

On the Flow and Noise of a Two-Dimensional Step Element in a Turbulent Boundary Layer

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Abstract This paper presents results of a study on the flow and noise generated by two-dimensional step elements attached to a flat plate. The step elements used in this study are equivalent to a forward–backward facing step pair and have length to height ratio of $l/h = 8, 4$ and 2.7 . Aerodynamic and acoustic measurements have been taken in an anechoic wind tunnel at the University of Adelaide. Numerical simulations of turbulent boundary layer flow over the step with $l/h = 2.7$ are also presented. The data given in this paper provide fundamental information on how a sub-boundary layer step element affects the noise and flow field.

Keywords Sub-boundary layer step noise · Step flow

1 Introduction

Aerodynamic sound is an important source of the noise produced by modern air, land and underwater vehicles. Surface discontinuities due to rivets, ribs, joints, environmental contamination or errors in machining can disturb the turbulent boundary layer that develops over a vehicle and generate increased levels of aerodynamic noise. Given the prevalence of surface discontinuity noise, it is important from a practical design perspective that this noise source is well understood and the baseline case of a step element attached to a flat plate is ideal for such a fundamental investigation. Previous research on step flows has largely focused on aerodynamic aspects of problem (Moss and Baker 1980) and the backward facing step is the most commonly studied configuration (Jacob et al. 2001). Leclerq et al. (2001) have conducted one of the few experimental studies on

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the sound generated by flow over a forward–backward facing step pair with length to height ratio of $l/h = 10$. This paper presents results of a study on the flow and noise generated by a two-dimensional forward–backward facing step pair with $l/h = 8, 4$ and 2.7 in low Mach number turbulent flow. Aeroacoustic measurements taken in an anechoic wind tunnel at the University of Adelaide are presented along with a numerical simulation of turbulent boundary layer flow over the step element with $l/h = 2.7$.

2 Experimental Method

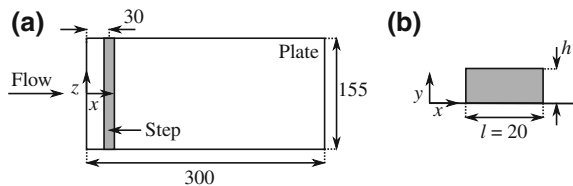
Experiments were conducted in the University of Adelaide’s anechoic wind tunnel with rectangular test section of 275 mm (width) \times 75 mm (height) (Moreau et al. 2011). The test model consists of a rectangular step element attached to a flat plate as shown in Fig. 1. Three different step elements are used in this study with height of $h = 2.5, 5$ and 7.5 mm corresponding to 26, 52 and 77 % of the local unperturbed boundary layer thickness. The step elements are located (one at a time) on the flat plate at a distance of 30 mm downstream of the jet exit plane.

Acoustic measurements were recorded at two locations using two B&K 1/2 inch microphones (No. 4190). The first microphone was located at an observer angle of $\theta = 90^\circ$ to the step at $x = 30, y = 137.5, z = 520$ mm while the second microphone was located at an angle of $\theta = 45^\circ$ to the step at $x = 550, y = 137.5, z = 520$ mm. Hot-wire anemometry was used to measure the mean flow velocity and turbulence characteristics downstream of the step. The sensor used was a TSI 1210-T1.5 single wire probe connected to a TSI IFA300 constant temperature anemometer system and positioned using a Dantec automatic traverse. Experiments were conducted at a flow speed of $U_\infty = 35$ m/s. Acoustic and flow data were recorded using a National Instruments board at a sampling frequency of 5×10^4 Hz for a sample time of 8 and 4 s, respectively.

3 Experimental Results

One-third-octave band noise spectra at the two observer locations for the side plate with and without a step are shown in Fig. 2. This figure shows the sound radiated by the step is broadband in nature and increases with step height. The smallest step

Fig. 1 Step element attached to the plate. **a** Front and **b** side view. Dimensions in mm



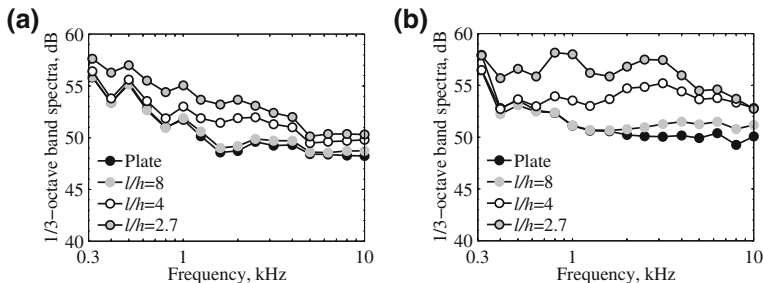


Fig. 2 One-third-octave band spectra at an observer angle of **a** $\theta = 90^\circ$ and **b** $\theta = 45^\circ$

with $l/h = 8$ only slightly increases the noise levels above those of the plate (no step) at high frequencies (above 1 kHz). In comparison, the spectra for the step with $l/h = 2.7$ sit well above the plate spectra at all frequencies, especially at an observer angle of $\theta = 45^\circ$. The step is expected to act as a dipole noise source which explains the higher levels of noise measured at an angle of $\theta = 45^\circ$.

Figures 3 and 4 show the normalised mean velocity (U/U_∞) and rms velocity (u'/U_∞) profiles measured at two locations downstream of the step. The mean velocity profiles show a significant increase in the boundary layer thickness with step height and downstream distance. The rms velocity profiles show the turbulent energy levels in the boundary layer downstream of the step increase with step height. Additionally, the point of maximum energy occurs further from the plate surface as step height is increased. The turbulent intensity peaks are observed to reduce in amplitude and move further from the plate surface as the measurement location moves further downstream of the step.

Spectral maps of the fluctuating velocity measured 50 mm downstream of the step in Fig. 5 show a significant increase in low frequency energy content (below 500 Hz) as the step height is increased. In agreement with the rms velocity profiles, regions of intense low frequency energy move further from the plate surface with increasing step height.

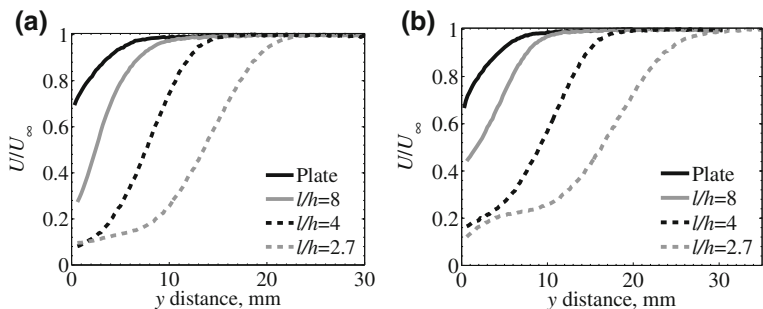


Fig. 3 Normalised mean velocity profiles at **a** 20 and **b** 50 mm downstream of the step

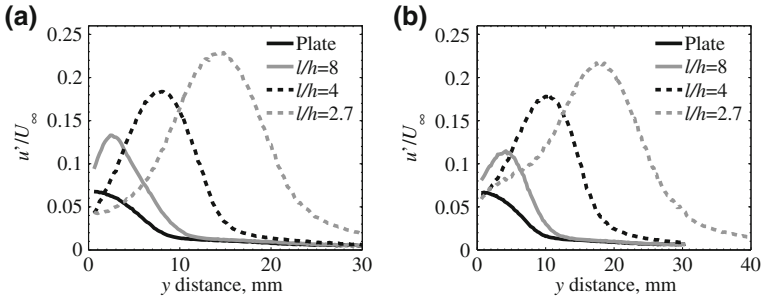


Fig. 4 Normalised rms velocity profiles at **a** 20 and **b** 50 mm downstream of the step

4 Numerical Simulation

A large eddy simulation (LES) of the experimental test case of flow over the step element with $l/h = 2.7$ was performed. The simulation used the one equation eddy model on a structured hexahedral mesh of 1.775×10^6 cells with upstream, vertical, downstream and cross-stream boundaries of 10, 30, 12.5 and 0.05 l , respectively. The LES was run from a steady state Reynolds Averaged Navier–Stokes solution using the realisable $k-\epsilon$ model for over 20 freestream passes (0.0115 s) of the step element, with statistical averages gathered over the final 10 freestream passes (0.00573 s).

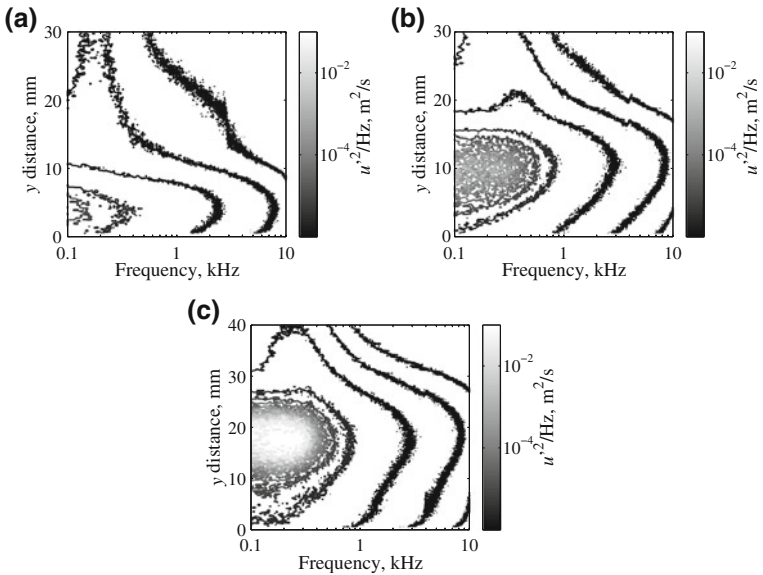


Fig. 5 Velocity spectral maps 50 mm downstream of the step with l/h of **a** 8, **b** 4 and **c** 2.7

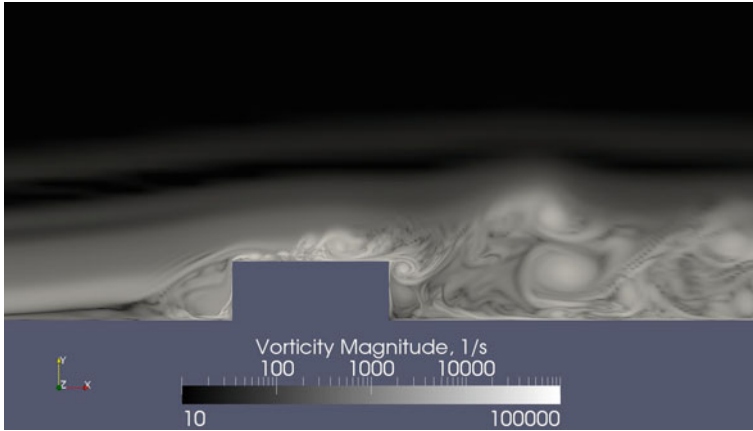


Fig. 6 Instantaneous vorticity magnitude at time $t = 0.0068$ s for the step with $l/h = 2.7$

Figure 6 shows instantaneous vorticity magnitude of flow over the step at time $t = 0.0068$ s. A recirculation region can be seen upstream of the step leading edge which periodically ejects flow onto the top surface of the step in the leading edge region. Vortices form at the leading and trailing edge corners and large vortex structures are observed downstream of the step. This is in agreement with the velocity spectral map in Fig. 5c which shows a region of high energy low frequency fluctuations downstream of the step. The reattachment point was determined from the mean flow field to occur at $9.9 h$ (74.1 mm) downstream of the step which is in broad agreement with the findings of others (Mohsen 1967).

5 Conclusion

A study on the flow and noise produced by a sub-boundary layer step element has been presented in this paper. Experimental results include far-field noise spectra as well as information on the mean and unsteady turbulent characteristics downstream of the step. A numerical simulation of flow over the step element has also been presented providing information on the important features of the flow field.

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