Flow and Noise Associated with The Interaction of A Square Cylinder with A Downstream Flat Plate

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I would like to dedicate this thesis to my late father...
Mat Ali Samsudin

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Declarations

This work contains no material which has been accepted for the award of any other degree or diploma in any university or other tertiary institution to MOHAMED SUKRI MAT ALI and, to the best of my knowledge and belief, contains no material previously published or written by another person, except where due reference has been made in the text.

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Mohamed Sukri Mat Ali

Abstract

Bluff bodies are commonly found in many engineering applications, such as aircraft landing gear, pantograph systems of high speed trains and the rear view mirrors of passengers cars. In the event of bluff body interaction with flow, various flow induced phenomena may occur, such as vibration, unsteady aerodynamic loading, high pressure drag and flow induced noise. These phenomena can be altered by locating a secondary body in the wake of, and close to the bluff body. This alteration is due to the modification of the bluff body wake structure by the secondary body.

The main objective of this study is to investigate the possibility of using a downstream flat plate for passive bluff body wake control. The success of this mechanism is evaluated by considering the reduction in unsteady aerodynamic loading together with the reduction in sound pressure level at an observer location. The observed new flow structures are explained using the results from a wide range of wake analyses to obtain a clear understanding of the physical phenomena of the wake-plate interaction.

The test case under investigation consists of a square cylinder as the primary bluff body and a flat plate as the secondary body. The plate length and its position downstream of the square cylinder are varied systematically. This allows the optimal configuration of the plate for the least aerodynamic loading and radiated sound to be determined. The flow is simulated using two-dimensional Direct Numerical Simulation (DNS) at a Reynolds number of 150, based on the side length of the cylinder of D. For the acoustic analysis, Curle's solution of Lighthill's acoustic analogy is used for a Mach number of 0.2 and the

sound pressure levels are calculated for an observer location of $80D$ directly above the cylinder. The results of the study are presented in the form of a chapter describing the mesh verification and validation studies and a collection of four published or submitted journal articles on the remaining results.

The effect of an attached downstream flat plate on the wake of a square cylinder is first investigated for plate lengths (L) of length $0 \leq L \leq 6D$. The plate, which is called a splitter plate, is attached to the downstream edge of the cylinder. It is found that the splitter plate interacts strongly with the near wake of the cylinder and that the length of the plate significantly affects the flow structure. The behaviour of the flow can be grouped into three regimes. For short plate lengths $0 < L \lesssim D$, the free shear layers are convected further downstream before rolling up into vortices as the plate length is increased. In this regime, the root mean square lift coefficient ($C_{L_{\mathrm{rms}}}$) and the mean drag ($C_{D_{\mathrm{mean}}}$) decrease with increasing plate length. For intermediate plate lengths $1.25D \lesssim L \lesssim 4.75D$, a secondary vortex is clearly visible around the trailing edge of the splitter plate and the shear layers begin to roll up closer to the trailing edge. A continued increase in $C_{L_{\mathrm{rms}}}$ is observed when the plate length is increased, but a reduction in $C_{D_{\mathrm{mean}}}$ still occurs, although at a lesser rate than the first regime. For long plate lengths $L \gtrsim 5D$, a regime is observed in which the free shear layers reattach to the splitter plate. Consequently, a sudden jump in $C_{L_{\mathrm{rms}}}$ is observed. The splitter plate study also proposes the minimum wake half-width as the length scale for a possible universal Strouhal number, which is found to be valid for $0 \leq L \leq 4D$.

The effect of the splitter plate on sound generation is also numerically investigated. When the length of the splitter plate is varied from $L = 0.5D$ to $6D$ the results can also be grouped into three distinct regimes. For the first regime ($L \lesssim D$), the sound pressure levels decrease with increasing plate length. An overall sound pressure level

reduction of 3 dB is obtained at the observer location when the length of the plate is D. For the second regime ($1.25D \lesssim L \lesssim 4.75D$), the sound levels increase with increasing plate length. For the third regime ($L \gtrsim 5D$), the sound pressure levels decrease as the length of the plate increases but the levels are higher than for the other regimes. Results also show that the lift fluctuation is the dominant sound source. These acoustic results are explained in terms of the fluid mechanics occurring in the near wake of the cylinder.

In the second part of the study, the sensitivity of the square cylinder wake structure to a detached plate is investigated by varying the gap distance (G) between the cylinder and plate along the wake centerline in the range $0 \leq G \leq 7D$. The length of the plate is kept constant and equal to the side length of the square cylinder. A critical gap distance, which separates the two flow regimes, is observed to occur at $G_\mathrm{c} \approx 2.3D$. Regime I is characterised by vortex formation occurring downstream of the gap while for regime II, formation occurs within the gap. Reductions in C_{L_rms} and C_{D_mean} can only be obtained in regime I, where the optimal gap occurs at the critical gap. When the gap distance is increased beyond its critical point (regime II), a significant increase for both parameters is observed. This is due to the re-establishment of the von Kármán vortex inside the gap.

The sound generation for the detached plate case is numerically investigated. The study found that the change in the sound pressure level with gap distance can be grouped according to the flow regimes identified earlier. An overall sound pressure reduction to the freestream can only be obtained in regime I ($0 \leq G \leq 2.3D$), where a 2.9 dB reduction in sound pressure level is obtained when there is no gap between the two bodies. In contrast, the sound pressure level increases by at least 8.0 dB when the plate is in regime II ($2.4D \leq G \leq 7D$).

Using the information from the flow simulation, the plate length is reduced in an effort to achieve sound cancellation in the far-field. This can be achieved when the noise generated by the cylinder and the plate are equal in magnitude but out of phase. Using a linear estimation method, the plate length and gap distance required to obtain sound cancellation are found to be $L = 0.26D$ and $G = 5.6D$, respectively. Acoustic analysis of the modified configuration shows a sound pressure reduction of 6.3 dB at the observer location when compared with the single square cylinder. A detailed flow-visualisation shows that the maximum sound pressure reduction attainable is limited by a non-linear unsteady stall process on the plate.

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