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AERODYNAMIC SOUND EMITTED FROM A RECTANGULAR BAR WITH ROUNDED EDGE(S) IN UNIFORM FLOW

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Abstract

A two-dimensional rectangular bar having roundness at a corner, with the corner pointing to the flow direction, can generate a considerable level of high frequency sounds for a relatively narrow region of angle of attack. The frequency is one order higher than that generated by the usual Karman vortex and basically proportional to the free stream velocity, but the proportional coefficient changes stepwise into the higher mode with increase of the velocity. The generation of the sound is directly related to the reattachment of the separated boundary layer from the rounded corner. The characteristics of the emitted sound and the behavior of the reattaching boundary layer on the bar surface downstream of the rounded corner are investigated experimentally under the free stream velocity from 4 m/s to 21 m/s.

INTRODUCTION

A lattice structure made of bars at equal interval is called a louver. If the bar has rectangular cross section and wind blows to the direction of the line-up with a small angle of attack, it may generate aerodynamic sound whose peak frequency is a few kHz. The authors call this sound as the “louver sound”. The peak frequency of the louver sound is not proportional to wind speed, but tends to depend on the interval of a lattice. Such structures can be used, especially in Japan, as handrails of the balcony of condominium housing and also as blindfolds of air conditioning equipments or something similar at the top of buildings. Emission of the louver sound inflicts serious hardship on the neighbouring inhabitants.

In the previous study (1), the authors indicated the generation of the louver sound is closely related to the separation and reattachment of the boundary layer developing around a corner of the lattice bar. An acoustic resonance in space between bars selects the frequency and intensifies the level of emitted sound. The same author has reported that rounding the corners reduces the louver sound considerably (2).

However, if we give the edge a too large radius in comparison with dimensions of the cross-section and a relatively large spacing pitch, then a high frequency aerodynamic sound can be emitted for a relatively narrow region of angle of attack. The peak frequency is now proportional to the free stream velocity and it is one order higher than that generated by the usual Karman vortex. This sound emission can occur even for an isolated bar with the rounded corner pointing to the uniform flow direction.

In this article, we will describe the characteristics of aerodynamics sound emitted from an isolated rectangular bar having a comparatively large curvature of radius, and explain relations between the generation of sound and the reattachment of separated boundary layer.

EXPERIMENTAL APPARATUS & METHOD

Measurements were performed in the downstream of the exit nozzle which had a 500 mm × 500 mm cross section of an Eiffel type wind tunnel designed to minimize the running noise level. The wind tunnel realizes a good quality of uniform flow and a low turbulence level in the nozzle exit over the flow velocity from 4 m/s to 21 m/s.

Figure 1 shows the schematic diagram of flow geometry. A two-dimensional rectangular bar with a cross-section of 15 mm × 50 mm and 450 mm long is made in pullout aluminium pipe. A rectangular bar has a rounded edge whose radius is one of three patterns (Figure 2), r=2.0 mm, 3.5 mm, 5.0 mm, and other edges are right angles as we do not cut a finger. We placed the bar perpendicular to the flow with its rounded edge pointed the uniform flow direction and angle of attack α is defined as shown in Figure 1. In order to assure the two-dimensional flow property, we put a transparent circular end plate of a 100 mm diameter to an unfixed end of the bar.

The uniform flow velocity was monitored by a Pitot tube at the nozzle exit and a digital manometer. The sound pressure level (SPL) of emitted sounds was measured by a sound level meter placed on the centre line of the bar outside the flow. The output signal from a sound level meter was recorded on a digital audio tape recorder and processed on a PC, or carried out the spectrum analysis by a FFT analyzer.

The pressure fluctuation on the windward face was measured by a pressure transducer probe (Kulite, XCS-062-5D). The diameter of the probe is ϕ=1.6 mm, and

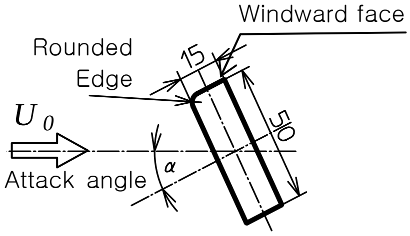

Figure 1 – Schematic of flow geometry.

Figure 2 – Cross section of rectangular bars (r=2.0, 3.5, 5.0mm).

it has a length of 5.0 mm. We put the probe at the center of the windward face of a bar and the points which were by 3 mm away from the center in both upper and down stream direction.

Velocity fields around the windward face were mesured with a four-beam two-color laser-Doppler velocimetery system (DANTEC) with the controlling and processing software (BSA Flow). A 2DThe measuring volume has a diameter of approximately 0.2 mm and a length of 2.5 mm.

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

RESULTS & DISCUSSION

Characteristics of Aerodynamic Sound from a Rectangular Bar

Figure 3 shows the SPL of the sound emitted from the bar with r=3.5 mm corner in a range of attack angle α from 10 to 40 degrees. As shown in the figure, it generates an aerodynamic sound about 5dB stronger than the background noise (BGN) in a range from 23 to 30 degrees. The dependence of the SPL variation on free stream velocity can be found very slight. At α=26 degrees, the SPL amounts to the maximum amplitude, irrespective of free stream velocity.

Figure 4 displays the corresponding spectra for several flow velocities at α=26 degrees. To distinguish each spectrum, they are shown shifted by 30dB. As can be seen in the figure, the peak frequency is one order higher than that generated by the usual Karman vortex and is basically proportional to the free stream velocity.

Dependence of the peak frequency on the free stream velocity is shown plotted in Figure 5 for all bars tested. A linear dependence can be observed irrespective of the curvature, but the proportional coefficient changes stepwise into the higher mode with increase of the velocity. It should be noted that the proportional coefficient changes in multiples of 0.05.

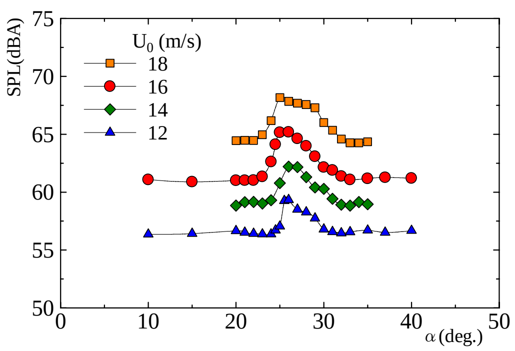

Figure 3 - SPL versus attack angle α (r=3.5 mm).

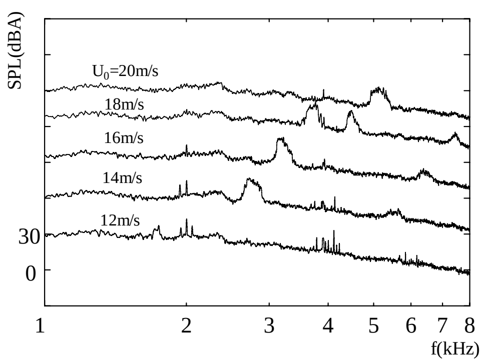

Figure 4 - Spectra of emitted sound (α=26 deg., r=3.5 mm).

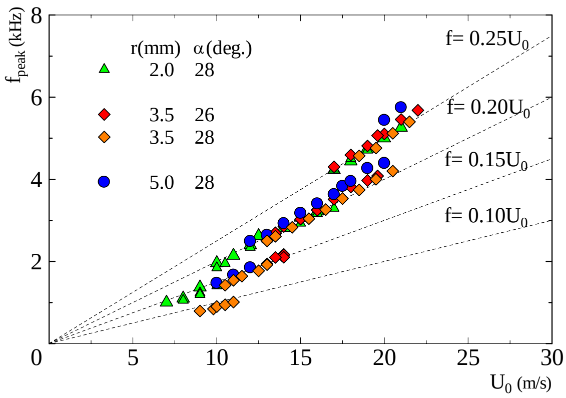

Figure 5 - Dependence of peak frequencies on U_0.

Pressure Fluctuation on the Windward Face of a Rectangular Bar

The pressure fluctuation on the windward face of the rectangular bar should be a key variable for the generation of sound, therefore, we made measurements by the Kulite transducer at three points mentioned before on the windward face of a rectangular bar with an r=3.5 mm curvature.

The mean pressure variation with angle of attack is shown in Figure 6, showing the mean pressure is negative at all points investigated when the bar emits the sound (α=23 to 30 degrees) and that the mean pressure there does not depend significantly on uniform flow velocity.

Spectra of the pressure fluctuation for each free stream velocity have sharp peaks nearly identical with emitting sound. Figure 7 shows the dependence of the peak frequencies of both the aerodynamic sound and pressure fluctuation on the free stream velocity. The proportional coefficient of the linear dependence changes stepwise into the higher mode with increasing the free stream velocity. It should be noted that for small velocity so that the aerodynamic sound is not emitted yet, the pressure fluctuation shows a clear peak already.

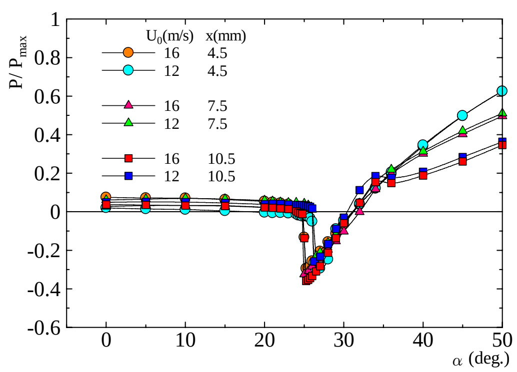

Figure 6 - Mean pressure at windward face of bar versus α (r=3.5 mm).

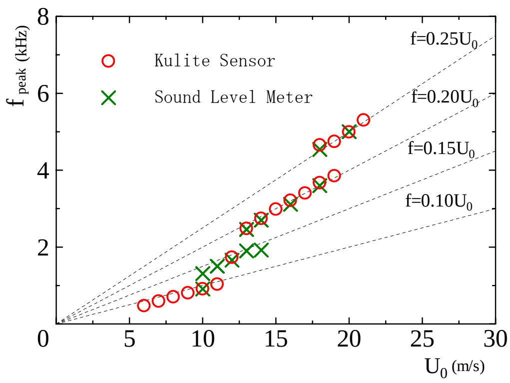

Figure 7 - Dependence of peak frequencies of fluctuating pressure on U_0.

Reattachment of Separated Boundary Layer to Windward Face of Bar

We made comprehensive measurements by means of LDV around the windward surface of bars. Typical results are shown in Figure 8 which shows the variation of mean velocity profiles for the bar having an r=3.5 mm curvature and placed in a uniform stream of U_0=16 m/s at α=26 degrees, that is, for the most typical case of emitting the aerodynamic sound. Figure 9 shows the fluctuating intensity counterpart of the same situation. Coordinates x in these figures are defined as the distance along the windward surface from the apparent leading edge without roundness.

We can see that the boundary layer separates from the surface at x=4.0 mm and reattaches at x=12.0 mm, an extremely thin separation bubble whose maximum thickness is approximately 0.5 mm is formed on the windward side of the rounded bar. The stagnation point, not shown in the figure, located at the point 15 mm down along the front surface of the bar.

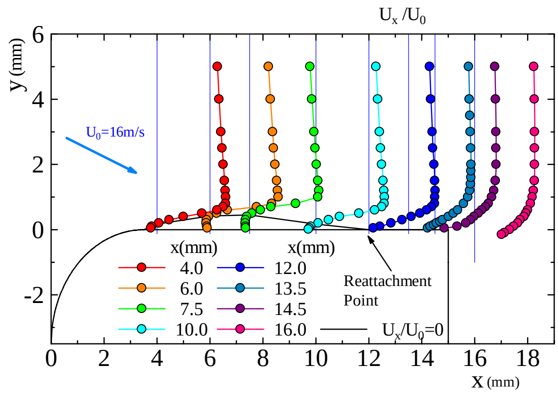

Figure 8 – Variation of mean velocity profile on the windward face (α=26 deg., r=3.5 mm).

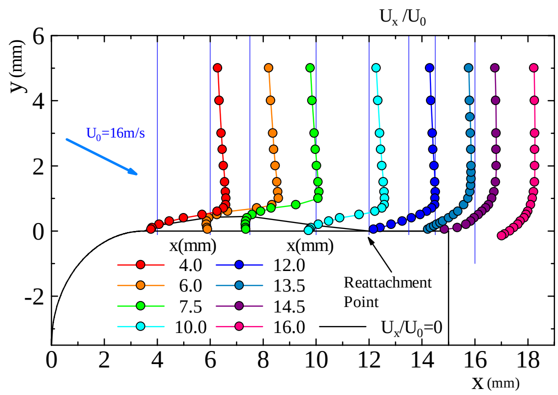

Figure 9 - Variation of fluctuating intensity on the windward face (α=26 deg., r=3.5 mm).

Similar results were obtained for the bar with r=5 mm, showing a little bit shorter separation bubble for the same velocity. Variations of the reattachment point x_r with the free stream velocity and the effects of the curvature and angle of attack are shown in

Figure 10. Generally, the reattachment point moves upstream with increase of the free stream velocity but the effects of the free stream velocity and the curvature is not uniform and seems very complex.

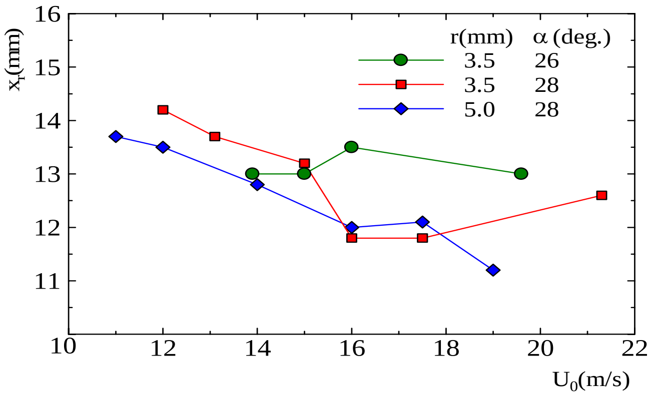

Figure 10 – Positions of reattachment points with flow velocity.

At the reattachment point, when the bar emits the aerodynamic sound, mean velocity and fluctuating intensity profiles show a flow similarity. Figures 11 and 12 exhibit mean velocity and fluctuating intensity profiles at reattachment points, respectively. Vertical axes are normalized by the external flow velocity U_e and the coordinates by the displacement thickness δ^*. The external velocity outside the boundary layer U_e at the reattachment point is approximately 1.2 times the oncoming velocity U_0.

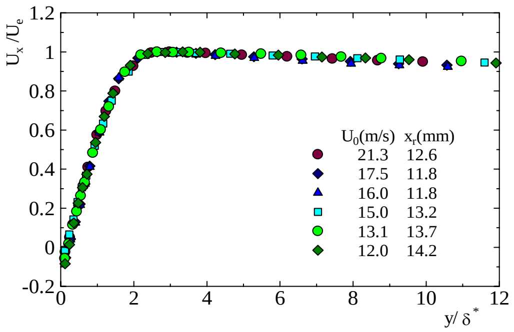

Figure 11 –Mean velocity profiles at reattachment points (α=28 deg., r=3.5 mm).

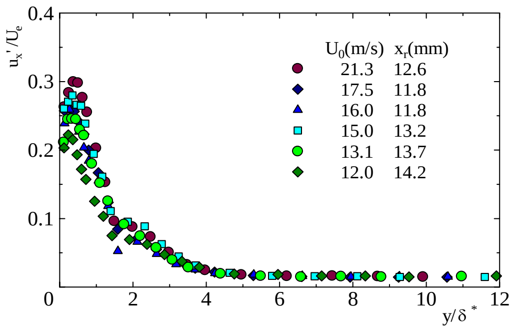

Figure 12 - Fluctuating intensity profiles at reattachment points (α=28 deg., r=3.5 mm).

Figure 13 shows the change in the mean velocity profile at a section of x=13.0 mm for U_0= 12, 13.9, 15 and 19.6 m/s. The aerodynamic sound is not emitted for U_0= 12 m/s and then the separated shear layer does not reattach to the bar surface. Increasing the velocity up to 13.9 m/s, an occasional emission of the sound starts and correspondingly the boundary layer repeats the separation and reattachment. For U_0> 15 m/s, it is almost always reattached to the surface.

Figure 14 shows the normalized histograms of instantaneous velocity at the points y=0.1, 0.6 1.0, 1.6 mm for U_0=13.9 m/s. At y=0.1 mm, the peak of the instantaneous velocity histogram exists near u=0. At y=0.6 and 1.0 mm it has two peaks, one in the negative region and the other in the positive, which means the boundary layer repeats reattaching and separating. At y= 1.6 mm, a large positive peak round 18 m/s shows the point is almost always in the external flow.

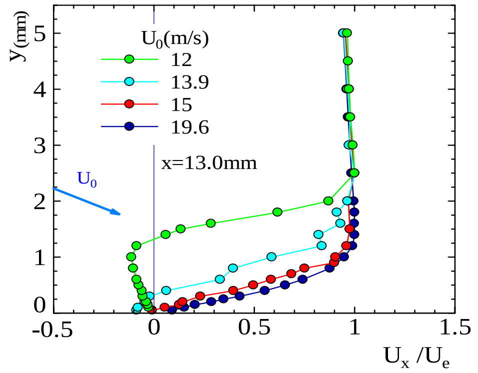

Figure 13 –Mean velocity profile at x= 13.0mm (α=26 deg., r=3.5 mm).

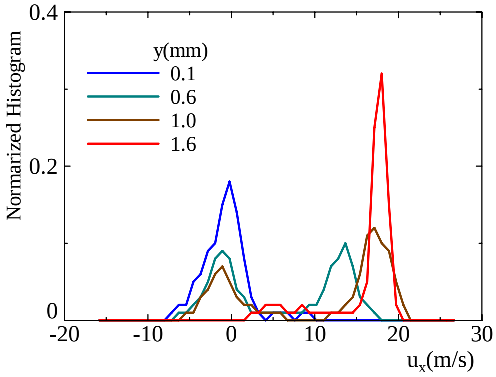

Figure 14 –Frequent distribution of flow velocity (α=26 deg., r=3.5 mm, U_0=13.9 m/s, x=13.0 mm).

Suppression of Sound by a Tripping Wire

In the foregoing section, we showed that the boundary layer did not reattach to the bar surface when the bar did not generate sound. It suggests that the prevention of detachment and reattachment of a laminar boundary layer by making it a turbulent one might affect the process significantly.

To confirm the conjunction, we stuck a tripping wire with a diameter of 0.3 mm on a rounded corner of the bar. The resulting spectrum of sound was shown in Figure 15, compared with the one without a tripping wire. The characteristic aerodynamic sound disappeared completely by the presence of tripping wire. The variation of mean velocity profiles on the windward surface for this situation was shown in Figure 16, demonstrating that the separated boundary layer could not reattach on the bar surface.

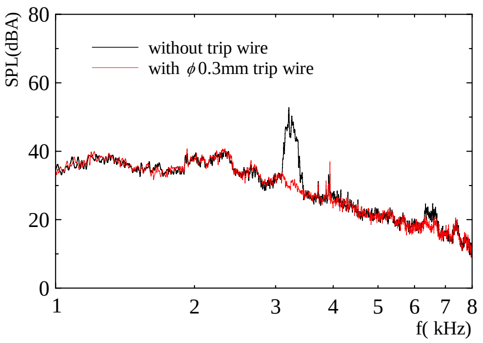

Figure 15 – A spectrum of sound emitted from a rectangular bar with trip wire (U_0=16 m/s, α=26 deg., r=3.5 mm).

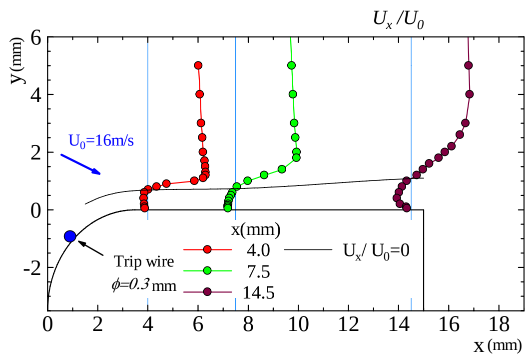

Figure 16 – Variation of mean velocity profile on the windward face with ϕ=0.3 mm trip wire (α=26 deg., r=3.5 mm).

Explanation for Emission of Sound from an Isolated Rectangular Bar

From the above-mentioned results, we can say that the emission of the aerodynamics sound from an isolated rectangular bar is directly related to the reattachment of the separated boundary layer developing just ahead of the rounded corner.

Separation occurs easier for the smaller radius of curvature, but correspondingly the reattachment becomes more difficult, hence there may exist "an appropriate" radius of curvature to emit the sound for a given bar section.

The stepwise increase of proportional coefficients between the peak frequency and on-coming wind velocity implies there exist an array of vortices in the free shear layer part of the separation bubble, which impinges successively upon the bar surface at the reattachment point.

CONCLUDING REMARKS

A rectangular bar with the rounded corner(s) can generate a considerable level of high frequency sound for a narrow range of angle of attack. For this limited angle of attack, the boundary layer separated from the rounded leading edge can reattach to the bar surface, forming a very thin separation bubble. The emission of sound is a direct consequence of this reattachment of the boundary layer, hence if the reattachment is disturbed, for example, by means of tripping wire, the sound emission stops completely.

The SPL depends strongly both on the free stream velocity and the radius of curvature. On the other hand, the linear relation between the frequency and the velocity is essentially the same, irrespective of the radius of curvature investigated.

The frequency corresponds to the number of vortices which collide with the wall at the reattachment point and the frequency shift to the higher mode seems to occur due to adding one more vortex in the separated shear layer. The process may be influenced by subtle conditions controlling the unstable shear layer and its reattachment. A further study is needed to clarify the mechanism of this sound emission.

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