AEROACOUSTIC INVESTIGATION OF THE EFFECT OF A DETACHED FLAT PLATE ON THE NOISE FROM A SQUARE CYLINDER

Aniket D. Jagtap[1], Ric Porteous[1], Akhilesh Mimani[1] and Con Doolan[2]

[1]School of Mechanical Engineering
The University Of Adelaide, SA 5005, Australia
Email: aniket.jagtap@student.adelaide.edu.au
Email: ric.porteous@adelaide.edu.au
Email: akhilesh.mimani@adelaide.edu.au

[2]School of Mechanical and Manufacturing Engineering
UNSW Australia, Sydney NSW 2052, Australia
Email: c.doolan@unsw.edu.au

Abstract

This paper presents an experimental investigation of the aerodynamic noise generated by a square cylinder in the presence of a detached thin flat-plate located in its wake. Experiments were performed in an Anechoic Wind Tunnel (AWT) at Reynolds numbers between 1.55 x $10^4 < Re_D < 2.3 \times 10^4$ (D being the width of the cylinder) and Mach numbers of $0.07 < M_0 < 0.1$. A flat-plate with a length $L = D$ was placed along the centreline of the wake at a gap distance G from its trailing-edge (TE). The gap was varied between $0 < G < 4D$ whereby the aeroacoustic behaviour was studied using microphone measurements. It was found that the thin detached flat-plate reduced the Sound Pressure Level (SPL) by approximately 7 dB at the Aeolian tone frequency.

1. Introduction

In past two decades, the investigation of the flow-induced noise from bluff bodies has been of a significant interest to researchers in the field of aerospace and automobile engineering. Numerous transportation systems are considered to be major contributors to airborne noise pollution. The flow around the bluff body components of aircraft, high-speed trains and automobiles radiates significant noise and considerable research has been carried out to address this problem [1-3]. Previous studies have helped understand the formation of various flow-regimes and the acoustic radiation generated due to the interaction of flow with bluff bodies. In modern aircraft, undercarriage noise during landing was found to be more dominant than the total airframe noise [4, 5]. Similarly, for high-speed trains and Maglev trains, pantograph systems were the primary source of aerodynamic noise which was dominant beyond a certain speed [6]. All these systems comprise of different basic bluff body geometries such as a cylinder and their interaction with the flow resulted in undesirable noise. A square cylinder has a simple bluff body geometry; however, the flow structure is complex. This occurs due to shear-layer instability, velocity fluctuation, vortex formation and flow separation in wake. This complexity increases when a secondary body is introduced in the wake of primary bluff body.

A previous numerical study concluded that for a square cylinder, flow begins to separate at Re_D =1.15 [7] and the length of the separation bubble increase approximately linearly with Reynolds number. Results from this study also suggested that the flow separates at a much lower Re_D for a square cylinder in comparison to a circular cylinder, leading to the formation of a bigger wake. It is noted that the flow generates a free shear-layer that becomes unstable at Re_D = 47 for a square cylinder. This unsteadiness is amplified at the near end of the body due to a strong base adverse pressure [8]. Thus, a large arrangement of eddies are formed due to alternately rolling up of the shear-layers which gives rise to von Karman vortex street [9] that occurs at the vortex shredding frequency f expressed in the dimensionless form ,

$$St = f\frac{D}{U_\infty} \tag{1}$$

where, f is the vortex shedding frequency, D is the cylinder diameter, U_∞ is the free stream velocity, St is the Strouhal number. Previous numerical studies of low Reynolds number flow over a square cylinder with splitter and detached flat-plates showed that a flat-plate acts as an efficient wake control mechanism and lift suppression is possible at a certain gap distance [10, 11]. The sound generation for the detached flat-plate case was numerically investigated and it was found that changes in Sound Pressure Level (SPL) with gap distance can be grouped according to different flow regimes. An overall SPL reduction of 2.9 dB was obtained when a detached flat-plate is located at $0 \leq G \leq 2.3D$ whereas the SPL increases by at least 8 dB when the plate is located in the regime $2.4 \leq G \leq 7D$.

A theoretical model based on Curle's formulation by Doolan [12] explained that the Aeolian tone generated by bluff body can be eliminated in the far-field by using a downstream body. Numerical analysis of a configuration consisting of a square cylinder followed by a thin detached flat-plate at Re_D=150 and Mach number 0.2 was investigated [13]. Acoustic results from this study showed significant reduction in SPL radiated from the square cylinder. Furthermore, the radiated sound from the plate was greater than that radiated from a single square cylinder due to strong shear-layer interaction. In addition to this study it was also found that plate altered the wake structure of the single square cylinder.

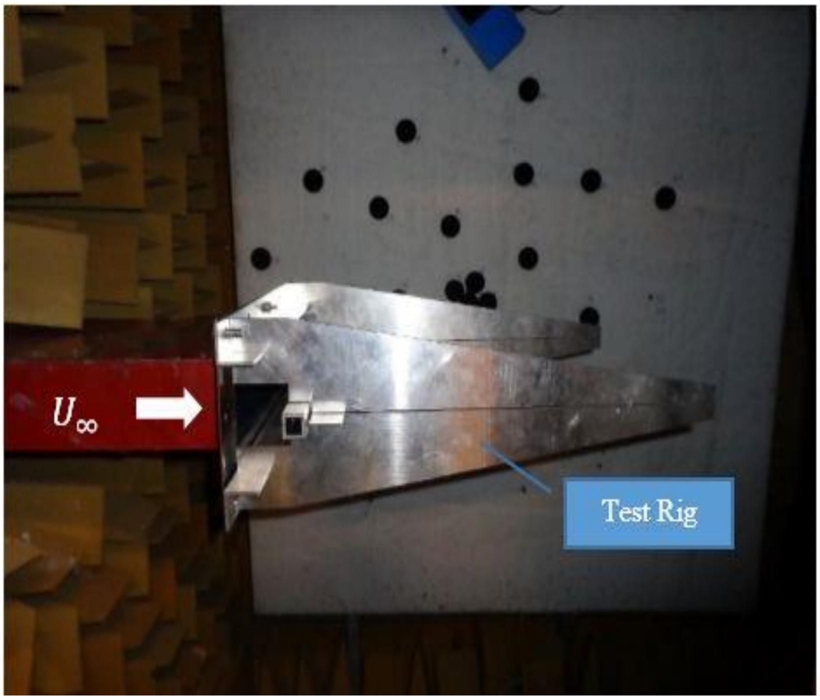
In another numerical study [13], it was reported that a downstream body can be employed as a sound cancellation device by varying the gap distance. It was shown that it is possible to use a downstream body as a sound cancellation mechanism provided that the acoustic field generated by the downstream body is of equal magnitude but out-of-phase with that radiated from the bluff body. Furthermore, the numerical simulation was shown to be in agreement with a theoretical model [12].

The aforementioned studies employed numerical simulations to verify the proposed theoretical models of using a downstream body as a sound cancellation mechanism. However, an experimental demonstration of this aeroacoustic phenomenon is not reported in the literature. The objective of this work is therefore to carry out an experimental investigation of changes in noise generation of a square cylinder when a detached thin flat-plate is placed in its wake.

2. Experimental Setup

The experimental investigation was performed in an Anechoic Wind Tunnel (AWT) at the University of Adelaide equipped with a spiral arrays of microphones as shown in Fig. 1(a) and a National Instruments PXI high-speed data acquisition system. The AWT has internal dimensions of 1.4 m × 1.4 m × 1.6 m. The walls of chamber are acoustically treated with foam wedges to approximate a reflection free environment at frequencies above 250 Hz. The contraction outlet of facility has rectangular cross section as shown in Fig. 1(a) with dimensions of 75 mm × 275 mm. The maximum flow velocity of the free jet is ~38 m/s and the freestream turbulence intensity is 0.33%. The acoustic measurements were measured using a B&K ½ "microphone (Model No. 4190). A spiral array comprising of 31 microphones recorded the acoustic pressure data for the different test-cases during aeroacoustics experiment. The microphones were calibrated post-installation to take into account the wind noise. National instruments data logger was utilised to collect data from these microphones. Although data from all microphones were recorded, only data from the central microphone is presented in this paper. This microphone was located a distance of 595 mm above the square cylinder.

(a)



(b)

Figure 1. Experimental setup in AWT (a) contraction outlet with spiral arrangement of microphones (b) Test rig with a square cylinder and a thin detached flat-plate

The geometry for investigation comprises of a square cylinder as a primary bluff body and a thin detached flat-plate as secondary body, which is placed in the wake of the square cylinder as shown in Fig. 1(b). Figure 2 shows the schematics of the geometry. It is noted that D = 10 mm is the side length of the square cylinder; L and h are the length and thickness of the thin detached flat-plate respectively. Furthermore, G is the gap distance between the square cylinder and thin detached flat-plate. The gap distance G between the square cylinder and the thin detached flat-plate is varied in the range of $0 < G < 4D$ with constant detached flat-plate length as $L = D$ and h = 1 mm.

Experiments were conducted at free-stream velocities between 25 m/s and 37 m/s corresponding to Re_D = 1.55 x 10^4 and 2.3 x 10^4 based on the square cylinder width. Acoustic pressure fluctuations were recorded for 40 seconds at a sampling frequency of 2^{16} Hz for each test case.

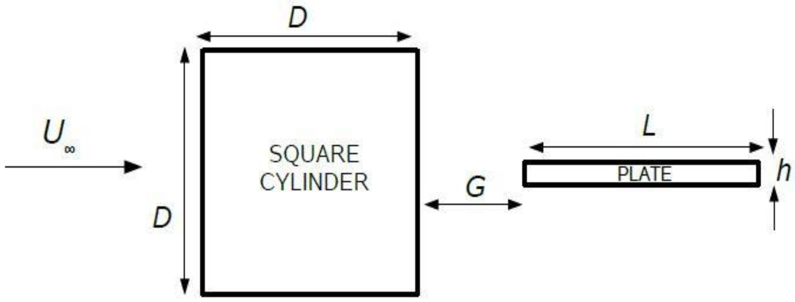


Figure 2. Problem geometry for square cylinder D = 10 mm with detached flat-plate.

3. Experimental Results

3.1. Acoustic spectra of reference cases

The acoustic spectra obtained using data recorded using the central microphone directly above the test rig for the reference cases (square cylinder of side length D) with no thin detached flat-plate is shown in Fig. 3. Free-stream velocity was varied from 25 m/s to 37 m/s. In the lower frequency range (~250 Hz to 450 Hz) a peak was observed at all speeds and the intensity of this peak was found to reduce as the free-stream velocity was reduced from 37 m/s to 25 m/s. These peaks represent the Aeolian tones generated by the square cylinder and it is evident from Fig. 3 that there is reduction in the magnitude of the Aeolian tone and broadband noise as the free-stream velocity reduces.

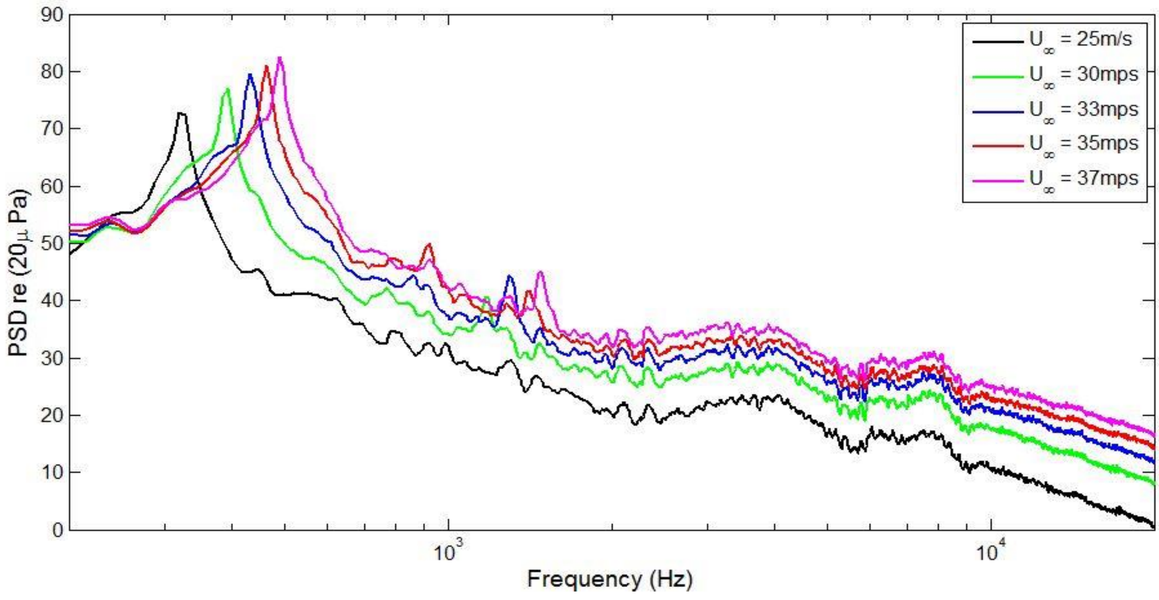


Figure 3. Comparison of acoustic spectra for square cylinder (reference case) at U_∞ = 25m/s, 30 m/s, 33 m/s, 35 m/s and 37 m/s.

3.2. Acoustic spectra of test cases with thin detached flat-plate

Figure 4 shows acoustic spectra against frequency plots for square cylinder (reference case) and different gap distances varying between $0 \leq G \leq 4D$ with freestream velocity of 30 m/s (Re = 1.870 x 10^4). It is evident that the magnitude of the Aeolian tone reduces when a thin detached flat-plate is attached to the rear surface of the square cylinder (G = 0). Previous numerical studies at low Reynolds number by Ali and Doolan [10, 14] concluded that critical gap distance G_c exists at $2.3D$. It is clear from Fig.4 that magnitude of Aeolian tone reduces when the gap distance is varied till it reaches $3D$. Any further increment in the gap distance G results in sudden increment in magnitude of Aeolian tone which is in agreement to the findings in the numerical studies by Ali and Doolan [10, 14], albeit this critical distance has increased at these higher Reynolds numbers.

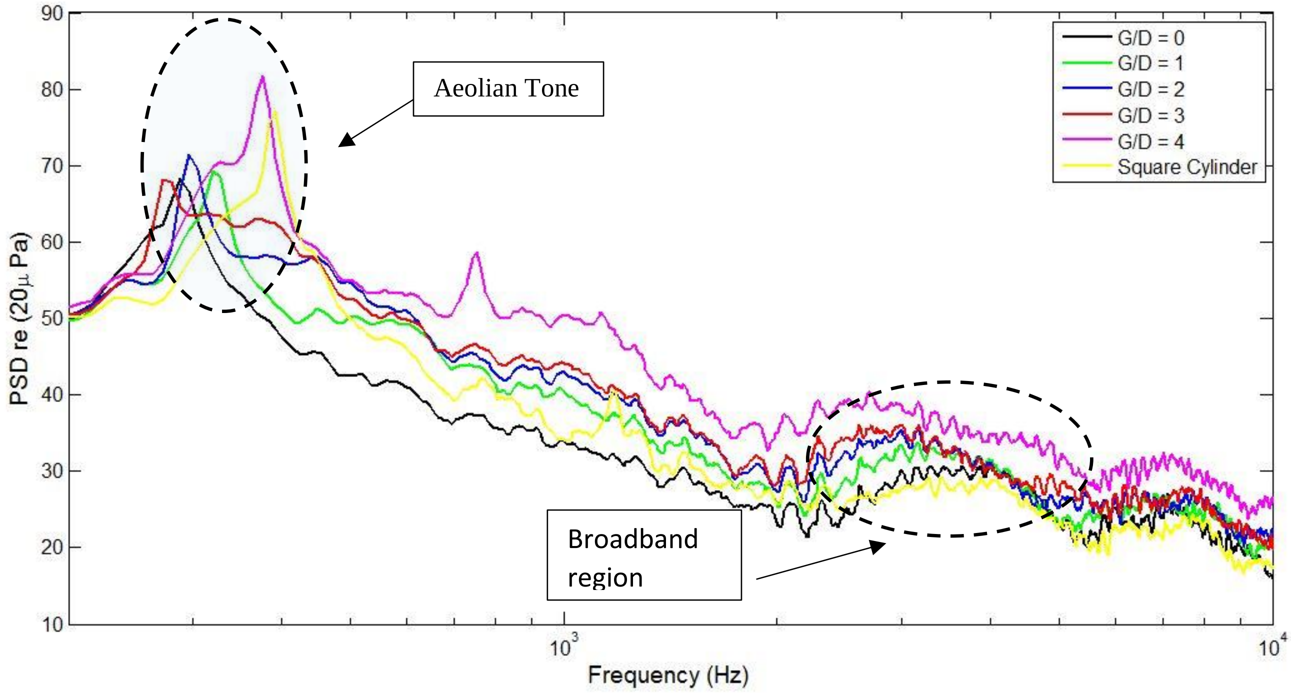


Figure 4. Comparison of acoustic spectra for square cylinder (reference case) and G/D = 0, 1, 2, 3, 4 at U_∞=30m/s

A comparison of magnitude of Aeolian tone (in dB) at free-stream velocity ranging from 25 m/s to 37 m/s for different gap distances varying between $0 \leq G \leq 4D$ is presented in Fig. 5. It was observed that when thin detached flat-plate was placed in the wake of square cylinder (test case G/D = 0) the magnitude of Aeolian tone was approximately reduced by 9 dB. Furthermore, when the gap distance was increased the magnitude of Aeolian tone increased but remained to be less than the magnitude of square cylinder (reference case). Any further increment in the gap distance above $G = 3D$ resulted in approximately 4.5 dB increase in the magnitude of Aeolian tone. Thus an average reduction of approximately 7 dB was observed when gap distance was varied in the range of $0 \leq G \leq 3D$.

3.3. Variation in Strouhal number (*St*) with gap distance (*G*)

Previous experimental studies concerning square cylinders notes that Strouhal number should be approximately 0.148 to 0.155, see Refs. [8, 14, 15]. Figure 6 shows variation in Strouhal number with change in gap distance at different free-stream velocities ranging from 25 m/s to 37 m/s.

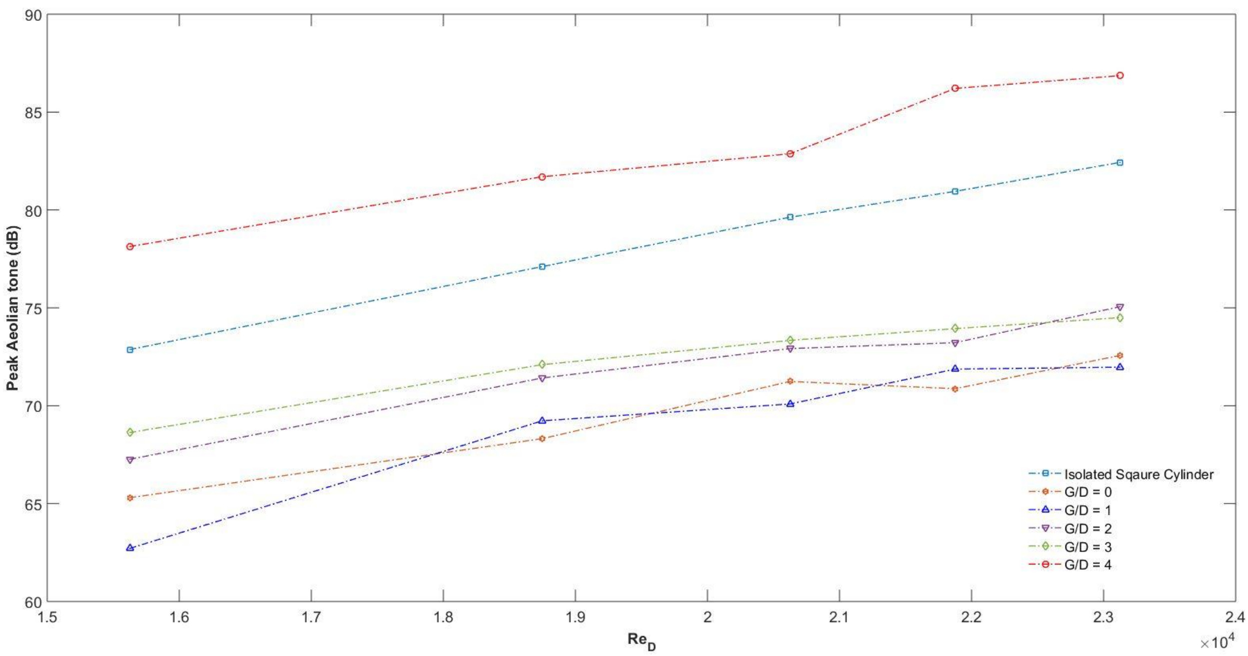


Figure 5. Comparison of magnitude of Aeolian tone generated by an isolated square cylinder and at G/D = 0, 1, 2, 3, 4 at U_{∞}= 25 m/s, 30 m/s, 33 m/s, 35 m/s and 37 m/s.

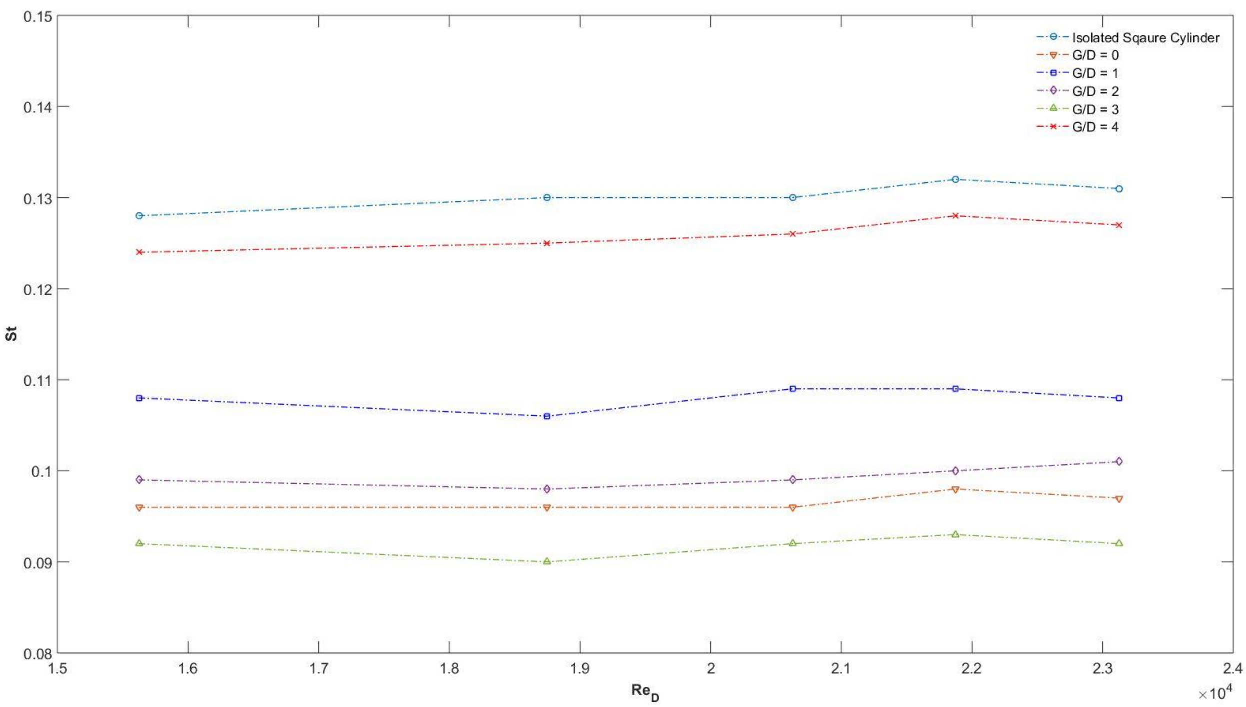


Figure 6. Comparison of Strouhal number by an isolated square cylinder and at G/D = 0, 1, 2, 3, 4 at U_{∞}= 25 m/s, 30 m/s, 33 m/s, 35 m/s and 37 m/s.

Table 1 presents the Strouhal number at peak vortex shedding frequency generated at different free-stream velocity corresponding to gap distance $0 \leq G \leq 4D$. It was found that when thin detached flat-plate was introduced in wake of square cylinder, Strouhal number was reduced from 0.137 to 0.097 at U_∞= 37 m/s.. Table 1 summarises the changes in Aeolian tone Strouhal number.

Table 1. Strouhal number of Aeolian tone at different free-stream velocity for G/D = 0, 1, 2, 3 and 4.

G/D	**Strouhal Number at peak frequency**				
	U_∞= **25 m/s**	U_∞= **30 m/s**	U_∞= **33 m/s**	U_∞= **35 m/s**	U_∞= **37 m/s**
Square Cylinder	0.128	0.130	0.130	0.132	0.131
0	0.096	0.096	0.096	0.098	0.097
1	0.108	0.106	0.109	0.109	0.108
2	0.099	0.098	0.099	0.100	0.101
3	0.092	0.090	0.092	0.093	0.092
4	0.124	0.125	0.126	0.128	0.127

4. Conclusion

An experimental aeroacoustic study showed that a thin flat plate placed in the wake of a square cylinder significantly modified the amplitude and frequency of the Aeolian tone. Noise level was found to be sensitive to the change in the gap distance *G*. Approximately 7 dB noise reduction was achieved when the gap distance was 3*D*. Any further increase in the gap distance resulted in an increase in sound pressure level. These results were found to be in general agreement to the previous numerical investigations of using flat-plate for reduction of noise by bluff bodies [10, 14], although some specific details (such as the critical distance where sound level increases, noise level changes and frequency changes) were different. These differences are attributed to the much higher Reynolds numbers of the experiments compared with the numerical studies. Simulations at higher Reynolds numbers range are required to in order to explain the observed differences.

Acknowledgement

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