LEADING EDGE NOISE SIMULATIONS OF A HEAVING AIRFOIL

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Airfoil leading edge noise is a significant noise source for aircraft and wind turbines. In this work, a hybrid computational aeroacoustic method was applied to investigate the noise generated by an airfoil with a chord length of 0.15m, heaving at a frequency of 20 Hz and a heaving amplitude of 0.02m, subjected to oncoming homogeneous isotropic turbulence. Computational fluid dynamics was used to obtain inviscid and viscous mean flow fields around the heaving airfoil. Fourier analysis was applied to specify the mean flow field as a time-harmonic field in a linearised Euler equations solver with gradient term suppression. The far-field noise and sound power level from the heaving wing were compared to a stationary airfoil under the same conditions of incoming turbulence. The results show that the heaving airfoil generates lower levels of noise by the airfoil leading edge.

Keywords: Computational aeroacoustics, leading edge noise, oscillating airfoil

1. Introduction

Airfoil leading edge noise is a major source of broadband noise in aircraft engines and wind turbines. This noise is generated by the interaction between the incoming turbulent flow and the airfoil leading edge. Amiet [1] developed an analytical model to predict the noise by a flat plate subjected to incoming turbulence. The model predictions were compared to experimental measurements by Paterson and Amiet [2] for a range of airfoils with varying thickness. They found that thicker airfoils radiated less noise at high frequencies and this phenomenon is due to the increased size of the stagnation region [3]. The effect of airfoil camber and angle of attack have also been investigated and found to have a small influence on the far-field noise levels [4, 5].

These previous studies have all assumed the airfoil to be perfectly rigid. This assumption can become invalid in the case of strong aerodynamic flutter [6], or in the case of helicopter blades where dynamic stall occurs [7]. Additionally, aeroacoustic studies on dynamic airfoils may become more significant extensive as a wide body of aerodynamic and numerical studies have observed lift enhancement and thrust generation potential by heaving airfoils under specific flow and heaving conditions, [8, 9].

The flow features around a heaving airfoil are affected by the flow and oscillation conditions. At low Reynolds numbers ($Re$), the vortex structures around trailing edge mainly depend on the Strouhal number based on the heaving amplitude [10] ($St_A = 2\pi f_H A_H / u_\infty$, where $u_\infty$ is the free stream velocity, $f_H$ is the heaving frequency, and $A_H$ is the heaving amplitude). At low $Re$ and high $St_A$, a reversed von-Kármán vortex street is formed in the wake of a heaving airfoil. For the $St_A < 1.2$, the flow structures in the wake region gradually transform into the von-Kármán vortices [11]. At high
Reynolds number and low $St_A$, the flow patterns behind the trailing edge are a wave-like turbulent layer [12].

The flow field around the leading edge of a heaving airfoil can also be complex. The Strouhal number based on the airfoil chord ($St_c = 2\pi f h c/\infty$, where $c$ refers to the airfoil chord length) has been identified as the dominant parameter of the leading edge noise vortices [13]. Additionally, under high $St_A$ and $St_c$, the flow patterns around the leading edge can become asymmetric and aperiodic [14].

In this work, we intended to investigate the effects of a heaving airfoil, following a sinusoidal motion on the turbulence-leading edge interaction noise. Hybrid CAA simulations were performed on a heaving NACA 0012 airfoil encountering synthetic turbulence [15]. The remainder of this paper is arranged as follows, Section 2 describes the numerical methods. Section 3 provides details on the flow and airfoil parameters used in this study and the results. Finally, a summary is given in Section 4.

2. Numerical Method

In this work, the airfoil leading edge noise for a heaving NACA 0012 airfoil was predicted in two stages. Firstly, the inviscid and viscous periodic mean flow was computed using an Euler solver and an Unsteady Reynolds-Averaged Navier-Stokes (URANS) solver, respectively. The URANS computation was performed with the $k - \omega$ SST turbulence model and the computational mesh used was refined near to ensure an adequate boundary layer resolution that satisfied $y^+ < 1$. The heaving motion of the airfoil was achieved by using a deforming mesh that was positioned two chord-lengths away from the airfoil.

In the second stage, a high-order finite difference computational aeroacoustics (CAA) code was used that solves the linearised Euler equations (LEE). This solver has been previously applied to duct noise radiation problems [16] and airfoil noise studies [3, 15]. The CAA solver utilises sixth-order spatial schemes [17] and a 4-6 stage Range-Kutta temporal scheme [18]. Non-reflective boundary conditions [19] were applied at the outer edges of the computation domain, and a filter [20] was used at the end of each time step to remove spurious oscillations. For all simulations, the Courant-Friedrichs-Lewy (CFL) number was set to be smaller than 0.5. In the CAA simulations, the reference frame was changed to the airfoil, such that the airfoil stayed stationary as the mean flow varied with time.

A modified digital filter [15] was used to synthesize a turbulent flow injected 1.6 chord lengths upstream of the airfoil leading edge. The resulting leading edge noise was fully resolved up to a reduced frequency of $k = f c/\infty = 18$, where $f$ is the frequency, $c$ is the airfoil chord length, and $\infty$ is the free-stream velocity. The far-field sound pressure level was calculated by an integral solution of Fowcs Williams and Hawkings (FW-H) equation [21].

The LEE are derived by decomposing the flow variables in the Euler equations into its mean and perturbed quantities. By assuming that the perturbed flow quantities are several orders of magnitude smaller than the mean values, the non-linear terms can be neglected, and the LEE (in vector notation) writes:

\[
\frac{\partial \rho'}{\partial t} + \rho' \nabla \cdot \mathbf{u}_0 + \rho_0 \nabla \cdot \mathbf{u}' + \mathbf{u}_0 \cdot \nabla \rho' + \mathbf{u}' \cdot \nabla \rho_0 = 0, \\
\frac{\partial \mathbf{u}'}{\partial t} + (\mathbf{u}_0 \cdot \nabla) \mathbf{u}' + (\mathbf{u}' \cdot \nabla) \mathbf{u}_0 + \nabla p' - \frac{\rho'}{\rho_0} \nabla p_0 = 0, \\
\frac{\partial p'}{\partial t} + \mathbf{u}_0 \cdot \nabla p' + \mathbf{u}' \cdot \nabla p_0 + \gamma (\rho' \nabla \cdot \mathbf{u}_0 + p_0 \nabla \cdot \mathbf{u}') = 0,
\]

where $t$ is the time, $\rho$ is the density, $p$ is the pressure, $\mathbf{u}$ is the velocity vector, $\gamma = 1.4$ is the ratio of specific heats, and $(\cdot)_0$ and $(\cdot)'$ represent the mean and perturbed quantity, respectively.
For the heaving airfoil case, the mean flow variables were further decomposed into a time-averaged and harmonic values e.g., \( u_0 = \bar{u} + \tilde{u} \). By assuming that the turbulent fluctuations have an insignificant effect on the harmonic mean-flow components, the periodic mean flow around a heaving airfoil can be implemented into the LEE solver. The governing equations resolve both acoustic and vortical disturbances. However, the numerical solutions around airfoil trailing edge can suffer from numerical Kelvin-Helmholtz (K-H) instabilities when the mean flow contains a strong shear layer. This instability can generate spurious noise around the airfoil trailing edge. Therefore, in this work, the gradient term suppression method [22, 23] was applied to overcome this numerical issue.

3. Leading edge noise of a heaving airfoil

The NACA 0012 airfoil with a chord length of \( c = 0.15 \text{m} \) was heaved at a frequency of \( f_H = 20 \text{ Hz} \) and an amplitude of \( A_H = 0.02 \text{ m} \) (see Fig.1). Under these conditions, the Reynolds number based on the airfoil chord is \( Re = 600,000 \), and the Strouhal numbers are \( St_c = 0.314 \) and \( St_A = 0.042 \). The flow structures generated by the heaving airfoil under the prescribed conditions are periodic, and no leading edge vortices (LEV) are generated. The latter avoids the additional noise due to scattering of LEVs around the trailing edge.

![Figure 1: Schematic of the heaving airfoil.](image)

Figure 1: Schematic of the heaving airfoil.

Figure 2 shows the aerodynamic properties of a heaving airfoil obtained by the Euler and URANS solvers. The surface pressure profiles at different periods in the heaving cycle are shown in the Fig.2(a) and show that the inviscid and viscous solvers provide similar results. Discrepancies in the pressure profiles are small and limited only towards the airfoil trailing edge. Figure 2(b) shows the lift coefficient against the effective angle of attack through a complete heaving period. The differences in lift coefficient profiles during the upstroke and downstroke are due to the effects of hysteresis [24].

![Figure 2: Aerodynamic properties of a heaving wing.](image)

Figure 2: Aerodynamic properties of a heaving wing.
3.1 Reconstruction of mean flow around a heaving wing

Due to the differences in time scales between the CFD and the CAA simulations, the periodic mean flow around a heaving wing could not be adopted as a steady mean flow in the LEE solver. A Fourier analysis was performed to extract the key components of the mean flow field, which was then expressed as an equation that could be used to accurately reconstruct the mean flow field at every Runge-Kutta time stage. To validate the reconstruction approach, the time traces of the mean velocity and pressure by the CFD and CAA solver were recorded at two points near the airfoil surface (see Fig.3). A near-perfect agreement between the CFD mean flow signal and the reconstructed signal is shown in Fig.4. The agreement across multiple heaving periods validates the numerical approach adopted in the CAA simulations.

Figure 3: Locations of monitor points A and B.

Figure 4: Comparison of the reconstructed mean flow signal to the original CFD results.

3.2 Turbulence-airfoil leading edge noise

The modified digital filter method [15] was used to synthesize divergence-free and quiescent turbulence along an injection region that followed a von-Kármán energy spectrum with an intensity of $T_u = 1.7\%$ and an integral length of $\Lambda = 0.008m$. These turbulence parameters were chosen based on a previous study that studied the same airfoil geometry without any heaving motion [25]. This work, therefore, follows a natural extension to the previous study. Figure 5 shows that digital filter accurately generates the desired turbulent spectrum for a stationary and heaving airfoil.
Numerical simulations of the leading edge noise by a heaving airfoil subjected to incoming synthetic turbulence were performed using an inviscid and viscous mean flow. Additional simulations using a stationary airfoil were conducted for comparison. Figure 6 shows the sound power levels (PWL) from the various simulations, and it highlights two features. Firstly, the PWL spectra obtained using inviscid mean flows are consistently greater than the PWL spectra obtained using viscous mean flows for $k > 12$. Secondly, the differences in the PWL between viscous and inviscid mean flows are significantly higher for a heaving airfoil.

The cause of the differences in the PWL for a heaving wing was found to come from the trailing edge region. The instantaneous vorticity fields, illustrated in Fig. 7, show that the turbulent fluctuations convected along the airfoil surface are closer when the mean flow is inviscid (see Fig. 7(a)). This results in a stronger pressure response along the airfoil surface as the heaving motion drives the wall boundary towards the convected vortices. When a viscous mean flow is used, the vortices convected along the sides of the airfoil are further away from the wall boundary. Additionally, significantly lower fluctuations around the trailing edge region using a viscous mean flow are found, which results in minimal scattering of the vortex structures along the trailing edge (see Fig. 7(b)). Therefore, the remainder of the results presented in this paper are limited to the results obtained by a viscous mean flow, as it applies less assumptions.

Figure 8 compares the far-field root-mean-square pressure ($P_{rms}$) directivity between a stationary and heaving airfoil. The directivity pattern of a heaving airfoil is lower compared to a stationary airfoil, for observer angles from $60^\circ$ to $120^\circ$.

Fourier analysis was used to extract the directivity patterns at discrete reduced frequencies (see Fig. 9). The results show that the noise reduction by a heaving airfoil is mostly focused around $k = 2$.

Figure 5: One-dimensional spectra measured 0.3 chord-lengths upstream of the airfoil leading edge.

Figure 6: Comparison of the sound power level.
Figure 7: Fluctuating vorticity field around the trailing edge.

Figure 8: Comparison of far-field directivity patterns.

and $k = 4$. Beyond $k > 4$ the directivity pattern of a stationary airfoil is unaffected by the heaving motion.

Figure 9: Far-field directivity patterns at discrete reduced frequencies.
4. Conclusion

Studies of turbulence-airfoil interaction noise often apply to a stationary airfoil. In this work, we investigated the noise generated by a heaving airfoil subjected to incoming turbulence using a hybrid CAA method. The heaving airfoil generated a periodic mean flow and led to a reduction in the leading edge noise, compared to the leading edge noise generated by a stationary airfoil. Previous studies have shown that size of the high-pressure region located around the leading-edge stagnation point has a strong influence on the leading edge noise. It is believed that the heaving motion of the airfoil effectively increases the size this region, and is the cause of the noise reduction.

Previous studies have also shown that an inviscid mean flow is suitable for leading-edge noise simulations for a stationary airfoil. However, the results obtained in this paper show large differences in the sound power level at high frequencies. Therefore, inviscid mean flows may be unsuitable for heaving airfoil studies.

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