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## Experimental study on vortex sound interaction of acoustic resonance and its suppression in a flow duct

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### ABSTRACT

Acoustic resonance induced by vortex shedding in flow passages is widely detected in various of engineering applications such as aeroengine compressors, tubular heat exchangers and so forth. The coupling between vortex and sound is still an open issue. Experimental results of vortex sound interaction in acoustic resonance induced by vortex shedding from bluff bodies in a flow duct are presented in this paper, with special attention being paid to the suppression strategy using acoustic treatment on the duct wall. Two sets of experiments, including hard wall condition and non-locally reacting liner condition, are conducted in a low-speed wind tunnel. The "dominant region" and "synchronous region" are observed in both the lock-in region of sound wave and vortex shedding signal. The frequency of the acoustic $\beta$-mode of the test section is different from the dominant frequency of the dominant region and the locked frequency of the synchronous region. And acoustic feedback plays an important role in it. The acoustic liner can effectively suppress the process of acoustic feedback. When one side of the duct wall is replaced by a non-locally reacting liner with a sound absorption coefficient of approximately 0.4, the lock-in region disappears and the resonant amplitude of sound pressure and the corresponding fluctuation velocity are greatly reduced, which indicates a convenient strategy for acoustic resonant suppression.

### INTRODUCTION

Fluid-induced acoustic resonance is a complex coupling phenomenon between the vortex and sound, and widely detected in various of engineering applications such as aeroengine compressors, tubular heat exchangers and so forth. In addition to noise pollution, acoustic resonance can induce structural vibration failure inside the compressor under certain special conditions. It has been confirmed by researchers that separated airflow leads to strong blade wake vortex when the compressor is working at off-design point, which may cause acoustic resonance inside the compressor and threaten the safety of the engine. And it is clearly classified as one of the main factors that cause the blade non-synchronous resonance (Holzinger et al., 2015).

Parker (1966) conducted a experimental research on acoustic resonance with a single flat plate in a wind tunnel for the first time. The researchers (Cumsty and Whitehead, 1971; Graham and Maull, 1971; Archibald, 1975; Stokes and Welsh, 1984; Stokes and Welsh, 1986) further studied this problem through experiments and simulations. The phenomenon of lock-in and some characteristics of amplitude variation was discovered in acoustic resonance. The simplest acoustic resonance mode caused by a flat plate placed in a flow duct is the $\beta$-mode and the vortex shedding generated by the trailing edge of the plate is the main sound source. The lock-in region can be detected during acoustic resonance. In this region, the resonance frequency remains unchanged with the increase of the flow velocity and the sound pressure level (SPL) reaches the highest value synchronously which is the primary feature of acoustic resonance. The influence of the geometrical size of the plate on the acoustic resonance and some detailed simulations can refer to the researches of Yokoyama et al. (2013) and Katasonov et al. (2015).

Although the basic process of acoustic resonance has been widely investigated, the interaction between sound waves and flow and the lock-in mechanism are still not well understood. Hong et al. (2020) numerically predicted that sound particle velocity is a bridge between the feedback sound and the vortex shedding modulation. The strength of the sound particle velocity can affect the value and width of the frequency lock-in. But these have never been validated by experiments. Some related findings are mentioned in Islam et al. (2020).

To suppress acoustic resonance, some common acoustic wave suppression methods are widely considered. Optimizing the structure of the bluff body to weaken the intensity of the vortex shedding, such as serrated trailing edge, or increasing the disturbance of the vortex shedding to stagger the lock-in frequency, such as vibratable bodies, may be a good way to solve the problem from the sound source. And placing a acoustic liner on the inner wall is a conventional engine noise reduction method which may eliminate acoustic feedback (Wu et al., 2019).

The objective of this study was to further clarify the mechanism of acoustic resonance frequency lock-in and the way in which acoustic feedback works through simultaneous measurement of the flow and sound results. To this end, a non-locally reacting liner with a specific sound absorption coefficient was used as the suppression strategy to weaken the strength of sound wave reflection, comparing with original rigid condition of a hard wall. A flat plat with semi-circular leading edge and square trailing edge was considered in this work. Hot-wire and microphone was used to measure the flow field and acoustic characteristics around the plate. The unsteady behaviour of the interaction between vortex shedding and sound wave during acoustic resonance are of the most interest to this investigation.

## EXPERIMENTAL SETUP

### Experimental apparatus

The experimental work was conducted on an open-circuit suction wind tunnel driven by a motor. The front part of the experimental section was composed of a filter screen, a pressure stabilizing chamber and a three-dimensional contraction section to ensure the uniformity of flow. As shown in **Figure 1**, it was a wind tunnel with *u* (flow velocity) ranging from 0 to 40 m/s and a turbulence intensity of less than 1%. The acoustic measurement equipment was NI 4431 data acquisition card and a 1/4-inch microphone with sensitivity of 1 mV/pa. The sampling rate was 51.2 K/s. Hot-wire was the main test device to measure velocity. A single-sensor probes (Model 55P11) was used to calibrate the flow velocity and detect the quality of the flow filed. The measurement of the fluctuation velocity along the flow direction and the vertical flow direction of the trailing edge of the plate depended on a dual-sensor probes (Model 55P61). All sensor probes were calibrated on Hot-wire Calibrator with two-point calibration mode.

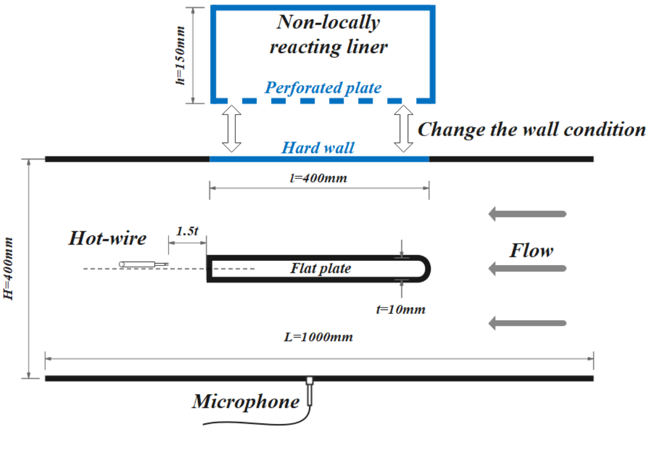


**Figure 1 Wind tunnel and frequency converter** **Figure 2 Schematic diagram of experimental device**

As shown in **Figure 2**, the test section is 300 mm of width (W), 400 mm of height (H) and 1000 mm of length (L). The thickness (*t*) of the plate is 10 mm and throughout the width of the section, and the reason for this choice will be illustrated in detail at the following part. The total chord length (*l*) of the flat plate with a semi-circular leading edge and square trailing edge is 400 mm along the flow direction. And the determination of this length was shown in the following part. The chord-to-thickness ratio (*l/t*) of the plate is 40. The surface of the plate is parallel to the streamline, which means the angle of attack is 0° while the air is flowing through the plate.

A non-locally reacting liner is flush mounted on the upper wall of the test section, with special attention being paid to the flatness of the perforated panel, which is necessary to eliminate the unwanted interference to the flow field. And it should be noted that only the upper wall is replaced by liner for convenient as a comparative experiment.

The microphone is kept flush with the lower wall surface inside the flow duct, with its axis pointing to the middle of the plate. These positions are determined according to the characteristics of the $\beta$-mode. Dual-sensor probes of hot-wire is fixed at 1.5 to 2 times $t$ away from the tailing edge of the plate.

### Design of the experimental parameter

The frequency of the vortex shedding of the plate, named as $f_1$, is determined by the formula

$$s_t = \frac{f_1 t}{u} \quad (1)$$

where $u$ is the flow velocity and $s_t$ is Strouhal number. The natural acoustic mode frequency of the experimental section, named as $f_0$, is given by the following formula

$$f_0 = \frac{0.5 \times \left(\frac{c}{l}\right)}{1 + \eta_1 \left(\frac{H/2}{l}\right)^{\eta_2}} \quad (2)$$

where the values of empirical parameters $\eta_1$ and $\eta_2$ are 0.7 and 0.84 respectively, $c$ is sound speed. According to the size and position of the plate, the frequency of the natural acoustic mode of the system is obtained. When $f_0$ is equal to $f_1$, acoustic resonance occurred and the corresponding flow velocity can be calculated.

As the velocity of the above-mentioned wind tunnel ranges from 0 to 40 m/s, the onset of acoustic resonance is designed to take place at the middle of the flow speed range, which is convenient to obtain the complete process of acoustic resonance. Based on Eq. (2) and the relevant parameters of the duct and plate, the predicted resonant frequency is approximately 306 Hz. Furthermore, our previous experiment reveals that the Strouhal number of the vortex shedding from the plate trailing edge is approximately 0.17. Therefore, the thickness of the plate is set to be 10 mm, which would give an obvious resonant state at the velocity of 19 m/s.

The dimensions of the perforated plate consisting a non-locally reacting liner is 580 mm × 300 mm × 0.4 mm, and the hole diameter is 0.5 mm with a perforation rate of 5%. It should be pointed out that the parameters of the perforate plate are not specially manufactured to obtain a high enough acoustic absorption coefficient, but an existing product on the market is chosen for convenience. The height of the back cavity is 150mm. The sound absorption ratio of the present liner is approximately 0.4, according to Guess (Guess, 1975).

## RESULTS AND DISCUSSION

The results of acoustic resonance and its suppression are illustrated from the two aspects of sound field and flow field. For the acoustic resonance part, we focused on the specific characteristics of frequency lock-in region, especially the double peaks appearing in the spectrum. The general characteristics of acoustic resonance was briefly described. And a detailed explanation was given for the change of sound field and flow field in the case with acoustic liner to demonstrate the affection of acoustic feedback on the vortex shedding behaviour.

In the following parts, $f_s$ represents the sound frequency measured by the microphone, $f_v$ is the vortex shedding frequency at the trailing edge of the plate measured by the hot-wire and $f_0$ represents the natural acoustic $\beta$-mode frequency of the duct. $f_{sl}$ and $f_{vl}$ are the frequencies of sound wave and vortex shedding with acoustic liner. The frequency resolution of experimental data processing is 1.56 Hz. The normalized fluctuation velocity is obtained by dividing the original velocity by 4 m/s.

### Result of acoustic resonance

**Figure 3** shows the tendency of the frequency and amplitude of sound waves and vortices shedding with flow velocity. The separated flow shedding from the trailing edge of the plate forms vortices which are important sound sources. Therefore, $f_s$ and $f_v$ maintain good consistency and increase synchronously with $u$. Until $u$ reaches a certain range, the vortex fluctuation stimulates the acoustical response of the duct. The $f_s$ and $f_v$ are detected to be locked near 306 Hz corresponding to the acoustic $\beta$-mode of the duct, which is basically consistent with the predicted results, as shown by the blue dotted line in **Figure 3**. When $f_s$ and $f_v$ are close to $f_0$, the amplitude of the sound pressure and the fluctuation velocity of the vortex shedding increase sharply. Sound pressure reaches the maximum value of 5.18 Pa, and almost at the same velocity the normalized fluctuaion velocity of the vortex shedding also reaches the peak of 0.6872. The lock-in state of the frequency and the sudden increase in sound pressure are considered to be the prominent characteristics of acoustic resonance. $f_s$ and $f_v$ increase almost linearly with the flow velocity increasing in other area. The reason for this linear tendency variation of sound frequency dues to the sound wave is generated by the vortex shedding from the trailing edge of the flat plate, which is in proportion to the flow velocity, giving raise to an approximately constant Strouhal number. The overall tendency of vortex shedding fluctuation velocity amplitude also increases, which means that the energy of the vortex increases with the flow velocity.

Lock-in region of $f_s$ appears with 17.38 m/s < $u$ < 20.99 m/s and $f_v$ appears with 19 m/s < $u$ < 20 m/s. The lock-in region of the acoustic frequency is obviously wider than the vortex shedding which means it is not suitable to define the lock-in range of the detected acoustic frequency as the acoustic resonance lock-in region (Hong et al., 2020). Although this phenomenon has been illustrated in the previous numerical work of Hong et al. (2020), it hasn't been validated by experiments. To that end, it is necessary to explore the evolution of vortex shedding and sound generation simultaneously to deepen the understanding of vortex sound interaction in acoustic resonance, which will be given in the following part.

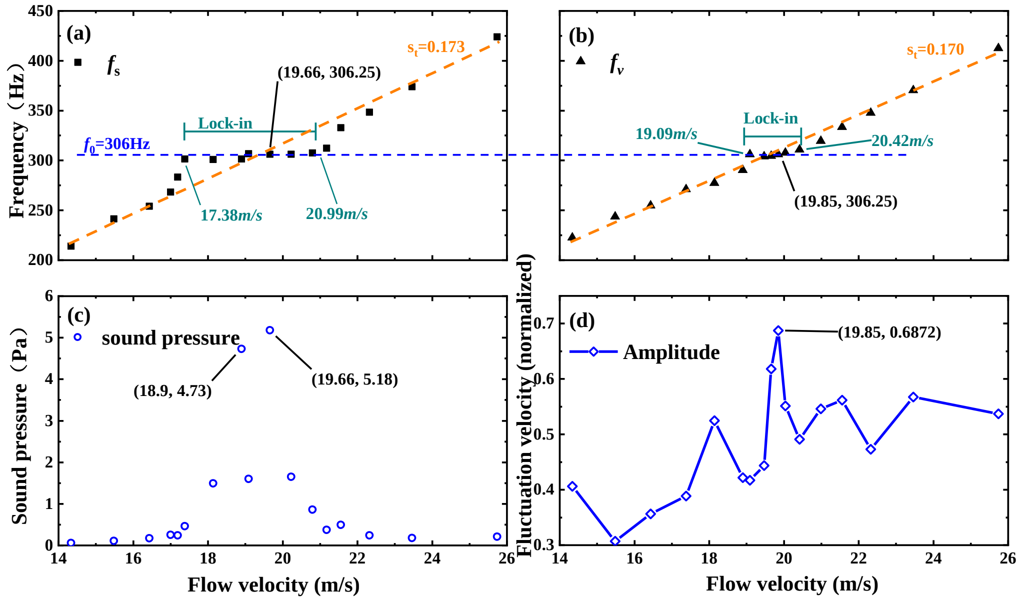


**Figure 3 The flow and sound field results in acoustic resonance: (a) frequency of sound field, (b) frequency of flow field, (c) sound pressure detected by microphone, (d) fluctuation velocity of vortex shedding**

*Domination and synchronization of lock-in*

According to Hong et al. (2020), the lock-in region can be divided into a $\beta$-mode dominant region and a synchronous region. Two distinct discrete components can be observed in the measured sound spectrum with the increasing flow. The one that is stably maintained near $f_0$, corresponds to the excited $\beta$-mode of the duct. The other increases synchronously with $u$ and corresponds to the acoustic frequency $f_s$ generated by the vortex shedding. There are two peaks (**Figure 4**) in the sound pressure spectrum outside the lock-in region. And the peak at $f_0$ is lower than that at $f_s$. When the flow velocity is small, $f_s$ and $f_0$ are far apart. Although the lock-in doesn't take place at this situation and the feedback effect of $\beta$-mode on the vortex shedding is negligible, it shows that the acoustical response relating to $\beta$-mode can be easily excited by the vortex shedding.

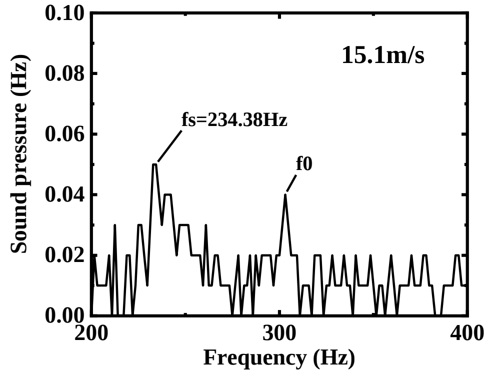


**Figure 4 Spectrum of sound wave when u=15.1m/s**

As the flow velocity increases continuously, the sound pressure of the responded $\beta$-mode gradually increases as $f_s$ approaches $f_0$. When $f_s$ and $f_0$ are close enough, the positions of $f_s$ and $f_0$ can still be distinguished (**Figure 5**). The starting position of the acoustic wave lock-in region ($u$=17.38 m/s) is also the position where the sound pressure starts to increase significantly. This shows that when the sound wave frequency is close enough to the $\beta$-mode frequency, the sound pressure of the acoustic mode will be strongly excited. The component corresponding to $f_0$ is clearly dominant, and this stage is called the "dominant region" (**Figure 6**). Dominant regions appear on both sides of the lock-in region. With further development, $f_s$ and $f_0$ become completely consistent, this stage is called the "synchronous region". The sound pressure reaches the highest at this stage which is the proper acoustic resonance frequency locked region.

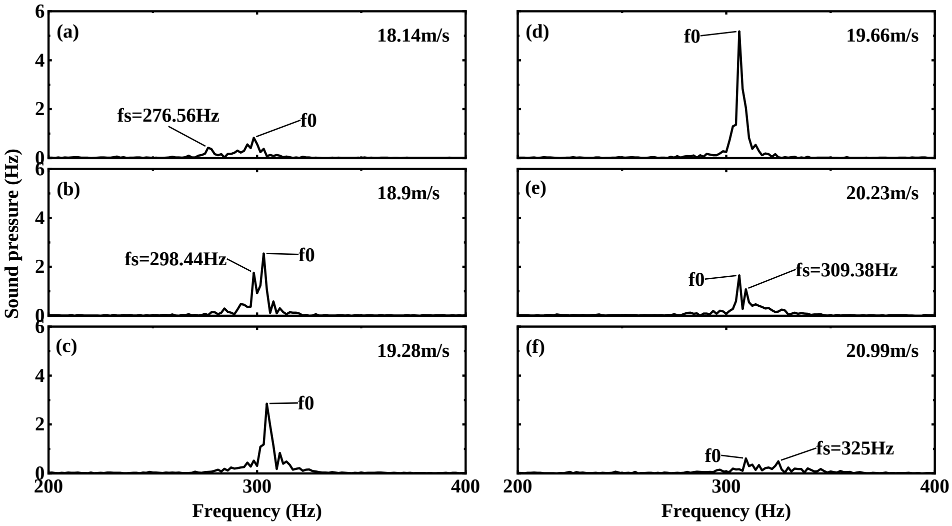


**Figure 5 Sound pressure spectrum of lock-in region with flow velocity**

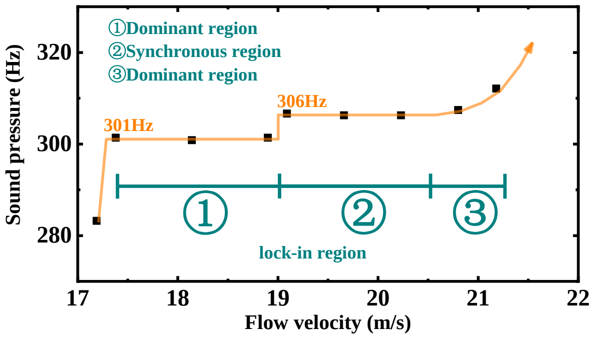


**Figure 6 Classification of sound wave lock-in region**

In the first dominant region, the dominant frequency is about 301 Hz. In the synchronous region, the locked frequency is 306 Hz. In the second dominant region, the dominant frequency is greater than 306 Hz and increases slightly with the flow velocity. The frequency of the three parts is stepped (**Figure 6**), which is a typical feature of a synchronous system (Pikovsky et al, 2001). The reason for this phenomenon may be caused by the turning effect of the sound wave feedback. The dominant frequency in the first dominant region is smaller than the frequency of the acoustic mode, which may be due to the mutual attraction between the sound wave and the acoustic $\beta$-mode. And if $f_s$ is completely modulated by the acoustic $\beta$-mode, then the value of the locked frequency in synchronous region should be the same as the frequency of acoustic $\beta$-mode. This shows that the acoustic feedback can adjust the behaviour of lock-in and the dominant frequency to an appropriate position according to the relationship of $f_s$ and $f_0$.

The synchronous region of $f_s$ (19 m/s < $u$ < 20 m/s) basically coincides with the entire lock-in region of the vortex shedding. The sound pressure in the acoustic synchronous region is large enough to provide the required energy to modulate the vortex shedding. This is also the reason why it is difficult to observe the two discrete components outside the lock-in region of the vortex shedding and only $f_v$ can be observed. In the lock-in region of the vortex shedding, the existence of the dominant region and the synchronous region was observed for the first time (**Figure 7**). In the experiment, when the sound pressure reaches about 1.5 Pa and the difference between $f_v$ and $f_0$ is less than 3%, the component at the position $f_0$ can be observed for dominance in the vortex shedding spectrum signal. When the difference between $f_v$ and $f_0$ is less than 1%, the synchronous region appears. The dominant region of the vortex shedding also appears on both sides of the lock-in region.

When the component of $f_0$ appears for the first time, the normalized fluctuation velocity of the vortex shedding at $f_v$ drops instead (**Figure 8(a)**). And amplitude of the component at the position $f_0$ is smaller than that of the $f_v$. It is because the vortex shedding at $f_v$ transfers part of the energy to the position of $f_0$ under the modulation of acoustic feedback. And the two energies are involved in each other, which is consistent with the phenomenon of acoustic signals. Due to this restraining relationship between energies, the peak position of the vortex shedding signal is extremely unstable in a narrow position in front of the dominant region, showing a wide peak area (**Figure 8(b)**). And it also can be observed that the amplitude suddenly increase while the component of $f_0$ disappears due to the same reason. In the synchronous region, $f_v$ and $f_0$ are locked to the same value. The energy of the vortex shedding and the sound wave are locked together, which stimulates a positive cyclic excitation to make the amplitude increase sharply.

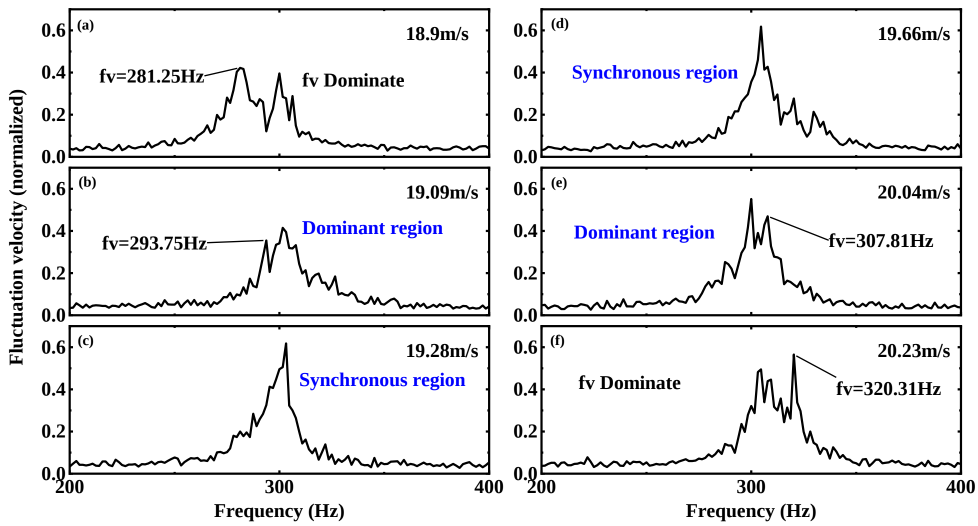


**Figure 7 Vortex shedding spectrum of lock-in region with flow velocity**

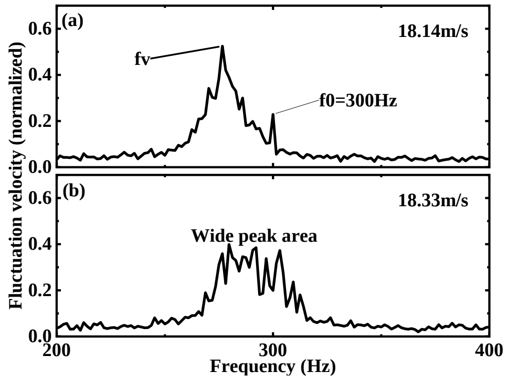


**Figure 8 Spectrum of vortex shedding when u=18.14m/s and u=18.33m/s**

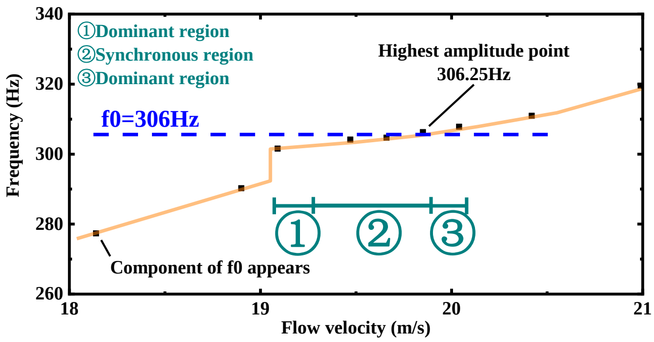


**Figure 9 Classification of vortex shedding lock-in region**

The frequency at the front-end dominant region is slightly lower than frequency of acoustic $\beta$-mode, and $f_0$ at the back-end dominant region is slightly higher than that (**Figure 9**). The whole area shows a slow increase tendency. The frequency of the three stages include dominant frequency and sync frequency is not kept at 306Hz. This should be the function of the joint adjustment of the sound wave feedback and the acoustic $\beta$-mode. The different frequency of the three regions can explain that the reason for this result is not only the acoustic $\beta$-mode, but also the modulation effect of acoustic feedback.

Although the lock-in state of sound wave and vortex shedding can be detected in a wide area, the synchronous region is only maintained in a narrow range. And in the synchronous region, $f_s$ and $f_v$ are not exactly the same although the sound waves are generated by vortices shedding. Whether it is the sound wave or the vortex shedding in the dominant region, the position of dominant frequency is a little bit less than the frequency of the acoustic mode which is due to the mutual attraction of two energies. The synchronous region of the vortex shedding is narrower than that of the sound wave and a little further behind. If it is a pure sound $\beta$-mode that works, all frequencies should remain consistent with it. And the position where the maximum amplitude of vortex shedding appears is also not at the position. These indicate that the acoustic mode is not all the reasons for the lock-in. The acoustic feedback plays a role in adjusting the frequency of the acoustic mode, the frequency of the sound wave and the frequency of the vortex shedding.

### Result with acoustic liner

The above part describes the acoustic resonance produced by flow passing through a flat plate under the condition of hard wall. The next part shows the results and discussion of the effect of non-locally reacting liner on the resonance. In the present study only the upper wall of the duct is replaced with acoustic lining for convenience.

**Figure 10** shows the tendency of the frequency and amplitude of sound waves and vortices shedding after changing the wall conditions. The lock-in region of the acoustic wave frequency and vortex shedding frequency disappears completely, and the whole area shows a law of linear growth with $u$, which corresponds to a nearly constant Strouhal number. The measured Strouhal number is basically the same as the previous experiment. The maximum sound pressure is reduced from above 5 Pa to about 0.5 Pa (**Figure 10(b)**). The maximum amplitude of vortex shedding drops from 0.687 to about 0.3 (**Figure 10(d)**). Outside the lock-in region, $f_{sl}$ and $f_s$ are completely consistent and the sound pressure continues to be the same as before. $f_{vl}$ and $f_v$ are also consistent and the fluctuation of the amplitude of the vortex shedding is maintained within the same range. And the fluctuation range meets the $3\sigma$ principle of normal distribution. In lock-in region, the sound pressure dose not show a significant increase, and so is the amplitude of the vortex shedding. Acoustic resonance has disappeared. The acoustic liner has a very significant suppression effect on acoustic resonance.

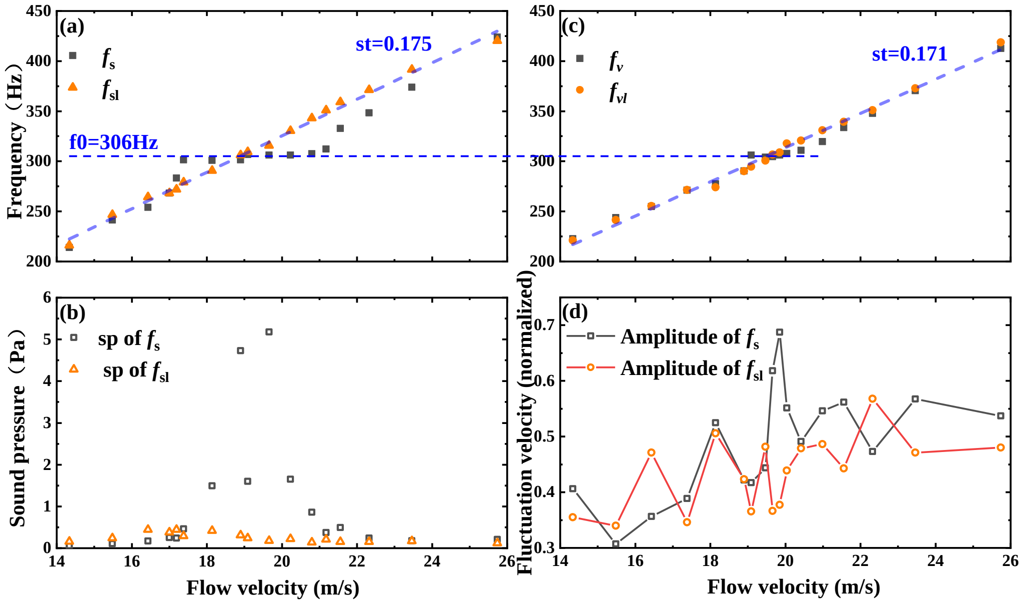


**Figure 10 The flow and sound field results in with acoustic resonance: (a) frequency of sound field, (b) frequency of flow field, (c) sound pressure detected by microphone, (d) fluctuation velocity of vortex shedding**

*Change of Domination and synchronization*

The vortex shedding can excite the acoustic mode at $f_0$=306Hz. As $u$ increases linearly, $f_s$ increases synchronously with $f_v$, and $f_{sl}$ increases synchronously with $f_{vl}$. The acoustic mode at $f_0$will gradually increase and become dominant, forming a dominant region. However, the existence of the acoustic liner suppresses the sound wave around 306Hz. The excited acoustic mode cannot appear and the dominant region disappears. Therefore, it is difficult to find discrete components in the position of $f_0$ in the frequency spectrum of the dominant region before the synchronous region.

Before the dominant region, the positions of $f_s$ and $f_{sl}$ are basically the same. But in the range of the first dominant region, $f_{sl}$ increases more slowly than $f_s$ (**Figure 11**). Because when the acoustic resonance exists, $f_s$ will be attracted by the acoustic mode at the position of $f_0$ and be turned toward the position of $f_0$ earlier. The acoustic liner has a relatively good absorption effect on the sound wave of the acoustic mode frequency. So that the attractive effect of the acoustic mode on $f_s$ disappears and $f_{sl}$ seem to move more slowly. Similarly, in the dominant region behind the synchronous region, $f_s$ is attracted by $f_0$ and increases more slowly, making $f_{sl}$ seem to increase faster. In the synchronous region, the sound pressure corresponding to $f_{sl}$ is much lower than that of $f_s$, and the sound waves near $f_0$ are well absorbed by the acoustic liner.

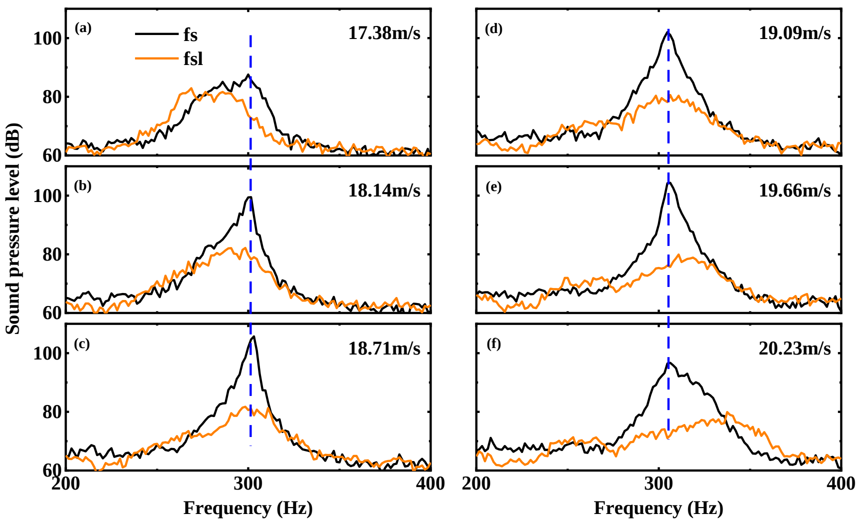


**Figure 11 Sound pressure level spectrum of lock-in region with acoustic liner**

Regardless of frequency or fluctuation velocity, $f_{vl}$ and $f_v$ maintain a high degree of consistency outside the lock-in region of the vortex shedding. In the lock-in region, $f_{vl}$ is no longer locked, and the discrete component of $f_0$ not appear. The reason is the same as the acoustic signal that the acoustic lining eliminates the influence of acoustic resonance. The same signs appeared in the two dominant regions of vortex shedding. In the first dominant region, $f_v$ is closer to $f_0$ than $f_{vl}$

(**Figure 12**). In the second synchronous region, $f_v$ leaves $f_0$ later than $f_{vl}$. This phenomenon is consistent with the performance of $f_s$ and $f_{sl}$ in the acoustic signal. Acoustic $\beta$-mode and sound wave feedback have an attractive and regulating effect on $f_v$, so that a part of the energy is used to excite the vortex shedding signal at $f_0$. The existence of the acoustic liner eliminates the $f_0$ component of the vortex shedding in the dominant region, so that the energy at $f_{vl}$ is no longer divided. In the synchronous region of the vortex shedding, $f_v$ and $f_0$ are completely locked. The positive cyclic excitation between the acoustic feedback and the vortex shedding greatly increases the amplitude of the fluctuation velocity. Therefore, the amplitude of the fluctuation velocity of $f_v$ in the synchronous region is much higher than the amplitude of $f_{vl}$.

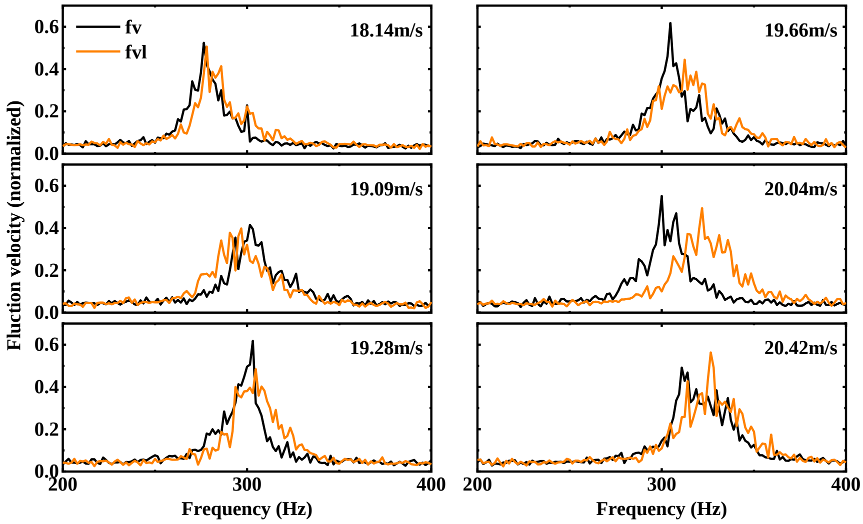


**Figure 12 Vortex shedding spectrum of dominant region and synchronous region with acoustic liner**

### *Position of maximum amplitude*

The position of $f_{sl}$=306Hz is at the front edge of the original $f_s$ synchronous region. The new sound pressure also reaches its maximum at this position. This shows that the strongest acoustic $\beta$-mode in the experimental duct should be in this position. After installing the acoustic liner, the sound wave frequency $f_{sl}$ is the same as the original $f_s$ until about $u$ =19m/s, indicating that this position is where acoustic $\beta$-mode excited. The maximum value of the original acoustic signal appears at $u$=19.66*m/s*. The frequency $f_{vl}$ of the vortex shedding is the same as the original $f_v$ until about $u$=19.2*m/s*. The maximum value of the original vortex shedding signal is $u$=19.85*m/s*. The position of $u$ where the maximum value of the acoustic signal and vortex shedding signal appear in the acoustic resonance state is slightly larger than $u$ at which $f_{sl}$ and $f_{vl}$ reach the position of $f_0$ after the acoustic liner is installed. This is probably due to that the acoustic feedback can delay the position of the maximum resonance state during acoustic resonance (cite Hong et al, JSV).

In acoustic resonance experiment, the position with the largest sound pressure is located behind the middle of the synchronous region. The difference between the two positions shows that in addition to the acoustic mode, acoustic feedback is the main factor that shifts the frequency locked position back. In the shedding vortex signal, the position of $f_{vl}$ =306Hz is also at the leading edge of the vortex shedding synchronous region instead of the highest amplitude position in the synchronous region. The appearance of acoustic liner makes these delay phenomena disappear completely. The acoustic mode does not cause this delay phenomenon, so the acoustic liner suppresses the effect of acoustic feedback very well which makes this phenomenon disappears. Until the strong sound wave excited by the vortex shedding near the acoustic mode is reflected by the wall, the feedback sound wave acts on the vortex shedding to lock $f_v$ to a position slightly larger than $\beta$-mode. The frequency of the sound wave generated by the locked vortex shedding is also locked at this frequency. Therefore, the positions where the maximum values of sound pressure and fluctuation velocity appear are slightly larger than the frequency of the sound mode.

When air flows through the bluff body in the duct, the vortex shedding generated by the separated flow excite the acoustic $\beta$-mode of the duct itself at a certain flow velocity. The sound wave preferentially shows the locking phenomenon. Until the sound energy is large enough, the shedding vortex will not show a lock-in phenomenon. The acoustic $\beta$-mode of the duct has a certain attraction to vortices shedding and sound waves. The sound waves are fed back to the vortex shedding through wall reflection. And excitation and delay effect are applied to the vortex shedding to form a vortex-sound interaction cycle, which makes the dominant frequency, synchronous frequency and acoustic $\beta$-mode frequency different. And the flow velocity corresponding to the maximum amplitude will be slightly delayed. The presence of the acoustic liner effectively suppresses the process of acoustic feedback, making the entire excitation cycle disappear. Therefore, the vortex shedding is no longer excited and delayed by the sound wave feedback. The sound pressure level has dropped by more than 20 dB, and the velocity fluctuation amplitude of the shedding vortex has dropped by 0.23. The frequency lock-in of the sound wave and the vortex shedding of the acoustic resonance almost completely disappeared. The acoustic liner has a good suppression effect on acoustic resonance and it can be considered that the acoustic liner fundamentally eliminates the acoustic resonance.

## CONCLUSIONS

In order to study the mechanism of vortex sound interaction in acoustic resonance and its suppression, a comparative experiment on the surface of the hard wall and the acoustic liner was conducted. The experimental results show that the acoustic liner has a good effect of suppressing acoustic resonance. The main conclusions are summarized as follows:

1. Both the dominant region and the synchronous region exist in the lock-in region of the sound wave signal and the vortex shedding signal in acoustic resonance. The synchronous region of the acoustic signal is basically the same as the entire lock-in region of the vortex shedding signal. The lock-in region of the vortex shedding appears in the acoustic synchronous region where the sound pressure is higher. The rules of the dominant region and the synchronous region in the two signals are the same. The dominant region appears at both ends of the signal lock region. There are two discrete components in the dominant region. One is that increases with the flow velocity, and the other is that stabilizes in the vicinity of the acoustic mode. The vortex shedding frequency and the acoustic $\beta$-mode frequency are locked to the same value.

2. The frequency of the sound wave and the frequency of the shedding vortex in the dominant region will approach the frequency of the acoustic $\beta$-mode under the action of excited acoustic mode. This phenomenon is well reflected in the experiment of acoustic lining. The strongly excited acoustic mode has an attractive effect on the original signal.

3. The frequency of the acoustic $\beta$-mode is not completely consistent with the dominant frequency in the dominant region and the locked frequency in the synchronous region. The same is true in the signal of the vortex shedding. The dominant frequency in the dominant region and the locked frequency in the synchronous region show a small increase tendency with the flow velocity, rather than maintaining the acoustic mode frequency or other specific value. The frequency of the acoustic $\beta$-mode is often in the middle of the lock-infrequency range. It shows that acoustic feedback plays a regulating role in this process.

4. The flow velocity corresponding to the maximum sound pressure position in the synchronous region is slightly larger than the flow velocity corresponding to the sound wave reaching the acoustic $\beta$-mode frequency. The same is true for vortex shedding. Moreover, the position of the maximum sound pressure and the position of the maximum vortex shedding amplitude are different, and the position corresponding to the vortex shedding is a little behind the position of the sound wave.

## NOMENCLATURE

| | |
|---|---|
| $c$ | Speed of sound (m/s) |
| $d$ | Depth of back cavity (mm) |
| $f_0$ | Frequency of acoustic $\beta$-mode (Hz) |
| $f_1$ | Frequency of vortex shedding in theory (Hz) |
| $f_s$ | Frequency of sound wave with hard wall (Hz) |
| $f_{sl}$ | Frequency of sound wave with non-locally reacting liner (Hz) |
| $f_v$ | Frequency of vortex shedding with hard wall (Hz) |
| $f_{vl}$ | Frequency of vortex shedding with non-locally reacting liner (Hz) |
| H | Height of the experimental section (mm) |
| $k$ | Wave number |
| $l$ | Chord length of the flat plate (mm) |
| L | Length of the experimental section (mm) |
| $s_t$ | Strouhal number |
| $t$ | Thickness of the flat plate (mm) |
| $t_0$ | Thickness of perforated plate (mm) |
| $u$ | Flow velocity (m/s) |
| $v$ | Kinematic viscosity of air |
| W | Width of the flat plate (mm) |

### Greek Symbol

| | |
|---|---|
| $\beta$-mode | A acoustic model named by Parker |
| $\sigma$ | Open area of perforated board |
| $\eta_1$ | A empirical parameter |
| $\eta_2$ | A empirical parameter |

### Subscript

| | |
|---|---|
| 0 | $\beta$-mode |

| | |
|---|---|
| *l* | Non-locally reacting liner |
| *s* | Sound wave |
| *v* | Vortex shedding |

## Abbreviations

| | |
|---|---|
| SPL | Sound pressure level |


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