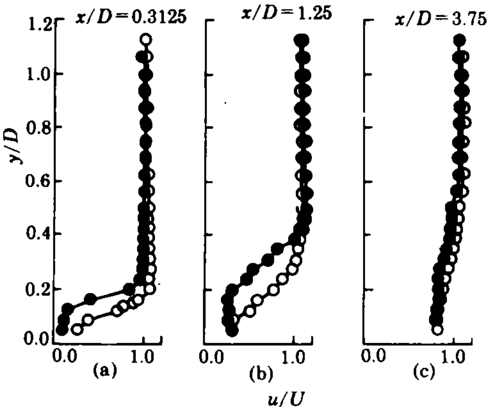

Fig.3 The effect of excitation on the mean velocity profile

图 3 激振对平均速度剖面的影响

○ f_e = 0Hz　●f_e = 100Hz

2.3 Isograms of Mean Velocity, Turbulent Energy and Reynolds Stress

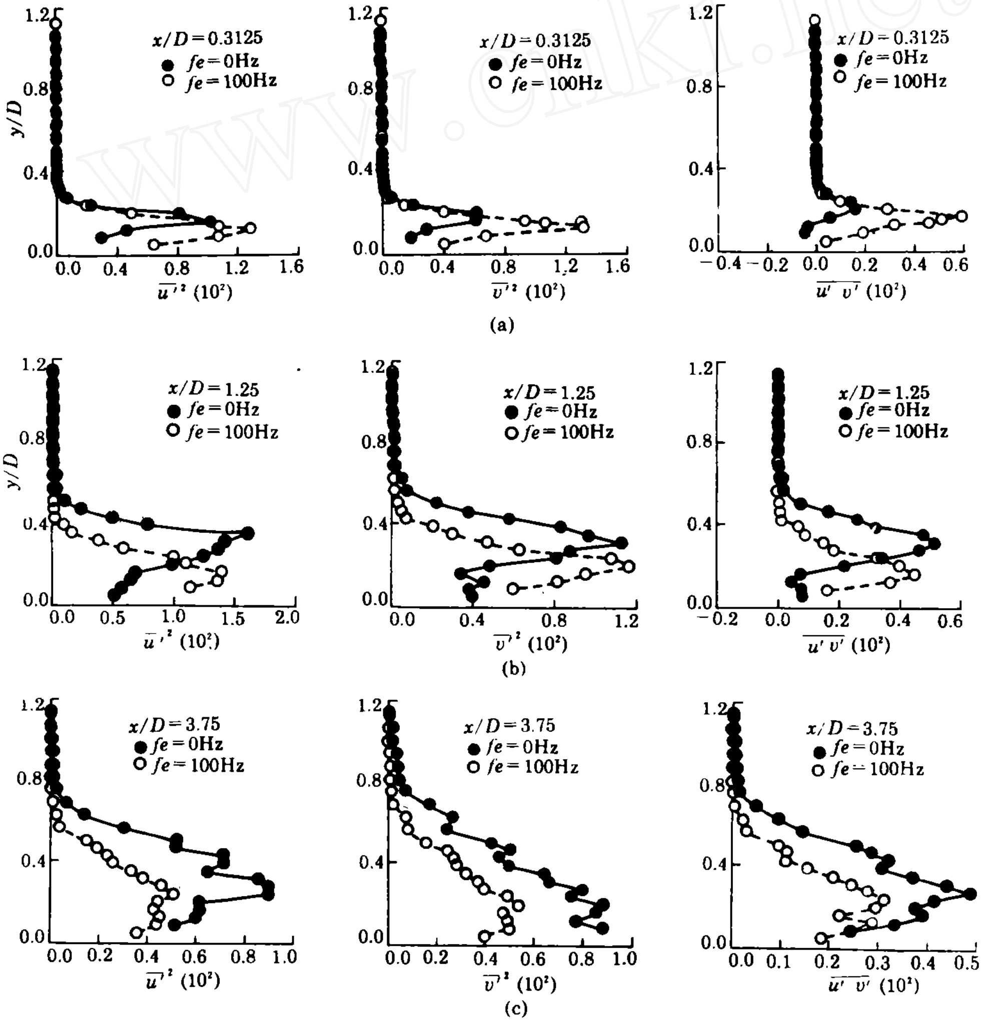

Fig.4 The effect of excitation on turbulent energy and Reynolds stress

图 4 激振对湍动能及雷诺应力的影响

Fig. 5 is the isogram of mean velcity with/without acoustic excitation. Obviously, the separation bubble region reduces under acoustic excitation. Fig. 6 and Fig. 7 are the isograms of the turbulent energy and Reynolds stress respectively. The position of the largest turbulent energy and Reynolds stress is nearer to the wall of the model with acoustic excitation than that without acoustic excitation, which means the reduction of the separation bubble.

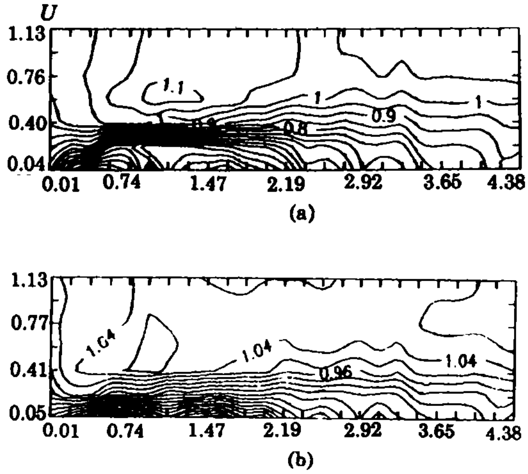

Fig. 5 The isograms of mean velocity

(a) without acoustic excitation

(b) with acoustic excitation, $f_e = 200\text{Hz}$

图5 等平均速度线

(a) 自然状态 (b) 声激励频率 $f_e = 200\text{Hz}$

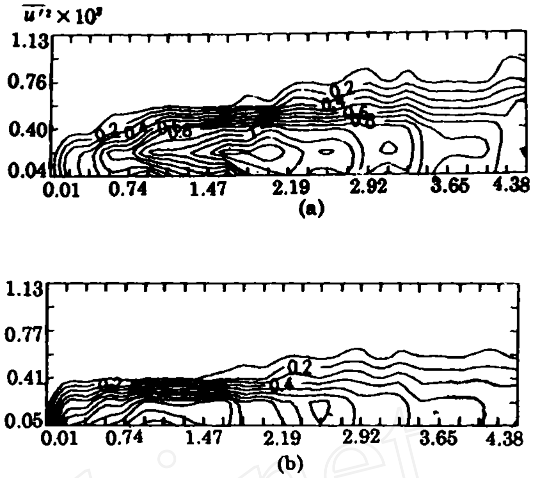

Fig. 6 The isograms of turbulent energy

(a) without acoustic excitation

(b) with acoustic excitation, $f_e = 200\text{Hz}$

图6 等湍动能($\overline{u'^2}$)线

(a) 自然状态 (b) 声激励频率 $f_e = 200\text{Hz}$

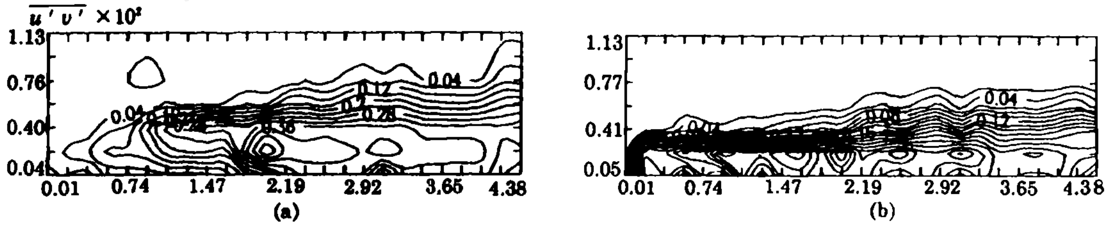

Fig. 7 The isograms of Reynolds stress

(a) without acoustic excitation (b) with acoustic excitation, $f_e = 200\text{Hz}$

图7 等雷诺应力线

(a) 自然状态 (b) 声激励频率 $f_e = 200\text{Hz}$

3 Conclusion

By analyzing the influence of acoustic excitation on the separation bubble, the preliminary conclusions are drawn as follows.

(1) The K-H unstable waves in the separated shear layer can be substantially affected by acoustic excitation, which means that the evolution of K-H unstable waves could be controlled. Strouhal number for the most effective acoustic excitation is independent of Reynolds number, and lies in the range of $St = 0.7 \sim 1.6$.

(2) Acoustic excitation can reduce the separation bubble at the leading of the bluff-body, and so does its drag. Besides this, acoustic excitation makes the turbulent energy and Reynolds stress in some certain regions increase, which means the ability of chaotic mixing and the transversal momentum transfer increase in these regions.

(3)A devil-staircase phenomenon occurs in the separated shear layer at certain cases of acoustic excitation, similar to what happens in non-linear mechanical systems of vibration.

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自然状态及声激励状态下轴对称尾流的流动显示结果

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摘要　流动显示演示了轴对称钝体前缘分离剪切层中 Kelvin-Helmholtz 不稳定波的演化发展情况。声激励状态下的流场结构与自然状态相比发生了很大的变化，分离剪切层与外加声激励的相互作用蕴含着魔鬼台阶现象，该现象经常在两个振子相互耦合的动力系统中产生。

关键词　K-H 不稳定波；分离剪切层；声激励；湍流控制；非线性动力系统
中图号　V211.4，TB52