17th Australasian Fluid Mechanics Conference
Auckland, New Zealand
5-9 December 2010

Aerodynamic Sound from Two Parallel Circular Cylinders with Angle of Attack in Uniform Flow

M. Miyata[1] and Y. Hayashi[2]

[1]Department of Mechanical Systems Engineering
University of Yamanashi, Kofu, Yamanashi, 400-8511, Japan

[2]Graduate Student
University of Yamanashi, Kofu, Yamanashi, 400-8511, Japan

Abstract

A critical position of the downstream cylinder of two parallel circular cylinders exists, where the vortex shedding from the upstream one is prohibited completely by the downstream one. The effects of spacing pitch and angle of attack on the sound generation from the two parallel circular cylinders in a uniform flow were investigated experimentally under a free stream velocity from 8 m/s to 21 m/s for cylinders with diameters of 3, 5 and 7 mm. If the cylinder separation is about four times the diameter of an upstream cylinder and an angle of attack is between 5 and 25 degrees, the sound emission becomes very strong and the transition occurs very suddenly. According to measurements of the mean velocity field by means of LDV, there exist two basic flow patterns for the flow past two parallel cylinders; in one the vortex shedding takes places more or less independently and in the other the shedding from the upstream cylinder is prevented by the downstream cylinder. In the transitional configuration, the vortices shed from the upstream cylinder interact strongly with the wall of a downstream cylinder, leading to a strong sound emission. A motivation for this study comes from the irritating sound emission from the wire netting used for the purpose of wind damping.

Introduction

The architectural structure composed of a permeable wall such as a wire netting may be effective for the purpose of reducing a strong wind localized near the ground around a high-rise building in an urban area, where the quietness is sometime one of the important features unlike the flexible net used for the agricultural application in the country side.

It is well known that a wire netting can generate a considerable aerodynamic noise for limited wind conditions. As shown in Figure 1, plain-weaved wire meshes with the open area ratio (OAR) of about 0.6 can emit a very strong sound for the wind making an angle of attack round 10 to 20 degrees [3]. The frequency of an emitted sound is inversely proportional to the wire diameter and proportional to the wind speed, i.e. it has a nearly constant Strouhal number of 0.13 to 0.15. In spite of its simple geometry, the characteristic of the sound emitted from the wire netting is found to be extremely difficult to reproduce in its detailed character.

The authors confirmed that an important character of the sound emission from a mesh screen can be well reproduced by two straight parallel cylinders with angle of attack in a uniform flow. Figure 2 shows the dependence of SPL on angle of attack α for the wire mesh (red), and two cylinders (blue and green). Data for p/d nearly equals 4 generate a stronger sound over 10 to 20 degrees. The peak frequency of sound generated from two cylinders is proportional to the wind velocity and inversely proportional to the diameter of wire.

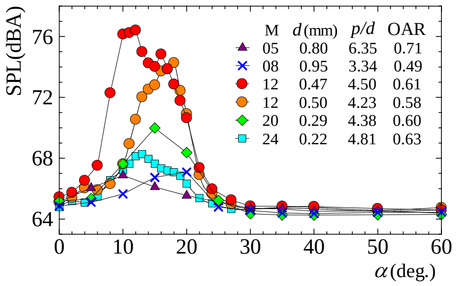

Figure 1. Dependence of SPL on angle of attack α for various wire meshes (U_0 = 15m/s).

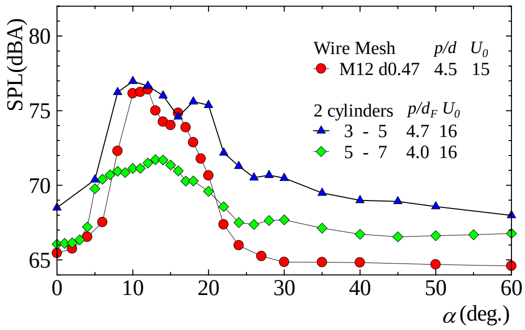

Figure 2. Dependence of SPL on α for the wire mesh and two cylinders.

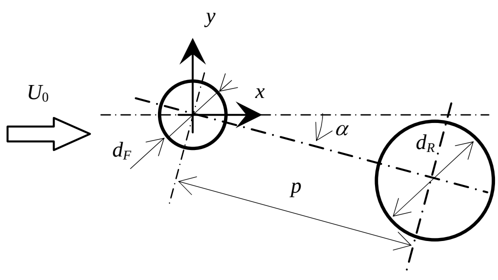

Figure 3. Schematic diagram of flow geometry.

The aerodynamic sound generated from a circular cylinder has investigated well and the sound source is concerned with shedding Karman vortices [1]. The flow around two circular cylinders with a tandem arrangement in a uniform flow has been investigated by several authors mainly concerning the flow field or the aerodynamic force, where an important parameter was found to be a distance between the centres of two cylinders [2, 5, 6]. The corresponding study concerning the sound emission is very scarce. This paper describes the experimental results on the characteristic of a sound emitted from two circular cylinders with a small angle of attack in a uniform flow and we propose a plausible explanation on the relation between the flow behaviour and the strong sound emission.

Experimental apparatus and method

Measurements were performed downstream of an exit nozzle with a 500 mm × 500 mm cross section in an Eiffel-type wind tunnel designed to minimize the running noise level. It achieves a good quality of uniform flow and a low turbulence level in the nozzle exit over flow velocities U_0 ranging from 4 m/s to 21 m/s.

Figure 3 shows a schematic diagram of flow geometry. The upstream cylinder is fixed at the horizontal axis of a turn-table which carries a linear traversing stage mounting the downstream cylinder, thus makes it possible to set the two cylinders continuously at an arbitrary separation and angle of attack in the uniform flow as shown in Figure 4.

We placed the cylinders perpendicular to the flow with the upstream cylinder 450 mm downstream the tunnel exit; the angle of attack α and the separation p between the centres of two cylinders are defined, as shown in Figure 3. Three kinds of circular cylinder with diameters of 3 mm, 5 mm and 7 mm were used. To assure two-dimensional flow, we placed a transparent circular end plate 200 mm in diameter at the unfixed end of the cylinders.

The uniform flow velocity was monitored using a Pitot tube at the nozzle exit and a digital manometer. The A-weighted sound pressure level (SPL) of emitted sounds was measured using a sound level meter placed on the centre line of the upstream cylinder outside the flow. The output signal from the sound level meter was recorded on a DAT recorder and processed on a PC, or spectrum analysis was performed using an FFT analyzer. Velocity fields around the windward face were measured using a four-beam, two-colour laser Doppler velocimetry system (DANTEC) with controlling and processing software (BSA Flow). A 2D measuring volume has a diameter of approximately 0.2 mm and a length of 2.5 mm.

The flow was seeded with liquid particles having an average diameter of nearly 1 μm generated using a fog generator (SAFEX) at the inlet of the wind tunnel.

Results and consideration

Measurements of the sound emission were conducted for all possible combinations of two cylinders from three different diameters including the identical ones, changing continuously the spacing distance between cylinders. The data for a continuous change in angle of attack were recorded only for the typical combination with the results of special interest. The obtained vast data are too complicated to explain in a simple manner. So we explain in the following by describing them in case of $d_R/d_F = 1$, $d_R/d_F < 1$ and $d_R/d_F > 1$ for a typical combination of cylinders. The characteristic length scale is chosen as the diameter of the upstream cylinder throughout in this paper.

An attention will be paid mainly on the behaviour for small spacing pitches because our interest is to make clear the complicated sound emission from the wire netting for the purpose of wind damping.

In case, $d_R / d_F = 1$

Figure 5 shows the dependence of the increment of SPL above the background level and the *St* number corresponding to the peak frequency of the emitted sound on the cylinder separation for the identical two cylinders, with the angle of attack increasing stepwise by 5 degrees. As can be seen in the figure, no significant effect can be found by the difference of cylinder diameter. ΔSPL takes the maximums at $p/d_F = 4$ and $p/d_F = 7$; the maximum value depends strongly on the angle of attack for the former configuration, but for the latter the peak value seems to be nearly constant of 6dB, irrespective of the angle of attack.

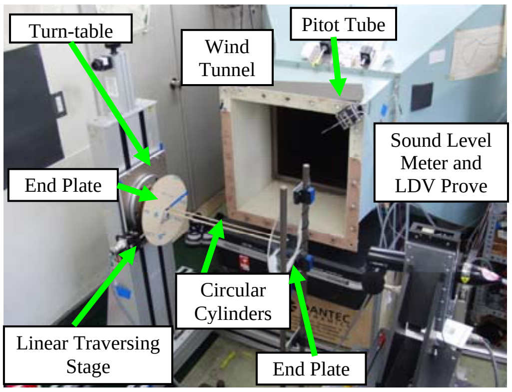

Figure 4. A photograph of experimental apparatus.

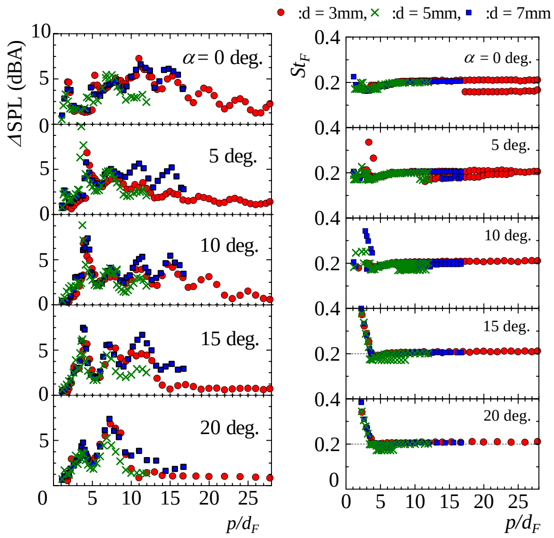

Figure 5. Dependence of ΔSPL and *St* on p/d_F ($d_R/d_F = 1$, $U_0 = 16$m/s).

For $p/d_F > 4$, the *St* number is nearly 0.2 as in a usual circular cylinder in a uniform flow and for $p/d_F < 3$ it decreases towards 0.2 with increasing p/d_F over the range $\alpha = 10$ to 20 degrees. In this region ΔSPL is small and the frequency depends more on the spacing p rather than the cylinder diameter d_F. The frequency dependence on the spacing p can be well described by the feed-back model [4] that the pressure waves generated at the downstream cylinder by the impinging of vortices convected with a mean velocity $U_c = 0.8U_0$ propagate upstream and excite the vortex shedding from the upstream cylinder, namely,

$$f_{FB} \cong \frac{U_C}{p}. \tag{1}$$

In case, $d_R / d_F > 1$

In this case, the overall character of sound emission depends considerably on the size of the cylinder, but the stepwise change in SPL described in the following can be found for almost every case tested.

Figure 6 shows the results for $d_R/d_F = 1.4$ ($d_F = 5$ mm, $d_R = 7$ mm) with $U_0 = 16$ m/s. ΔSPL shows two peaks at nearly $p/d_F = 4$ and $p/d_F = 7$ as in the case for the cylinder with the same diameter. The peak at $p/d_F = 4$ becomes prominent for $\alpha = 5$ to 20 degrees. In the figure, there appear two data arrays for the *St* number because here the *St* number is shown plotted based on the diameter of the upstream cylinder, although both vortices have the same *St* number of 0.21 when calculated with the proper diameter of vortex-shedding cylinder.

It should be noted that the *St* number around the peak in ΔSPL at p/d_F = 4 takes only one value for α = 5 to 20 degrees, namely the vortices contributing the sound emission from both cylinder has the same frequency; the vortices from upstream cylinder predominate the flow field and those from the downstream cylinder are locked in them. This lock-in phenomena cannot be specified when d_R/d_F = 1 because the vortices from both cylinders have the same frequency. In that case too, the lock-in of vortices from the downstream cylinders would occur.

<u>In case, d_R / d_F < 1</u>

The sound emission in this case shows a lower level for all combinations. Figure 7 shows the results for d_R/d_F = 0.71 (d_F = 7 mm, d_R = 5 mm) with U_0 =16 m/s.

Also in this case, we can observe the sudden increase of the ΔSPL at p/d_F = 4 though the maximum value is about 4dB, moreover there exist no prominent peak at p/d_F = 7. For the attitude of α = 20 degrees, there appear the two data arrays in the *St* number, showing that both the upstream and the down stream cylinder contribute to the sound emission and that at the peak at p/d_F = 4, the upstream cylinder solely contributes to the sound emission.

Mean flow field around the parallel cylinders

A sudden change of the SPL at nearly p/d_F = 4 for the small angle of attack less than 20 degrees suggests that the flow pattern will change drastically when crossing a critical condition. A comprehensive measurement by LDV has been performed for the cylinder separation of p/d_F = 4 at the two angle of attack of 4 degrees and 10 degrees under a uniform velocity of U_0 = 16 m/s. The difference of 6 degrees in the angle of attack was necessary to exclude the effect of an inevitable unstable flow situation. The resulting velocity vectors were shown plotted in Figs. 8 and 9 for the cylinder with d_F = 5mm and d_R = 7mm; the typical combination of a strong sound emission and a high spatial resolution. The mean flow pattern with the cylinder separation p/d_F = 3.5 at the same angle of attack of 10 degrees as in Figure 9 was shown in Figure 10.

Figure 11 shows the streamwise variations of fluctuating intensities *u*' and *v*' along the *x*-axis for conditions corresponding to those in Figs. 8, 9 and 10. The data for Figure 9 shows much higher fluctuating intensities near the end of re-circulating region ($x/d_F \cong 1.5$) where vortices from the upstream cylinder roll up.

In Figs. 8 and 10, the rolling-up of vortices from the upstream cylinder was prohibited completely by the downstream one and the flow between the cylinders re-circulates quietly, without making any vortex shedding on a large scale. An elongated re-circulating region reaches to the downstream cylinder. A sound level is low during this flow pattern keeps going.

Just after the angle of attack or the spacing between the cylinders reaches the critical value such as those in Figure 9, the upstream cylinder sheds vortices alternately as a usual cylinder in a uniform flow. The re-circulating region of the upstream cylinder seems to be shortened a little bit; indicating a stronger vortex is shed.

Figure 12 shows the histogram of instantaneous velocity of vertical direction V_{inst} at a position of (x/d_F, y/d_F) = (2.8, 0.7) as indicated by "×" in Figure 9. The histogram has double peak in both negative and positive regions, which indicates the passage of counter rotating vortices. Here Figure 13 shows a power spectrum of velocity components and sound signal at the same position as at Figure 12. The peak frequency of velocity fluctuations coincides with that of sound.

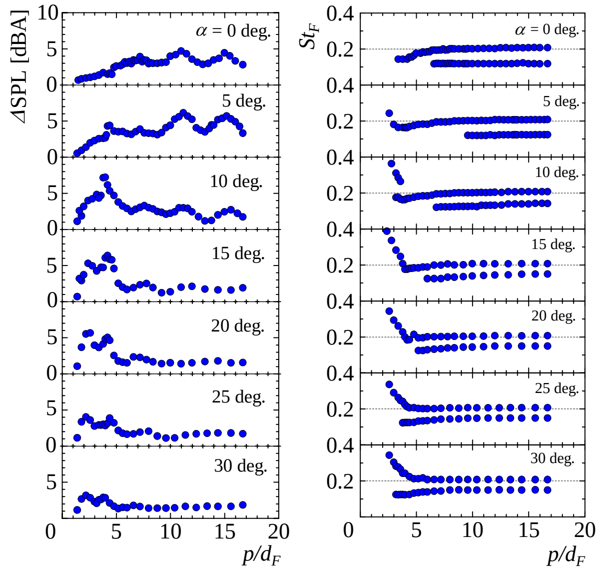

Figure 6. Dependence of ΔSPL and *St* on p/d_F (d_R/d_F = 1.4 (d_F = 5mm, d_R = 7mm), U_0 = 16m/s).

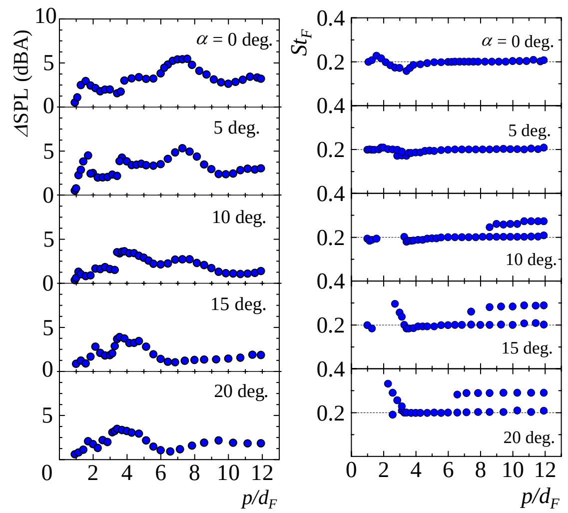

Figure 7. Dependence of ΔSPL and *St* on p/d_F (d_R/d_F = 0.71 (d_F = 7mm, d_R = 5mm), U_0 = 16m/s).

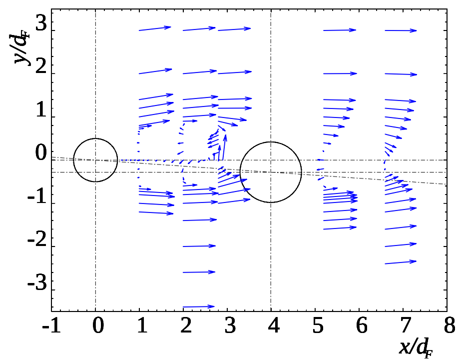

Figure 8. Variation of mean velocity vectors (d_R/d_F = 1.4 (d_F = 5mm, d_R = 7mm), p/d_F = 4, U_0 = 16m/s, α = 4 °).

The vortices roll up just upstream the downstream cylinder and interact strongly with it, leading to a much stronger sound emission than usual condition. As explained above, the vortex shedding from the downstream cylinder is locked in to that from the upstream one, therefore the sound signal has a single peak frequency in this condition.

Concluding remarks

With decreasing the separation distance of two parallel cylinders inclined slightly to the uniform flow direction, the downstream cylinder suddenly prohibits the rolling-up of vortices from the upstream cylinder, forming a relatively large quiet re-circulating region between them. The transition from the alternately shedding flow pattern to the non-shedding one occurs very suddenly and is highly sensitive to the relative position and the attitude of the two cylinders.

The sound emission reaches the maximum just before the transition will occur, irrespective of the angle of attack, where the vortices shed from the upstream cylinder interact strongly with the downstream one, the contribution of the vortices from the downstream cylinder is almost negligible. This switching of flow pattern and the corresponding strong sound emission is found commonly for all combination of cylinders irrespective of the difference of cylinder diameter.

The arrangement of two parallel cylinders with p/d_F nearly 4 has the open area ratio of about 0.7, which can thus explain the critical dependence of a much more complex arrangement of wire netting on the mesh geometry, which occurs for the wire mesh having the open area ratio of 0.6.

Acknowledgments

The authors would like to thank Mr. Z. Kakiuchi, Mr. K. Yoshida and Mr. T. Watanabe for their helps in performing the measurements. The authors also appreciate a financial support by Asahi Building-Wall Co., Ltd. for a part of this study.

References

[1] Iida, A., Otaguro, T., Kato, C. & Shimode, S., Analysis of aerodynamic sound source with measurement of static pressure fluctuation, *JSME international. J.* Series B, **42**, 4, 1999, 596-604.

[2] Jester, W., Kallinderis, Y., Numerical study of incompressible flow about cylinder pairs, J. Fluids and Structures, **17**, 2003, 561-577.

[3] Miyata, M., Hayashi, Y. & Ishikawa, Y., Aerodynamic Sound Generated from an Inclined Array of Circular Cylinders in Uniform Flow (in Japanese), *Proc. of Yamanashi District Conference* 2007, No. 070-4, 80–81.

[4] Mochizuki, O., Kiya, M., Suzuki, T. & Arai, T., Vortex-Shedding Sound Generated by Two Circular Cylinders Arranged in Tandem (in Japanese), *Trans. of Jpn. Soc. of Mech. Eng. B*, **60**, 578, 1994, 3223–3229.

[5] Sakamoto, H., Alam, M. M., Kim, S. & Takai, K., A Study on Flow Around Two Circular Cylinders in Staggered Arrangements: 2nd Report, Estimation of Strouhal Number Using in Combination with Wavelet Analysis (in Japanese), *Trans. of Jpn. Soc. of Mech. Eng. B*, **70**, 699, 2004, 2830–2837.

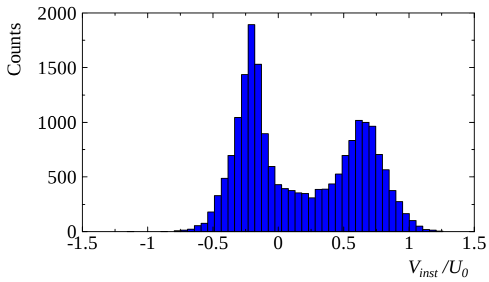

Figure 12. Histogram of instantaneous velocity V_{inst} at $(x/d_F, y/d_F) = (2.8, 0.7)$, $(d_R/d_F = 1.4$ $(d_F = 5\text{mm}, d_R = 7\text{mm})$, $p/d_F = 4$, $U_0 = 16\text{m/s}$, $\alpha = 10°)$.

[6] Zdravkovich, M.M., Flow induced oscillations of two interfering circular cylinders, *J. Sound and Vibration*, **101**, 4, 1985, 511-521.

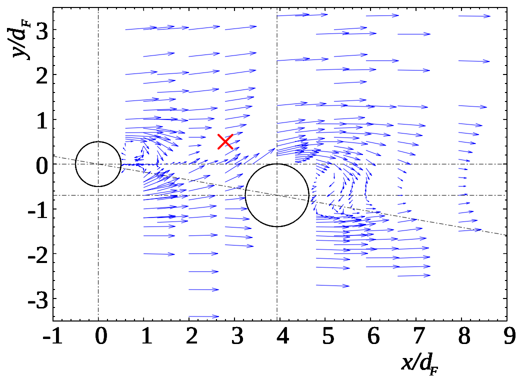

Figure 9. Variation of mean velocity vectors $(d_R/d_F = 1.4$ $(d_F = 5\text{mm}, d_R = 7\text{mm})$, $p/d_F = 4$, $U_0 = 16\text{m/s}$, $\alpha = 10°)$

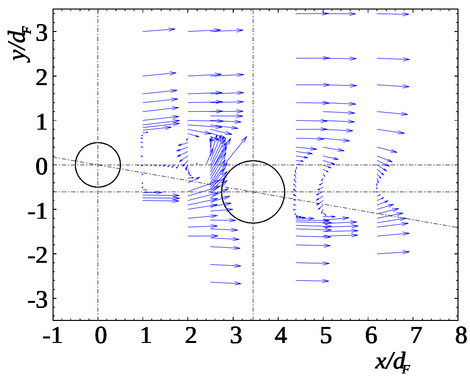

Figure 10. Variation of mean velocity vectors $(d_R/d_F = 1.4$ $(d_F = 5\text{mm}, d_R = 7\text{mm})$, $p/d_F = 3.5$, $U_0 = 16\text{m/s}$, $\alpha = 10°)$.

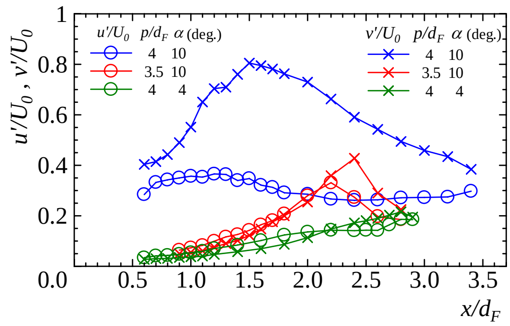

Figure 11. Fluctuation intensity on x-axis $(d_R/d_F = 1.4$ $(d_F = 5\text{mm}, d_R = 7\text{mm})$, $U_0 = 16\text{m/s})$.

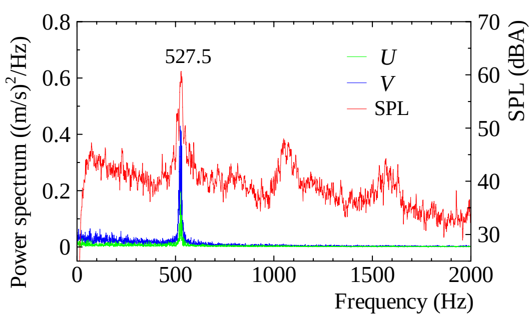

Figure 13. Power spectra of velocities and sound at $(x/d_F, y/d_F) = (2.8, 0.7)$, $(d_R/d_F = 1.4$ $(d_F = 5\text{mm}, d_R = 7\text{mm})$, $p/d_F = 4$, $U_0 = 16\text{m/s}$, $\alpha = 10°)$