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Numerical study of turbulent trailing-edge flows with base cavity effects using URANS

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Abstract

Turbulent flows over lifting surfaces exhibiting trailing-edge vortex shedding often cause adverse and complex phenomena, such as self-induced vibration and noise. In this paper, a numerical study on flow past a blunt-edged two-dimensional NACA 0015 section and the same section with various base cavity shapes and sizes at high Reynolds numbers has been performed using the unsteady Reynolds-averaged Navier–Stokes (URANS) approach with the realisable κ–ε turbulence model. The equations are solved using the control volume method of second-order accuracy in both spatial and time domains. The assessment of the application of URANS for periodic trailing-edge flow has shown that reasonable agreement is achieved for both the time-averaged and fluctuating parameters of interest, although some differences exist in the prediction of the near-wake streamwise velocity fluctuation magnitudes. The predicted Strouhal numbers of flows past the squared-off blunt configuration with varying degrees of bluntness agree well with published experimental measurements. It is found that the intensity of the vortex strengths at the trailing-edge is amplified when the degree of bluntness is increased, leading to an increase in the mean square pressure fluctuations. The numerical prediction shows that the presence of the base cavity at the trailing-edge does not change the inherent Strouhal number of the 2D section examined. However, it does have an apparent effect on the wake structure, local pressure fluctuations and the lift force fluctuations. It is observed that the size of the cavity has more influence on the periodic trailing-edge flow than its shape does.

Keywords: Trailing-edge flow; Vortex shedding; Base cavity; Unsteady RANS

1. Introduction

Blunt-edged aerofoils or hydrofoils submerged in high Reynolds number turbulent flows often exhibit undesirable self-induced discrete tonal noise. The presence of the blunt trailing-edge induces a periodic vortex shedding phenomenon, causing fluctuations of the surface pressures, which can lead to self-sustained structural vibrations as well as change the magnitude and spectrum of the acoustic energy at the trailing-edge (Bourgoyne et al., 2000). The control of this vortex shedding has inspired many experimental and numerical studies in this field over the last decade. For example, very high Reynolds number flows over a hydrofoil were studied experimentally by Bourgoyne et al. (2003, 2005) and numerically

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Nomenclature

A_c	characteristic cavity area as defined in Table 1
A_h	reference cavity area, $h \times h$
C	chord length
h	trailing-edge height
f	frequency
l	characteristic length scale
p	pressure
C_d	drag force coefficient, $F_d/q_\infty C$
C_l	lift force coefficient, $F_l/q_\infty C$
C_p	pressure coefficient, $p/q_\infty C$
l_f	wake formation length
y_f	cross-wake shear layer thickness
U_∞	freestream velocity
q_∞	dynamic pressure, $\rho U_\infty^2/2$
St_l	Strouhal number based on l, fl/U
Re_l	Reynolds number based on l, $(\rho U_\infty l)/\mu$
δ^*	displacement boundary layer thickness

by Date and Turnock (2002) and Paterson and Peltier (2005) to improve the understanding of the rich physics, and its association with the noise generation were investigated numerically and analytically by Blake (1975), Howe (1999, 2000, 2001) and Wang and Moin (2000). Recently, the self-sustained vibration of a NACA 0012 foil subjected to a low-to-moderate Reynolds number was studied experimentally by Poirel et al. (2008). Howe (1991) calculated the sound generated by an aerofoil of serrated trailing-edge analytically and concluded that a significant noise reduction was achieved with the serrated trailing-edge. Blake (1986) comprehensively reviewed experimental data of various studies and concluded that turbulent flow-induced tonal noise can be eliminated by making the trailing-edge sufficiently sharp. However, due to manufacturing limitations and the structural requirement for aerofoils to withstand tremendous lift and drag forces, especially for hydrodynamic applications, the enclosure of the trailing-edge always results in a certain degree of bluntness in practice. This dilemma represents a challenge for marine and aerospace engineers alike, in minimising tonal noise emissions and preventing fatigue failure caused by coincidences of the vortex shedding frequency and the natural frequency of the structure.

The understanding of bluff-body wake dynamics has improved significantly due to the rapid development of advanced experimental and numerical techniques over the last two decades (Williamson, 1996). However, it cannot be directly applied to the near-wake of a streamline body because of differences between the two wake dynamics, such as the larger distance between the front and rear stagnation points and the stronger dependence on the rear geometry for a streamline body wake (Bourgoyne et al., 2005). Blake (1975) carried out aerodynamic and hydrodynamic surveys of the wake dynamical characteristics of a simple symmetric aerofoil (referred as a lifting strut) with a squared-off blunt trailing-edge that exhibits vortex shedding, using techniques proposed by Bearman (1965). The subsequent studies by Blake (1976), Blake et al. (1977) and Gershfeld et al. (1988) used these inherent wake characteristics, in particular the vortex formation length (l_f), cross-wake shear layer thickness (y_f) and trailing-edge pressure fluctuations, in the prediction of mode displacement amplitudes, location of the vortices and the acoustic spectrum in the immediate wake region. Recently, Bourgoyne et al. (2005) conducted an experimental study of the vortex shedding from an asymmetrical NACA 0016 with 45° and 60° apex angles. They confirmed that the vortex strength was controlled by the vertical velocity fluctuation near the trailing-edge and a strong vortex shedding occurred when the trailing-edge was sufficiently blunt. However, to the best of the authors' knowledge such information has been limited, even more so for the conventional streamlined and symmetrical hydrofoils containing a blunt trailing-edge. The inadequate literature available prevents generalisation of the behaviour of such wake characteristics across different sections and trailing-edge profiles, when different flow conditions are imposed. Further, more questions remain as to how these wake length scales, the Strouhal number and the intensity of the surface pressure fluctuations vary with the trailing-edge Reynolds number (Re_h) for a particular trailing-edge configuration.

The influence of a trailing-edge cavity on the vortex-induced structural vibration of two-dimensional thick flat plates (with circular leading edge) has been extensively studied [see, e.g., Donaldson, 1956, Heskestad and Olberts, 1960, Toebes and Eagleson, (1961)]. It is clear from these studies that the presence of the cavity leads to a change in the vibration amplitudes relative to the basic squared-off blunt configuration. Heskestad and Olberts (1960) explained that the bound circulation strength (about the section) is reduced to account for the rotational fluid trapped inside the cavity, hence resulting in a reduction of the exciting lift force. On the other hand, the influence of the cavity on the shedding frequency is less certain. Toebes and Eagleson (1961) compared a section with a squared-off blunt trailing-edge and the same section containing a triangular cavity, while Zhdanov and Eckelmann (1994) examined a squared-off blunt profile and various rectangular cavity profiles, both studies reported that the shedding frequencies were altered. The change reported by Toebes and Eagleson (1961) was very small. However, Heskestad and Olberts (1960) observed an unchanged vortex shedding frequency for the comparison between a section with a squared-off blunt trailing-edge and the same section with a semicircular cavity. It is the intention of this work to use numerical methods to re-examine