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AN EXPERIMENTAL STUDY ON THE CONTROL OF THE VORTEX-INDUCED VIBRATION OF A CIRCULAR CYLINDER BY ACOUSTIC EXCITATION

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A series of experiments over a Reynolds-number range of 2.2×10^4~6.3×10^4 was conducted to understand the effect of acoustic excitation on the vortex-induced vibration of a circular cylinder. The frequency and the intensity of the applied sound were varied. The following results are obtained: (1) The most effective frequency of the acoustic excitation in suppressing the vortex-induced vibration approximately corresponds to the frequency of transition waves in shear layers separated from the cylinder surface; (2) Although the applied sound is less effective in reducing a large vortex-induced vibration amplitude, the applied sound with stronger intensity can suppress the vibration more effectively.

Key Words *: acoustic excitation, transition wave, shear layer, instability, vortex-induced vibration, circular cylinder, wind tunnel experiment, wind engineering*

1. INTRODUCTION

It is important to suppress the flow-induced vibration of flexible structures such as long-span bridges, tall buildings, towers and so on. The vortex-induced vibration of a bluff body like a circular cylinder is well known as the typical flow-induced vibration phenomenon observed in relatively low wind speed range. In a typical case, the vortex-induced vibration is explained to occur when the shedding frequency of large-scale vortices formed behind a body coincides with the natural frequency of the body. Although the vortex-induced vibration has limited amplitudes and therefore it is not catastrophic, it causes the fatigue problems, psychological discomfort in a vibrating structure. There are many countermeasures to suppress the vortex-induced vibration: suppressing the large-scale vortices formed around a body by changing the cross-sectional shape of the body, raising the wind velocity of the beginning of lock-in resonance by increasing stiffness of the body, installing dampers like TMD, ATMD and so on.

In the field of aeronautics, an acoustic excitation technique has been studied to improve the properties of the lift force of a stationary airfoil [1)~5)] or change the characteristics of the flow around a stationary circular cylinder [6)~13)]. This technique is an attempt to alter the flow around a body by exciting instabilities of boundary layers or separated shear layers with applied sound. On the other hand, Matsumoto [14)] employed acoustic excitation to examine the characteristics of the vortex-induced vibration of a bridge deck section. However, few studies have been made to control the vortex-induced vibration with acoustic excitation. The purpose of this study was to investigate the effect of the applied sound on the vortex-induced vibration through a series of wind tunnel experiments.

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2. APPARATUS AND EXPERIMENTAL METHODS

The experiment was conducted in a suction

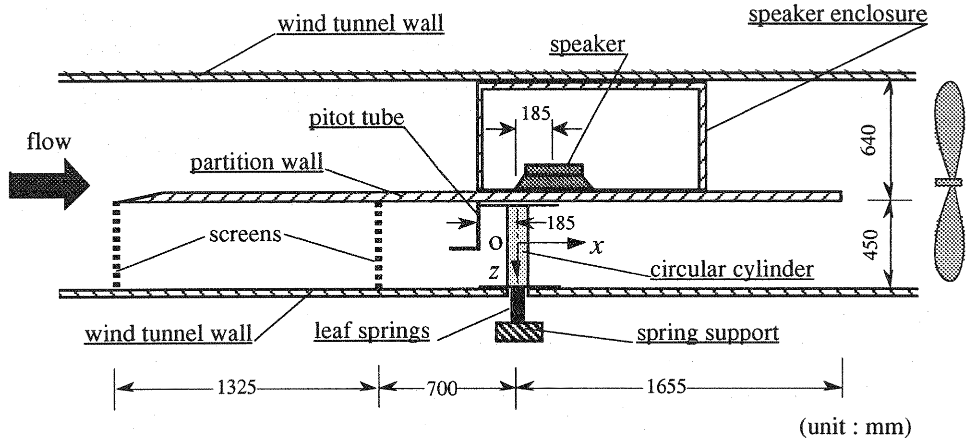


Fig.1 Experimental apparatus in plan

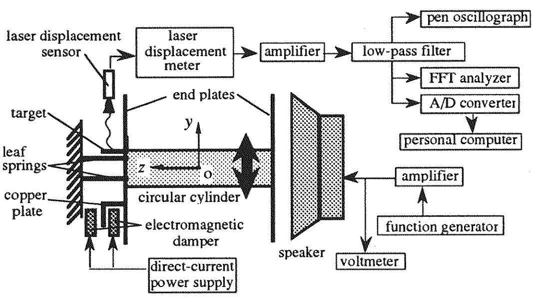


Fig.2 Data acquisition setup

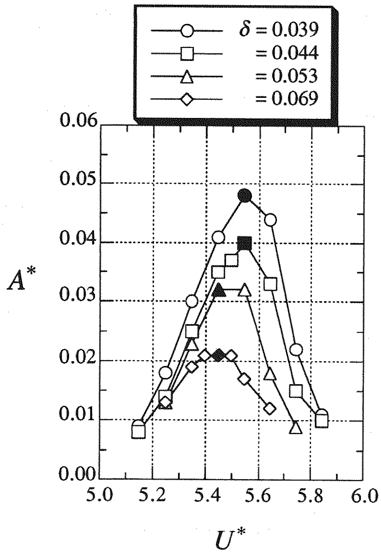
wind tunnel with a 1.80 m × 1.09 m test section, as shown in **Fig.1**. The test section was separated into two parts by a vertical partition wall. In one part, a speaker system was installed; in the other part, a elastically-supported circular cylinder model was placed. The circular cylinder had a diameter (D) of 100 mm, span of 400 mm and mass of 0.989 kg. It was made of acrylic plastic, and circular end plates with 400 mm diameter were attached on its both sides. One side of the cylinder was supported by parallel two leaf springs. These leaf springs were rigidly fixed on the end plate and the support so that the cylinder was allowed only the heaving motion without the locking. The coordinates axes were defined as x-axis in the mean wind direction, y-axis in the cylinder vibration direction (i. e., across-flow direction) and z-axis in the cylinder spanwise direction. The origin of the coordinates was set at the center of cross-section of the model in the middle of the cylinder span. Sound with monotonic frequency was applied in the z-direction by a 400 mm diameter loudspeaker (Fostex FW405) attached on the partition wall. Reynolds-number (Re) based on the cylinder diameter was ranged from 2.2×10^4 to 6.3×10^4, and the turbulence intensity of the approaching flow in the wind tunnel was lower than 2.0%.

Fig.2 shows a schematic of the data acquisition setup of the experiment. Displacements of the circular cylinder were measured with a laser displacement sensor (Omron 3Z4M-J12) and analyzed with an FFT analyzer. The cut-off frequency of a low-pass filter was set at 110 Hz. Also, the displacement signals were converted to digital data with an A/D converter (sampling frequency: 500Hz, sampling time: 300sec) and the r.m.s. response displacement was calculated by a personal computer. The value of $\sqrt{2}\times$ (r.m.s.) was defined as the vortex-induced vibration amplitude of the cylinder. Signals generated with a function generator were amplified with an amplifier (Panasonic RAMSA) and drove the loudspeaker. An electromagnetic damper system provided the additional damping to the cylinder model. The magnitude of the damping force was controlled by varying direct-current power supply voltage to the electromagnets.

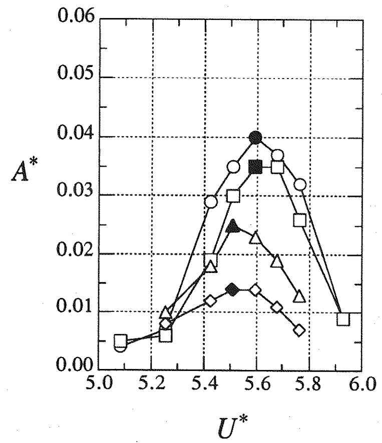
3. RESULTS AND DISCUSSION

(1) Characteristics of the vortex-induced vibration without applied sound and acoustic field of applied sound inside the wind tunnel

In the experiment, two natural frequencies (f_n) of 10.1 Hz and 5.9 Hz were used with the same model by changing the stiffness of the leaf springs. For each of these frequencies, logarithmic decrement (δ) was set at 0.039, 0.044, 0.053 and 0.069. **Fig.3** shows the relation between reduced velocity

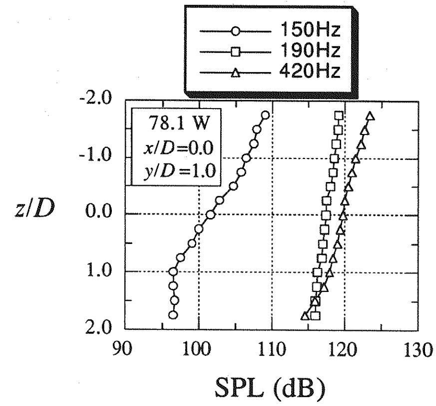


(a) f_n = 10.1 Hz

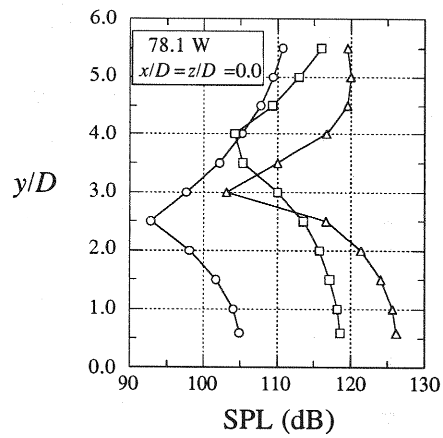


(b) f_n = 5.9 Hz

Fig.3 A^* versus U^* for several structural dampings (without sound)



(a) z-direction



(b) y-direction

Fig.4 Acoustic field in wind tunnel (without wind)

U^* ($= U/(f_nD)$) and nondimensional amplitude A^* ($= A_0/D$) of the models. The solid marks in **Fig.3** represent the maximum amplitudes for each case.

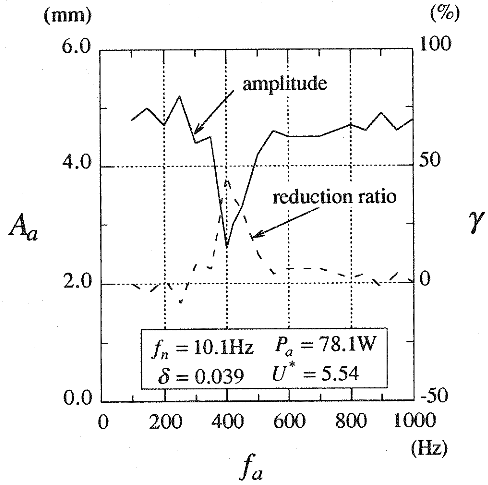
The sound pressure level (SPL) generated in the wind tunnel without wind was measured (**Fig.4**). The electric power that drives the loudspeaker (P_a) was kept 78.1 Watt for each sound frequency. SPL in the z-direction gradually decreased with the increased distance from the speaker. On the other hand, acoustic resonance modes seemed to occur in the y-direction showing node-like decrease of SPL around $y/D = 2.5 \sim 4.0$ ant its location depended on the sound frequency.

(2) Applied sound frequency effective in suppressing vortex-induced vibration

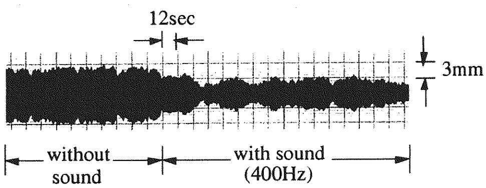
An example of the experimental results is presented in **Fig.5** (a). During this measurements, the electric power that enters the speaker (P_a) was kept 78.1 Watt for each operated sound frequency (f_a). In this figure, γ represents the reduction ratio of the vortex-induced vibration amplitude when sound was applied. It is defined as follows :

$$\gamma = \left(1.0 - \frac{A_a}{A_0}\right) \times 100 \quad (\%) \qquad (1)$$

where A_a and A_0 represent vortex-induced vibration amplitudes with and without applied sound,



(a) Response amplitude and reduction ratio versus sound frequency



(b) Time history of response

Fig.5 An example of experimental results

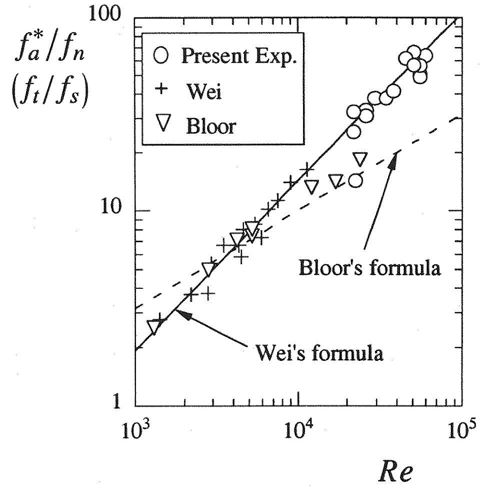


Fig.6 Comparison of effective frequencies and transition wave frequency

respectively. As shown in the figure, the effects of the applied sound on the vortex-induced vibration varies with the operated sound frequency. In the sound frequency range of 100 Hz ~ 1 kHz, applied sound with a 400 Hz frequency was the most effective to suppress the vortex-induced vibration for this case, where the reduction ratio was almost 50 %. **Fig.5** (b) presents the effect of this sound with 400Hz frequency on the response amplitude as a time history.

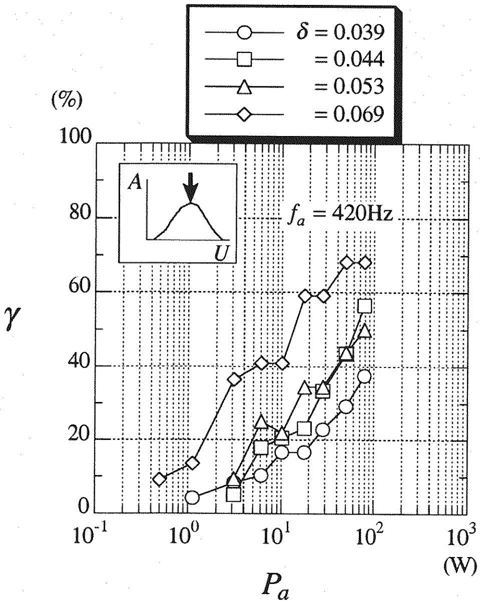
Similarly, the effective sound frequencies (f_a^*) observed in the present experiments and preliminary experiments[15] are summarized versus Reynolds-number in **Fig.6**. Also, the transition wave frequencies (f_t), which were measured in the separated shear layers around a stationary circular cylinder without sound by Wei [16] and Bloor [17], are plotted in the figure (where f_s denotes Karman-vortex shedding frequency of a stationary circular cylinder). The solid line represents Wei's regression line of the transition wave frequency and the broken line is Bloor's one. The expression of the lines are given as follows :

$$\frac{f_t}{f_s} = \left(\frac{Re}{470}\right)^{0.87} \quad \text{(Wei's formula)} \qquad (2)$$

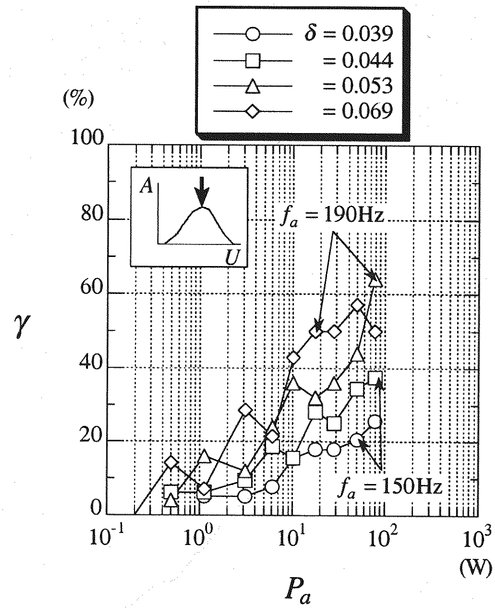
$$\frac{f_t}{f_s} = 0.1Re^{0.5} \quad \text{(Bloor's formula)} \qquad (3)$$

It is known that the transition waves [18)~21)] are generated by instabilities of the shear layers separated from the cylinder surface and play an important role in the transition to turbulence. Many experimental studies [6)~13)] reported that applied sound with the frequency in the vicinity of the transition wave frequency was effective in changing the characteristics of the flow around a stationary circular cylinder. Similarly, we can recognize a significant correlation between the transition wave frequencies and the effective sound frequencies in suppressing the vortex-induced vibration in **Fig.6**. It appears that stimulating the transition waves in the separated shear layers with the applied sound is the most effective in reducing the vortex-induced vibration amplitude.

It is worth mentioning that the effect of the applied sound with a Karman-vortex shedding frequency on the vortex-induced vibration. The preliminary experiment [15)] conducted before the present experiment showed that the applied sound with Karman-vortex shedding frequency, which was about 15 Hz, did not affect on the vortex-induced vibration, although their sound pressure level was not so high. Also, Yamanaka [13)] reported that the applied sound with such a frequency was less effective than sound with a frequency near the



(a) f_n = 10.1 Hz



(b) f_n = 5.9 Hz

Fig.7 Effect of vortex-induced vibration amplitude without sound on reduction ratio

transition wave frequency in changing the characteristics of the flow around a stationary circular cylinder.

(3) The effect of vortex-induced vibration amplitude on the reduction ratio

Fig.7 shows the effect of the structural damping (logarithmic decrement δ = 0.039, 0.044, 0.053, 0.069) on the reduction ratio γ when the sound was applied. All of these results were obtained at the wind speed of the maximum vortex-induced vibration amplitude denoted with the solid marks in **Fig.3**. Sound with the most effective frequency in each case was chosen to apply: for the model with a 10.1 Hz natural frequency, applied sound with the frequency of 420 Hz was employed in all structural damping cases ; for the model with a 5.9 Hz natural frequency, sound with the frequency of 150 Hz was applied for δ= 0.039 and 0.044 and 190 Hz for δ= 0.053 and 0.069. As shown in the figure, there is a tendency that the applied sound has less effect on lower-damping cases, that is, larger-amplitude vibration. However, the figure also indicates that the applied sound with lager intensity can suppress the vortex-induced vibration even if its amplitude is large.

4. CONCLUSIONS

The effect of the applied sound with monotonic frequency on the vortex-induced vibration of a circular cylinder over a Reynolds-number range of 2.2×10^4 to 6.3×10^4 was studied through a series of wind tunnel experiments. The main findings are summarized as follows:

(1) The most effective sound frequency in reducing the vortex-induced vibration amplitude approximately corresponded to the transition wave frequency predicted by Wei's formula. This result implies that exciting the transition waves in the separated shear layers around a body with the applied sound is effective in suppressing the vortex-induced vibration.

(2) Applied sound is less effective in reducing the vortex-induced vibration when its amplitude without sound is large. However, the applied sound with larger intensity could suppress the vortex-induced vibration even if its amplitude without the sound was large.

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