Experimental Thermal and Fluid Science 72 (2016) 47–58

Contents lists available at ScienceDirect

Experimental Thermal and Fluid Science

journal homepage: www.elsevier.com/locate/etfs

Flow-induced noise generated by sub-boundary layer steps

Con J. Doolan *, Danielle J. Moreau

School of Mechanical and Manufacturing Engineering, The University of New South Wales, Sydney, NSW, 2052, Australia

ARTICLE INFO

Article history:
Received 27 April 2015
Received in revised form 21 October 2015
Accepted 22 October 2015
Available online 11 November 2015

Keywords:
Sub-boundary layer step
Flow-induced noise

ABSTRACT

The sound generated by a turbulent boundary layer with a smaller two-dimensional step was investigated and related to the perturbed flow field via a new scaling law. Experimental results were obtained using two types of sub-boundary layer steps (rectangular and triangular). Flow visualisation revealed an upstream separation zone and a downstream reattachment point. The sub-boundary layer steps, in general, resulted in a rapid thickening of the shear flow near the wall. The integral boundary layer results show the effect of the steps on the boundary layer can be likened to a disturbance followed by a boundary layer re-establishment region. The noise data revealed the nature of the noise created by the steps. The steps can be considered as acoustically compact (height much less than acoustic wavelength) and radiate noise in both streamwise and cross stream directions, suggesting the existence of compact superimposed dipole sources. The shape of the step has a large effect on the noise level, suggesting the front surface of the step has a dominant role in noise production. A new scaling law based on the perturbed boundary layer height was able to successfully collapse the noise data.

1. Introduction

The surfaces of submarines, aircraft and other vehicles exposed to fluid flow are not smooth; they contain many small surface irregularities (due to manufacturing processes, corrosion, biofouling, doors, hatches, sonars, fasteners, etc.) that cause many small zones of flow separation and reattachment. The hydrodynamic pressure field of these separated flow zones interact with surface irregularities to create a complex, broadband noise field that must be more completely understood in order to reduce noise from transportation and industrial flow equipment. While there have been many studies of the flow and noise created by obstacles that are larger than the boundary layer [1–3], there are few that concern themselves with the noise created by obstacles that are smaller than the boundary layer that approaches them. These so-called *sub-boundary layer steps* are the topic of this paper.

The flow field created by two-dimensional obstacles that are of the same order as the boundary layer they are immersed in has been studied in reasonable detail previously [4–12]. Most studies concentrate on either forward-facing or backward-facing sharp-edged steps, and a sub-set of these are concerned with the two-dimensional forward–backward facing step pair (or wall-mounted rectangular prism). None consider alternate geometries, apart from Agelinchaab and Tachie [10], who investigate a two-dimensional semi-circular wall-mounted block. The general flow structure for the forward-facing step and rectangular step-pair is similar and is illustrated in Fig. 1. It consists of a region of upstream separation (extending a distance x_U upstream of the step front face), a perturbed flow region where the boundary layer is separated from the surface and a reattachment point that occurs a distance x_R downstream. Note that this reattachment point is shown here to occur beyond the trailing edge of the step, but may reattach on the top surface of the step in some instances. A flow recovery region exists after the reattachment point, where the turbulent boundary layer begins to re-establish itself. The flow field about the step is dominated by the perturbed flow region which must affect noise production through the development of unsteady surface pressures on the obstacle.

Sherry et al. [11] provide a good review of mostly forward-facing step flows, showing that x_R is sensitive to the ratio of step height to undisturbed boundary layer height (h/δ) and Reynolds number based on step height (Re_h). This review showed that for $0.2 \lesssim h/\delta \lesssim 3$ and $1000 \lesssim Re_h \lesssim 50,000$, the reattachment length varies $x_R/h = 1.4 - 5$. Schofield and Logan [6], who concentrate their work on the two-dimensional sub-boundary layer rectangular step-pair in plate and pipe boundary layers, suggest that the reattachment length may extend to $x_R/h \gtrsim 10$. The variability of the value of x_R is due to the effects of turbulent mixing in the separated shear layer that dominates the perturbed flow region [11]. The level of mixing is controlled by both the step height relative to boundary layer (h/δ) and the Reynolds number (Re_h). Sherry et al. [11] show that there are two regimes, defined by a critical

---

* Corresponding author.

http://dx.doi.org/10.1016/j.expthermflusci.2015.10.024

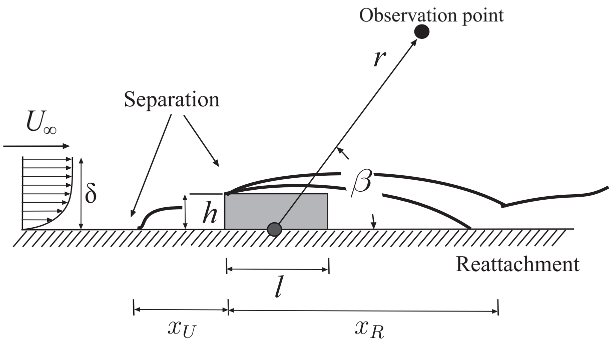

Fig. 1. Illustration of the sub-boundary layer forward–backward step-pair flow field, major parameters and coordinate system (not to scale).

Reynolds number ($Re_h \sim 8500$), below which the perturbed flow regime is controlled by a transitional separated shear layer, and above the perturbed flow region can be understood in terms of turbulent separation and reattachment. Similarly, when $h/\delta < 1$ the obstacle is affected by the particular flow structures it encounters within the boundary layer. As the height of the step becomes smaller, the momentum of the on-coming flow that interacts with the front face of the step is reduced, reducing x_R/h. Conversely, when $h/\delta > 1$, x_R/h increases.

The turbulent structures that approach and interact with the step will affect mixing and the perturbed flow region. However, this will be controlled by the upstream separation region. While the size of the upstream separated region is of the same order as the step ($x_U/h \sim 1$) [4,7], the relationship between Re_h, the flow structures and turbulent mixing in the perturbed region is still not well understood, despite notable recent work [13].

Noise from backward-facing steps immersed in laminar and turbulent boundary layers ($h/\delta = 0.45$–5, $Re_h = 23{,}000$) were first studied by Farabee and Zoccola [14]; however, they were not able to detect a signal above the background level of the wind tunnel. Jacob et al. [15] were able to measure noise from backward-facing steps under a wall jet ($h/\delta = 0.07$–0.43, where δ in this case is the wall jet thickness, $Re_h = 57{,}000$–$343{,}000$ and wall jet Mach number $M_j = 0.17$–0.4). They showed the source was approximately $2h$ downstream of the step and radiates more strongly upstream with an intensity proportional to $U_j^{6.2}$, where U_j is the wall jet velocity.

Farabee and Zoccola [14] also presented noise data from forward-facing steps ($Re_h = 13{,}000$–$38{,}000$, $h/\delta = 0.25$–0.47) and showed that noise level was weakly dependent on step height and was proportional to U_∞^7, where U_∞ is the free stream velocity. Becker et al. [16] presented data from an aeroacoustic study of a forward facing step ($Re_h \sim 24{,}000$, h/δ unspecified) and the reported noise level was proportional to U_∞^6.

Ji and Wang [17] performed a computational investigation of forward-facing and backward-facing steps ($Re_h = 328$–$21{,}000$, $h/\delta = 0.0083$–0.53). Computational aeroacoustics simulations can either be carried out using a direct approach, where the full compressible Navier Stokes equations are solved in the time domain and acoustic waves resolved to the free-field, or using a hybrid approach, where an analytical acoustic analogy is used with the hydrodynamic data from a numerical flow simulation [18]. Ji and Wang [17] use a hybrid approach because it allows computational resources to be concentrated upon the fluid dynamics, rather than propagation of acoustic waves. Their results agree with previous experimental measurements, in that for large h/δ, the sound from backward-facing steps is much lower than forward facing ones. This was found to occur because the sound sources were located further from the backward step than the front step. Further, sound is created at the backward step via a diffraction process, whereas the front step modifies the turbulent flow, creating strong sources of sound near the step. As step height reduces, this turbulence modification becomes less significant, and the noise source strengths of the forward and backward steps become comparable.

Catlett et al. [19] performed a comprehensive experimental study of forward-facing and backward-facing steps ($Re_h = 3000$–$72{,}000$, $h/\delta = 0.085$–1.02) under a wall jet, as well as symmetric and non-symmetric gaps. For the step cases, forward-facing steps produced noise 10 dB higher than backward facing steps, agreeing with previous studies. Noise data collapsed on each other when frequency was normalised by undisturbed δ and U_j, and levels were scaled with h and U_j^5.

Catlett et al. [19] also observed the effects of acoustic non-compactness (meaning that the height of the step is of the same order or larger than the acoustic wavelength) in the far-field autospectra, which manifested itself as regions of destructive

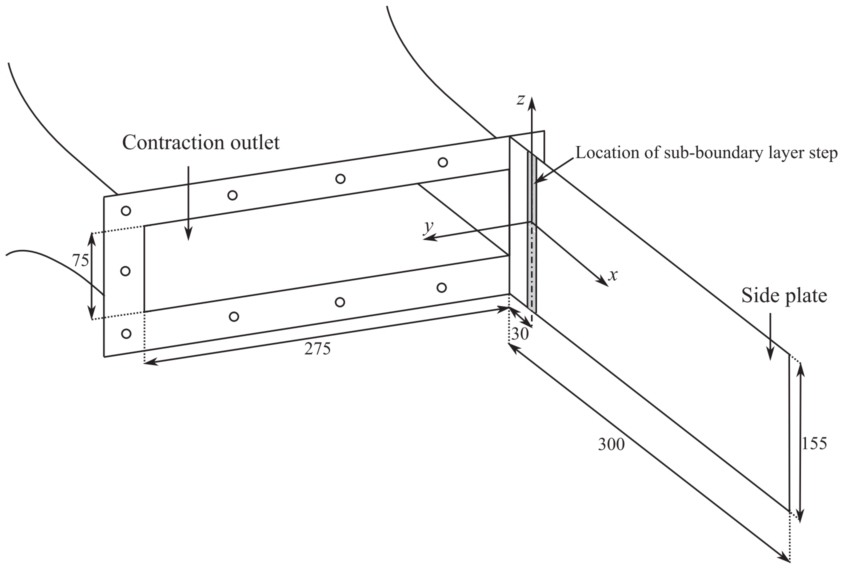

Fig. 2. Side plate showing location where the steps are attached to the contraction outlet. Dimensions are given in mm.