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Surface curvature effects on the tonal noise performance of a low Reynolds number aerofoil

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ABSTRACT

This paper presents wind tunnel experiments to illustrate the effects of surface curvature on the aeroacoustic performance of airfoil E387. For the first time, surface curvature effects are considered in an investigation of the airfoil's self-noise. To distinguish the effects of surface curvature, the CIRCLE method is applied to the airfoil E387 to remove slope-of-curvature discontinuities and the redesigned airfoil is denoted A7. Anechoic wind tunnel tests were performed with E387 and A7 at three low Reynolds numbers to investigate aeroacoustic performance by measuring airfoil self-noise at different angles of attack (AoA) and spatial positions. At 2° and 4° AoA, A7 presents a tone with a reduced amplitude compared with E387 due to its improved slope-of-curvature distribution. It is concluded that improving surface curvature distribution improves airfoil aeroacoustic performance.

1. Introduction

At low Reynolds numbers the flow on an aerofoil separates due to a sufficiently large magnitude of the adverse pressure gradient and changes in flow geometry including local surface curvature variations. The flow experiences transition to turbulence and can result in a stall (without turbulent re-attachment) or a laminar separation bubble (with turbulent re-attachment) [1]. The turbulence produced in the boundary layer and near wake interacts with the aerofoil surface, producing aerofoil self-noise which contains tonal and broadband noise at low Reynolds numbers.

The mechanism of tonal noise has been researched since 1970s and it is often treated as a low Reynolds number phenomenon [2]. Most researchers [3–5] believe that this sound amplifying phenomenon occurs at certain frequencies via an acoustic feedback mechanism in the vicinity of the trailing edge. Sandberg et al. [6] suggested that the unsteady wake interacting with the trailing edge and pressure fluctuations due to vortex shedding are also responsible for the tonal noise generation, which is consistent with the category of Brooks et al. [7]. They also indicated that the aerofoil profile geometry affects the flow wake frequency. Desquesnes et al. [8] proposed a secondary feedback loop mechanism. They pointed out that the instabilities of boundary layer from suction side of the aerofoil are also important to the tone noise generation while the main tone noise frequency is decided by the boundary layer before the separation bubble along the pressure side. It has been found that for a symmetric aerofoil at zero angle of attack, the primary tonal noise amplitude decreases with the increasing of Reynolds number [9], the reasons why airfoils at low Reynolds numbers produce high levels of tonal noise still remains unclear.

It must be noted that the main attentions of the research works performed on the tonal noise mechanisms are paid on symmetric aerofoils, especially NACA0012. Little attention was paid to asymmetric aerofoils which also exhibit tonal noise phenomenon as will be presented in this paper. It should also be noticed that the experimental studies reviewed above may vary from each other depending on the testing conditions, e.g., the differences of turbulence intensity in the testing sections [10], the manufacturing precision of the testing aerofoil especially the surface finishing, etc. Although there are several different proposed mechanisms [5,8,9,11,12] regarding the generation of tonal noise, it is agreed that a necessary condition for acoustic tones is that the laminar separation bubble (LSB) is adequately close to the TE of the aerofoil, i.e., the position of laminar-turbulent transition must be sufficiently down-

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stream so the large scales in the flow can be presented near the TE. This necessary condition has been used in the hypothesis of Jones et al. [13] on the feedback loop that can promote tonal noise in turbulent flows.

On the other hand, in terms of surface curvature effects, researchers have shown that aerofoil boundary layer behavior can be improved by making the curvature distribution of an aerofoil continuous and smooth [14,15]. The idea came originally from high-efficiency turbomachinery blade design, in which the distribution of surface curvature is an important factor [16,17]. Massardo et al. [18,19] used streamline curvature distribution calculations to determine the 3D variation of inlet and outlet flow angles for axial-flow compressor design and improved the compressor efficiency. Korakianitis et al. proposed a design method [20] to optimize aerofoils by ensuring continuous distributions of curvature and gradient-of-curvature along the surfaces, and showed that the aerodynamic and heat transfer performance strongly depended on curvature and gradient-of-curvature distribution. Based on surface curvature distribution, Song et al. [21] showed that continuous curvature distribution at the LE blending position of a compressor blade improves performance by helping to eliminate the separation bubble.

On low Reynolds number airfoils, researchers found that surface curvature and slope-of-curvature have impacts on the behaviour of the boundary layer on an airfoil by affecting the size of the laminar separation bubble (LSB). Korakianitis et al. [22] applied smooth curvature distributions to two wind turbine airfoils and numerically presented the aerodynamic improvements of the airfoils. Based on that, Shen et al. [23] expanded the work to three Reynolds numbers and a range of angles of attack, and they numerically [24] and experimentally [25] concluded that continuous surface curvature and slope-of-curvature distributions improved the aerodynamic performance through the effects on the laminar boundary layer including the LSB size contraction. These effects on the LSB size at low angles of attack have potential effects on the on airfoil acoustic performance in low Reynolds numbers, especially the tonal noise performance. Hence in this paper we experimentally examine the effects of slope-of-curvature on the aeroacoustic tonal noise performance of an airfoil.

The CIRCLE method [26] is used to redesign the airfoil by removing the slope of surface curvature discontinuities from LE to TE. A typical low Reynolds number airfoil E387 is judiciously selected for the investigation due to the existence of discontinuities of slope-of-curvature, its widespread use and the availability of detailed experimental measurements of airfoil performance [27,28]. The newly designed airfoil is denoted as “A7”. Both airfoils are manufactured in Queen Mary University of London (QMUL). The anechoic wind tunnel experiments were carried out in Beihang University. The experimental results of two airfoils are compared to analyze the aeroacoustic performance differences caused by the different curvature distributions. These experimental measurements deepen our knowledge of the effects of slope-of-curvature discontinuities on the airfoil self-noise including tonal noise.

2. Redesign of the airfoil E387 with the CIRCLE method

Many airfoil geometries including E387 have discontinuities in surface slope-of-curvature distributions [26]. These discontinuities are observable as unsmooth “kinks” in airfoil curvature distributions. A smooth curvature distribution is equivalent to a continuous slope-of-curvature distribution. Based on this, the CIRCLE method, which was previously documented [26], is applied to the airfoil E387 to remove the discontinuities in slope-of-curvature distributions. The original and redesigned airfoils are presented in Fig. 1. The curvature distributions are presented in Fig. 1(a) and the geometries are compared in Fig. 1(b). The curvature distributions are calculated from the definition of surface curvature, as shown in Eq. (1), and the definition of slope-of-curvature is presented in Eq. (2). The sign of the curvature is usually defined as the direction of the unit tangent vector moving along the curve. In order to clearly present the curvature distributions of both suction and pressure sides simultaneously, we define curvature as positive if the vector rotates clockwise (suction side) from the LE, otherwise it is negative (pressure side).

$$Curv = \frac{1}{r} = \frac{y''}{(1+y'^2)^{(3/2)}} \tag{1}$$

$$Curv' = \frac{d(Curv)}{dx} = \frac{y'''(1+y'^2) - 3y'y''^2}{(1+y'^2)^{(5/2)}} \tag{2}$$

In Fig. 1(a) the unsmooth parts (slope-of-curvature discontinuities) including two obvious “kinks” in the magnified figure are exhibited on both sides of the airfoil E387, although most of the slope-of-curvature discontinuities are in the suction surface. The airfoil A7 has a smooth curvature distribution without any slope-of-curvature discontinuities. The continuous slope-of-curvature distribution of A7 results in very slight differences in thickness and camber distributions.

3. Experimental facility and measurement techniques

Anechoic wind tunnel measurements were performed to the original airfoil E387 and the redesigned airfoil A7 at chord-length based Reynolds number 100,000, 200,000 and 300,000 to investigate their aeroacoustic performance. The airfoil self-noise was measured at different angles of attack (AoAs) and different spatial positions.

3.1. Wind tunnel facility

This experimental study was conducted in the D5 subsonic wind tunnel with a 7 m × 6 m × 6 m ($L \times W \times H$) anechoic chamber. It is a closed-circuit type tunnel with a 9:1 contraction ratio. An open testing section is applied for aeroacoustic measurement purpose, and the length of the open testing section is 2.5 m. The cross-section size of the testing section is 1 m × 1 m ($W \times H$). The wind speed in the test section can be increased up to 100 m/s, driven by a 210 kW AC motor and a 16-bladed fan with a 2.26 m diameter.

The schematic layout of the wind tunnel structure is presented in Fig. 2. The whole tunnel is located on the same floor. During the tests the flow originates from the power section and converges to the testing section. The flow subsequently passes through the first diffusion section, returns to the power section and recycles with new generated flow. The turbulence intensity that was measured at the centerline of the open testing section is found to be lower than 0.1% for all tests described in this paper.

3.2. Airfoil models

Tests were separately conducted on two airfoil models. The chord length and span length of each model is 200 mm and 1000 mm respectively. The model is composed of five 200 mm sections, and each section was manufactured from ABS M30 using a 3D printing process with a Stratasys Fortus 450mc 3D printer. This printer has an achievable accuracy of 0.127 mm (0.005 in.). The airfoil models were built with high precision.

Three studding rods are fixed through all five 200 mm sections with nuts at the end of the top section. Three 5 mm Dowel pins are used to connect each pair of neighboring sections. Each airfoil