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Tonal and Silent Wake Modes of a Square Rod at Incidence

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Summary

The tonal sound produced by a rod with square cross section placed with its axis normal to a uniform subsonic flow has been measured. The angle of incidence of the flow with respect to the basis of the cross section has been varied. The most interesting deviation between literature and the present experiments is the appearance of a silent wake mode. This silent mode appears by default when the wind tunnel is started for angles between 25 and 65 degree. It is metastable, an upstream perturbation, from small perturbations to hand waving, triggers the tonal wake mode. By perturbing the flow in wake of the rod, the silent mode can be recovered. The tonal mode appears spontaneously for angles between −25 and 25 degree. For the tonal mode we compare the measured oscillation frequency and radiated pressure amplitude with literature data. Some small, but significant, differences are observed.

1. Introduction

Flow around bluff bodies is intrinsically unstable at high Reynolds numbers. This results into a fluctuating force exerted by the flow on the body. The reaction to this force acting on the fluid is a source of sound. It is a dipolar source of sound which will dominate at low subsonic flow speeds.

Under certain conditions the instability of the wake results in periodic vortex shedding characterised by a Strouhal number $St_D = fD/U_0$, product of frequency f and convection time D/U_0, where D is the characteristic width of the body and U_0 the main flow mean velocity. Whistling of cylinders in cross flow has been extensively studied since the early work of Strouhal [1]. More recently the sound produced by rods with rectangular or square cross sections have received considerable attention in view of applications in civil engineering. The generic case of a rod with square cross-section is considered. The present work focuses on the tonal sound.

The oscillating forces are dominated by periodic vortex shedding at specific Strouhal numbers reported by Okajima [2], Norberg [3], Knisely [4] and Chen [5]. A detailed discussion of literature and flow pattern is provided by Mueller [6]. Mueller [6] also provides Large Eddy Simulations. The literature reports spectacular changes in flow behaviour around a critical value of the incidence angle α (angle between the incident flow and the inner normal to the front wall) close to $\alpha_{cr} = 13°$, at which the flow separated from the front lower edge starts re-attaching to the lower side wall.

The sound generated by a square rod at incidence was studied previously by Fujita [7] and Hutcheson [8]. Results obtained in a similar set-up are presented here. The main difference is that in the present set-up one observes a silent wake mode next to the whistling mode, which was not reported in the literature. To characterise this flow some information is provided on the static pressure distribution. After discussing this unexpected result, the whistling frequency and sound pressure level obtained are compared for the whistling mode with data from the literature. This might on the long term provide possible clues for the reason of appearance of the silent wake mode.

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2. Experimental set-up

A rod with square cross section placed with its axis normal to the flow direction is used. In the right-handed cartesian coordinate system (x_1, x_2, x_3) the origin is at the centre of the rod. The x_1 axis is in the main flow direction. The x_2 axis is normal to the x_1 and the rod axis. The whistling sound generated by the oscillation in the lift force is studied. The rod cross section width is D=0.036 m. The rod length is $L = 12.5D = 0.450$ m. Its surface is polished and edges have been kept as sharp as possible. Paint limits the radius of curvature of the edges to 0.1 mm. The rod is hollow, with a wall thickness of 2 mm. Sixteen static pressure taps, with a diameter of 0.5 mm, are drilled in the rod. Each hole is connected to a metal tube extended by a silicon hose connected to a manometer. This Esterline pressure scanner delivers the static pressure measurements to a Chell CANdaq pressure acquisition system. These static pressure measurements are used to characterise the flow.

The rod is mounted horizontally between two vertical 12 mm thick plexiglass plates fixed to the sides of the nozzle exit (exit cross section $L \times W = 0.45\,\text{m} \times 0.35\,\text{m}$, so that $W/D = 9.7$) of the silent wind tunnel of UTwente (Figure 1). The plates have a length of $L_{plate} = 0.575$ m in the flow direction and a height of 0.350 m. The trailing edge of the plates forms a semi-circle of 0.175 m radius. The rod is placed at the centre of this circle, which corresponds to a distance of $x_{\text{rod}} = 0.400\,\text{m} = 11D$ from the nozzle outlet . The trailing edges of the side-plates are rounded in order to reduce broad band flow noise. The rod can be rotated around its axis to change its angle of attack α (angle between the main flow direction and the front wall inner normal). This angle is measured within 0.1 degree by means of an electronic level meter using the bottom plate of the nozzle as a reference. The experimental conditions reported by Fujita [7] are similar ($D = 2$ cm, $L/D = 10$ and $W/D = 15$), however the end plates are much larger ($L_{plate} = 1$ m). Hutcheson and Brooks [8] have a narrower rod ($D = 2.5$ cm) with $L/D = 36$ and $W/D = 24$.

The silent wind tunnel of UTwente is a closed circuit free jet facility driven by a centrifugal fan. The noise from the fan is attenuated by two silencers located on either sides of the fan. Upstream of the downstream silencer a water cooling system controls the temperature of the flow. The settling chamber has a cross-section of (2.25 m × 2.80 m). The small nozzle ($L \times W = 0.45\,\text{m} \times 0.35\,\text{m}$) used here allows reaching a free jet (test section) velocity of 75 m/s. The turbulence level of the flow at the nozzle exit is 0.2%. The centre of the nozzle exit is at 1.10 m from the vertical wall and at 1.70 m from the floor of the anechoic room ($V = 4\,\text{m} \times 6\,\text{m} \times 6\,\text{m}$) used for the acoustical measurements. On the opposite vertical wall there is a flush cir-

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cular intake. The intake has an edge radius of curvature of 0.5 m and leads to a duct of 1.4 m cross section radius.

The acoustic measurements are obtained by means of two LinearX microphones (type M51). The microphone positions are $\vec{x}_I$ = (0.21 m, 0.55 m, 0 m) and $\vec{x}_{II}$ = (0.21 m, −0.55 m, 0 m) with respect to the coordinate system (x_1, x_2, x_3). These positions have been chosen within the reverberation radius of the anechoic room associated with the whistling frequencies. For the velocity range considered 20 m/s ≤ U_0 ≤ 75 m/s the whistling frequency is in the range 63 Hz ≤ f ≤ 315 Hz. The corresponding 60 dB reverberation time of the room is in the range $1.77s \geq T_{60} \geq 0.15s$. Microphones were calibrated by using a Brüel&Kjær reference source (1 kHz) before each experiment. By correlation of the signals of opposite microphone pairs as proposed by Blake [9] the sound production by the rod is extracted from background noise (see [6]).

The sound pressure level is defined by $SPL = 20\log_{10}(p_{rms}/p_{ref})$ where p_{rms} is the root mean square amplitude of pressure fluctuations and p_{ref} = 20 µPa. The SPL of the whistling tone is determined by integration of the cross-spectrum of the pressure measured by microphones $\vec{x}_I$ and $\vec{x}_{II}$ over the frequency range 0.5 Hz < f < 20 kHz.

3. Silent and whistling wake modes

For angles of attack in the range $-25° < \alpha < 25°$ the wake is always unstable and periodic vortex shedding occurs corresponding to the tonal mode. For angles of attack in the range $25° < \alpha < 65°$ next to the tonal mode a stable silent wake mode can be observed. The choice between the silent and tonal modes depends on the history of the flow. For $25° < \alpha < 65°$ the silent mode appears by default when the wind-tunnel is started. One can switch the tonal mode on by perturbing with the hand the flow upstream of the rod. Perturbing the flow in the wake of the rod with the hand enables to switch back to the silent mode. Placing a tuft in the flow indicates that the wake is much broader in the silent mode than in the tonal mode.

Pressure coefficient $Cp = 2(p - p_\infty)/(\rho U_0^2)$ measured for two modes can be seen in Figure 2 for $Re_D = 46000$ and $Re_D = 92000$. The pressure p is the static wall pressure and p_∞ is the far field surrounding (atmospheric) pressure. There is no significant dependency on the Reynolds number. The difference ΔCp between pressure coefficients of the tonal and silent modes is, at the back side of the rod ($0 < s/D < 2$), of the order of unity ($\Delta Cp = O(1)$). The coordinate s corresponds to the distance from one of the edges of the rod along the perimeter of the rod.

Figure 3 shows the spectra of the microphone signal at U_0 = 60 m/s. One can see that the tonal mode displays a sharp peak close to $St_D = fD/U_0 = 0.1$. The silent mode does not show this peak and the broad band noise in this case is close to the noise measured in the set-up when the rod has been removed. This is why this mode is called the "silent mode". It was observed in the entire Reynolds number range considered ($4.6 \cdot 10^4 \geq Re_D \leq 1.6 \cdot 10^5$) and quite stable for $\alpha > 30°$. Both the silent and whistling modes became increasingly stable as the Reynolds number was increased.

4. Strouhal number, coherence length and amplitude of whistling mode

The influence of the angle of attack on the Strouhal number of vortex shedding (lift oscillation frequency) can be seen in Figure 4. A maximum around $\alpha = 13°$ is found in all available data.

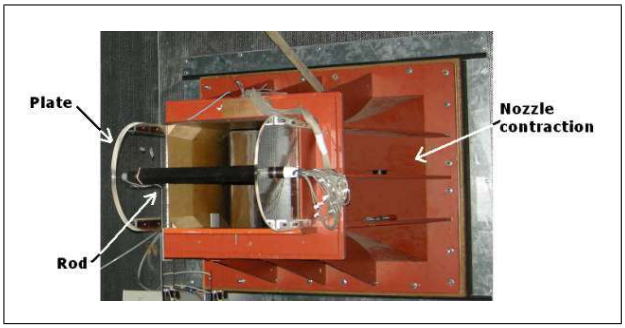


Figure 1. Set-up with plexiglas end-plates (colour online).

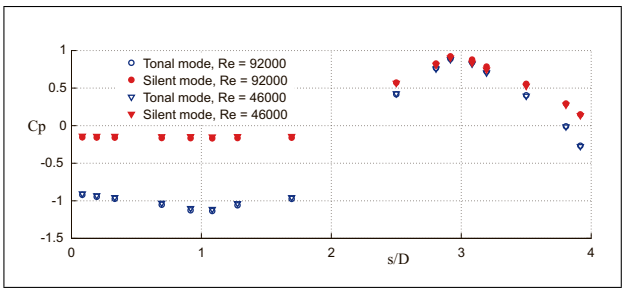


Figure 2. $Cp = 2(p - p_\infty)/(\rho U_0^2)$ as a function of surface coordinate s/D at $\alpha = 45°$, tonal and silent mode. The leading edge of the rod corresponds to the origin $s/D = 3$. The trailing edge is at $s/D = 1$. (colour online)

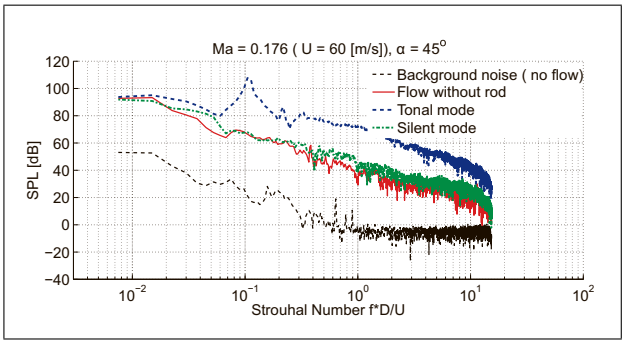


Figure 3. Comparison of tonal and silent mode (colour online).

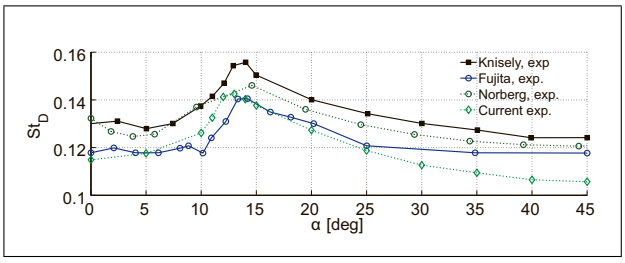


Figure 4. Strouhal numbers at different angles of attack for the lift force oscillation of the whistling mode. $Re_D = 144000$, Norberg [3], $Re_D = 5000$, Knisely [4], $Re_D = 22000$ to 62000, Fujita [7], $Re_D = 10000$, average over the Reynolds number of current experiment [6](colour online).

Below $\alpha = 25°$, the present experimental data agrees well with the one of Fujita [7]. However for the angles $25° < \alpha < 45°$ it is lower than other literature data, being 15% lower at $\alpha = 45°$. It is interesting to note that this corresponds to the range in which

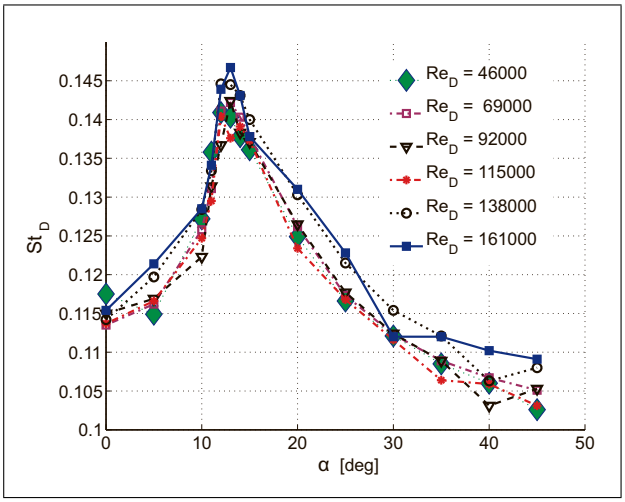


Figure 5. Strouhal numbers for the whistling mode at different angles of attack for the lift force oscillation at different Reynolds numbers. Current experiment [6] (colour online).

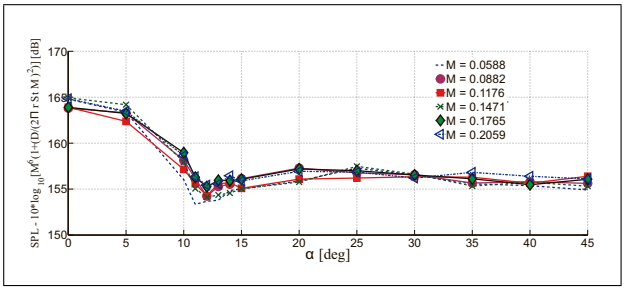


Figure 6. SPL vs. angle of attack for the whistling mode - experiment [6] scaled with $M^6(1+(D/(2\pi r St M))^2)$ (colour online).

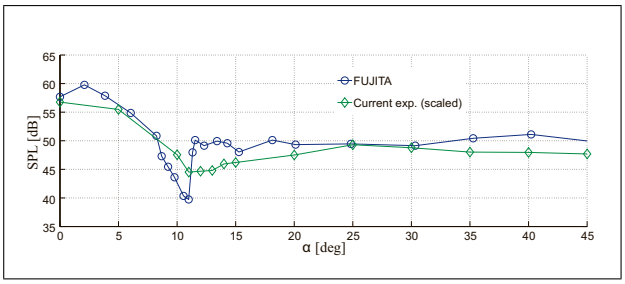


Figure 7. SPL vs. angle of attack for the whistling mode-comparison with literature. Fujita [7], Current exp. [6]. All plots scaled to $Re_D = 10000$. Rod dimensions: $L = 20\,\text{cm}$ and $D = 2\,\text{cm}$. (colour online).

the silent mode can be observed. A slight increase of 5% in St_D is observed as Re increases from 46000 up to 161000 (see Figure 5).

The coherence length for pressure fluctuations along the rod were measured by Fujita [7]. The coherence length varies between 8 D around $\alpha = 0°$ and 30 D around $\alpha = 45°$. Hot wire measurement in the wake of the rod with $\alpha = 13°$ were carried out in the present set-up. The result agrees perfectly with the data of Fujita [7]. In both experiments the coherence length is comparable or larger than the rod length. This is a significant difference with the experiments by Hutcheson and Brooks [8] for which the rod is larger than the coherence length. Figure 6 shows the angle of attack dependency of the SPL generated at all Mach numbers measured in our experiment. It is scaled with $M^6(1+(D/(2\pi r St M))^2)$ taking into account near and far field influence. The distance $r = \sqrt{x_1^2+x_2^2+x_3^2}$ is measured from the centre of the rod to the microphone. As expected it follows the same trend as the lift fluctuations reported in the literature [4], [6]. All the scaled curves collapse within about 1 dB for all angles of attack.

In Figure 7 the data are scaled with reference to the SPL of Fujita [7] assuming that the experiments of Fujita were performed at $M = 0.0235$ ($Re_D = 10000$) using rod of $D = 0.02\,\text{m}$ and $L = 0.2\,\text{m}$. The position of the microphone is $\vec{x}_f = (0, 1\,\text{m}, 0)$. While there is a fair global agreement the present data does show a less pronounced minimum in SPL at α_{cr}. Note that the proposed scaling does not correct for the sound reflection on the side walls supporting the rod. A correction is proposed by Mueller [6].

5. Conclusion

The most significant deviation between the present experiment and literature is the appearance (for $25° < \alpha < 45°$) of a silent flow mode. This is not yet understood and deserves further study, because it was not reported by other researchers. For the whistling mode, the measured Strouhal number in the present experiments agrees well with data from the literature up to $\alpha = 25°$. For larger angles of attack it is lower. At $\alpha = 45°$ a deviation of 15% is observed for $Re < 10000$. For $Re = 161000$ this deviation amounts 10%. It is interesting to note that this range ($25° \leq \alpha \leq 45°$) corresponds exactly to the range in which the silent mode can be established. A scaling is proposed to allow comparing the sound pressure level (SPL) in different experiments at different Mach numbers and in different set-ups, which provides results accurate within 2 dB. The largest Strouhal number is found at the critical angle $\alpha_{cr} = 13°$, this corresponds to the angle at which reattachment of the flow starts to occur at the lower side wall of the rod. At this point the radiated sound pressure level displays a minimum. This minimum is more sharp and deeper in the experiments of Fujita [7] than in the present measurements. The present results are similar to the results that can be deduced from fluctuating lift force measurements of Kinsely [4]. The rod length used here and by Fujita [7] is comparable to the coherence length of the vortex shedding or smaller, while Hutcheson and Brooks [8] use a much larger rod length. The possible influence of end effects should therefore be studied. Hence the present results display small but significant differences from data present in the literature.

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