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Tonal noise production from a wall-mounted finite airfoil

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ABSTRACT

This study is concerned with the flow-induced noise of a smooth wall-mounted finite airfoil with flat ended tip and natural boundary layer transition. Far-field noise measurements have been taken at a single observer location and with a microphone array in the Virginia Tech Stability Wind Tunnel for a wall-mounted finite airfoil with aspect ratios of $L/C = 1$–3, at a range of Reynolds numbers ($Re_C = 7.9 \times 10^5$–1.6×10^6, based on chord) and geometric angles of attack ($\alpha = 0$–6°). At these Reynolds numbers, the wall-mounted finite airfoil produces a broadband noise contribution with a number of discrete equispaced tones at non-zero angles of attack. Spectral data are also presented for the noise produced due to three-dimensional vortex flow near the airfoil tip and wall junction to show the contributions of these flow features to airfoil noise generation. Tonal noise production is linked to the presence of a transitional flow state to the trailing edge and an accompanying region of mildly separated flow on the pressure surface. The separated flow region and tonal noise source location shift along the airfoil trailing edge towards the free-end region with increasing geometric angle of attack due to the influence of the tip flow field over the airfoil span. Tonal envelopes defining the operating conditions for tonal noise production from a wall-mounted finite airfoil are derived and show that the domain of tonal noise production differs significantly from that of a two-dimensional airfoil. Tonal noise production shifts to lower Reynolds numbers and higher geometric angles of attack as airfoil aspect ratio is reduced.

1. Introduction

The interaction of flow with a wall-mounted finite airfoil is an important source of sound in many situations of engineering interest such as turbomachinery blade and end-wall flows, aircraft wing and body junction flows and ship appendage and hull junction flows. While a large body of literature exists describing experimental studies of airfoil noise [1–8], these have focused on two-dimensional or semi-infinite airfoils with the noise mechanisms now reasonably well identified [2]. In comparison, the noise generated by a wall-mounted finite airfoil is not as well understood. The flow around a wall-mounted finite airfoil is more complicated as it is three-dimensional, with boundary layer impingement at the airfoil-wall junction and flow over the airfoil tip. How these flow features and airfoil three-dimensionality affect noise production is the focus of the present experimental study on wall-mounted finite airfoil noise.

The three-dimensional flow structure of a wall-mounted finite airfoil is shown in Fig. 1. At the airfoil-wall junction, a horseshoe vortex forms at the airfoil leading edge with streamwise legs of opposite rotational sense that stretch around the

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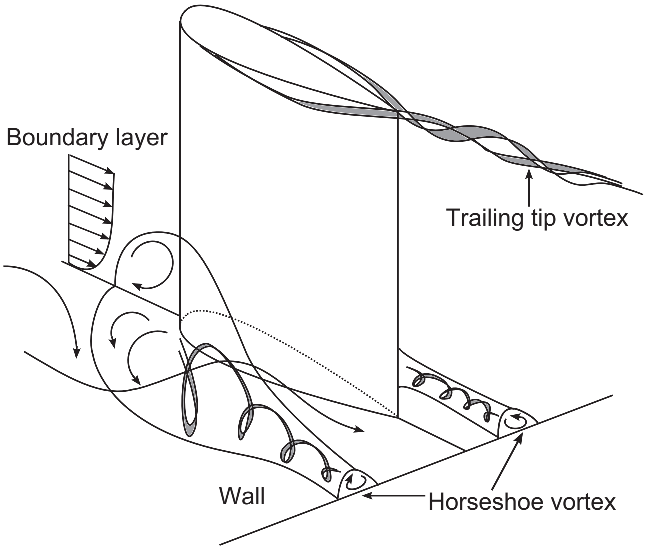

Fig. 1. Flow structure of a wall-mounted finite airfoil.

airfoil base and convect downstream [9,10]. This vortical flow structure forms due to the large adverse pressure gradients created by the airfoil that cause the incoming boundary layer to separate and then roll up around itself. In addition to a horseshoe vortex at the junction, vortex structures may also form at the airfoil tip. This vortical flow is convected downstream of the trailing edge and eventually forms a trailing vortex. At zero angle of attack, the flow profile about the airfoil tip is symmetric and formed by a pair of counter-rotating vortices. These vortices form on the sides of the airfoil and are fed by downwash at the tip [11]. At non-zero angle of incidence, the pressure difference between the airfoil pressure and suction side accelerates the flow around the tip and this, combined with flow moving in the streamwise direction, produces multiple vortices on the tip surface that merge and interact to form the trailing tip vortex system [12–14].

For a wall-mounted finite airfoil in low Mach number flow, the flow structure and hence the radiated sound will depend on Reynolds number, aspect ratio (L/C, where L is the airfoil span and C is the airfoil chord), airfoil geometry, the nature of the boundary layer on the airfoil surface and the incoming wall boundary layer thickness [11,15]. A recent study by the authors' [16] examined the effect of airfoil aspect ratio and flow speed on wall-mounted finite airfoil noise at zero angle of attack and low-to-moderate Reynolds numbers of $Re_C = 9.2 \times 10^4$–1.6×10^5, based on chord. The wall-mounted finite airfoil was found to radiate noise similarly to a two-dimensional airfoil when $L/C > 1$ with junction and tip flow suppressing tonal noise production for airfoil's up to $L/C = 1$.

Only two other experimental studies of wall-mounted finite airfoil noise have been reported in literature. In the early work of Kendall [17], wall-mounted finite airfoil noise was examined using a tripped NACA 0012 airfoil with an aspect ratio of $L/C = 2.3$ at a Reynolds number of $Re_C = 2.8 \times 10^5$ and geometric angles of attack to $\alpha = 13°$. Measurements taken with a directional microphone system showed that the dominant noise source was located at the corner of the airfoil tip and trailing edge. Later, Brooks and Marcolini [18] examined the sound produced by a wall-mounted finite airfoil in an effort to develop a tip vortex noise model. In their study, acoustic measurements were taken for a tripped wall-mounted finite NACA 0012 airfoil with 5 different aspect ratios between $L/C = 1$–6 at Reynolds numbers of up to $Re_C = 1 \times 10^6$ and geometric angles of attack to $\alpha = 14.4°$. By comparing the sound generated by the three-dimensional airfoils to that of their two-dimensional counterpart, a semi-empirical tip noise model was developed.

Airfoil tip noise generation has also been investigated in studies on flap side-edge noise [19–23]. The noise radiation of flat, flanged and round flap-edge geometries was examined by Brooks and Humphreys [22] with the acoustic spectra for each configuration found to scale with flow speed, flap angle and surface roughness based on their aerodynamic and boundary layer properties. Recently, Guo [21] developed a semi-empirical prediction model of flat tip flap side-edge noise. In this model, high frequency noise is attributed to flow separation near the sharp corners of the forward half of the tip and low-to-mid frequency noise is due to vortex interactions with the sharp corners of the aft half of the tip. Noise predictions obtained with the model were found to compare well with experimental noise data when certain scaling parameters were used. Using a similar modelling approach to Guo [21], Rossingol [23] developed a semi-empirical prediction model for flat tip flap side-edge noise that requires only the flap chord length and lift coefficient to produce accurate estimates of the far-field noise radiation.

Published information on the flow-induced noise mechanisms of a wall-mounted finite airfoil is scarce. In particular, no prior study has examined noise measurements for a wall-mounted finite airfoil at high Reynolds numbers ($Re_C > 1 \times 10^6$) with natural boundary layer transition nor has any study investigated how aspect ratio and angle of attack affect noise generation under these conditions. This paper presents a novel experimental investigation of the flow-induced noise produced by a wall-mounted finite airfoil with natural boundary layer transition performed in the Stability Wind Tunnel at