MEASUREMENT OF TRAILING EDGE NOISE FROM A HEAVING AIRFOIL

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The trailing edge noise from a heaving wing with a constant NACA 0012 airfoil section was studied at a Reynolds number of $1.98 \times 10^5$ using an anechoic wind tunnel. The airfoil was fixed at an incident angle of 0°. The heaving frequency and amplitude were selected as 8Hz and 10mm, corresponding to a reduced frequency of 0.08 and a Strouhal number of 0.008 based on the chord length. A microphone array was utilized to detect the position and the strength of the noise source at different frequencies. For a stationary wing, the source strength of the broadband noise spreads evenly across the whole wing span while the source of the discrete tones appears as a pair of spanwise cells symmetrical about the spanwise centre. Short-time Fourier transform and a wavelet-based real-time beam-forming algorithm were used to analyse the time dependence of the sound spectra and the source strength in one heaving period, respectively. The sound pressure levels of the discrete tones increases while the wing passing over the mean phase position and experiencing the largest effective angle of attack, and it is attributed to the enhancement of the source strength at the corresponding time.

Keywords: aeroacoustics; airfoil self-noise; heaving airfoil; trailing edge noise; anechoic wind tunnel.

1. Introduction

For many airfoil applications at low Reynolds-numbers, such as nature flyers [1], micro air vehicles (MAVs) [2], as well as small helicopters [3], wing oscillation is a commonly observed phenomenon. The aerodynamics and aeroacoustics of an oscillating wing have attracted a lot of research interests. For flying insects and flapping wing based MAVs, the noise generation directly relates to the flapping motions of the wings [4]. On helicopters, the blade oscillation has an essential effect on the accurate prediction of the blade vortex interaction (BVI) noise as the unsteady motion of the blade changes the wake vortex shed from the trailing edge of the preceding blade [5].

An airfoil in heaving motion leads to an unsteady flow situation. Knoller [6] and Betz [7] proposed an inviscid theory to account for the thrust generating mechanism of a plunging wing, which is later known as the Knoller-Betz effect. This theory was later experimentally verified by Katzmayr [8]. Since then, further understanding of the flow had been achieved through computational analysis and wind tunnel...
tests \cite{9,10,11,12}. It was reported that for a plunging symmetrical airfoil, when the Strouhal number (St = \( \pi f_h A / U_\infty \), where \( A \) is the heaving amplitude, \( f_h \) is heaving frequency, and \( U_\infty \) is the incident flow speed) was low, a Kármán vortex street can be observed in the wake flow, generating a drag force on the airfoil; as St increases, the wake pattern turns into a reversed Kármán vortex street, leading to a thrust force \cite{9,10}.

A series of water tunnel experiments on a plunging wing were conducted at low Reynolds number (Re<30000) by Cleaver et al. \cite{13,14,15}. Their results indicated that the strengths of the leading-edge vortex (LEV) and trailing-edge vortex (TEV) were proportional to the reduced frequency (\( k = \pi f_h c / U_\infty \), where \( c \) is the chord of the airfoil) of the plunging motion. For high \( k \) cases (e.g., \( k > 2.4 \)), LEV appeared in both the upstroke and the downstroke processes. At low Strouhal numbers (e.g. St = 1.0), a strong vortex-airfoil interaction occurred as the LEVs convected downstream, leading to deformation and breakdown of the vortices. Similar results were also observed by Lewin and Haj-Hariri \cite{11} in a numerical study of a two-dimensional heaving airfoil.

Sound radiated from a flapping wing was investigated by Bae and Moon \cite{16}. Their computational results revealed two different sound generation mechanisms. The primary mechanism is the transverse motion of the wing that causes a dipole-like tone at the flapping frequency. Similar conclusions were reached by Sueur et al. \cite{4} in a study of the sound from a fly. The secondary mechanism is the vortex scattering by the trailing edge during the tangential motion, which leads to tones with higher frequencies. Moreover, the interaction between the wing and vortices makes the sound spectrum more broadband, especially under the forward flight condition.

Noise from a turbulent flow convecting over a rigid and elastic trailing edge was investigated by Schlanderer and Sandberg \cite{17,18} using direct numerical simulations (DNS). They concluded that compared with the rigid trailing edge, the elastic trailing edge could either damp or amplify the noise at the dominant frequency, and the far-field noise spectrum of the elastic trailing edge had discrete tones at the natural frequencies of the structural motion. Similar conclusions were reported by Manela \cite{19} with a computational model solved by the Powell-Howe acoustic analogy. For an elastic airfoil actuated by a sinusoidal pitching motion, the pitching motion amplifies the noise level when the pitching frequency is close to the structural eigenfrequency. At frequencies away from the natural frequency, it reduces the acoustic radiation.

Manela \cite{20} also studied the vibro-acoustic signature of a thin rigid airfoil in a sinusoidal heaving motion by applying Powell-Howe acoustic analogy. The effects of the reduced frequency were discussed. When \( k / 2\pi \ll 1 \), the effect of the heaving motion was small, and the acoustic response could be approximated by considering the static case; for \( k / 2\pi \gg 1 \), the heaving motion exerted a larger impact, radiating sound from a dipole oriented along the heaving direction; for \( k / 2\pi \approx 1 \), an intermediate state could be obtained.

Regarding the aeroacoustic characteristics of a heaving airfoil, the published works are still very limited. In this study, beam-forming measurements were conducted to investigate the sound source as well as the spectra from a heaving NACA 0012 airfoil. Real-time algorithms were utilized to study the time dependence of the sound features in one heaving period. The main parts of this paper is organized as follow. The introduction of experimental apparatus and data processing methods are given in Section 2. The measurement results are illustrated and discussed in Section 3. The conclusions are listed in Section 4.
2. Experimental apparatus

2.1 Wind tunnel and airfoil

The experiments were conducted in the open-jet facility, Ultra-quiet Noise Injection Test and Evaluation Device (UNITED) [21], at the Hong Kong University of Science and Technology (HKUST). It has a cross test section of 400mm × 400mm and a maximum flow speed of 70m/s. The turbulence intensity within the test section is lower than 0.32% within the flow speed range of 10-60m/s. The anechoic tunnel has an anechoic chamber with dimensions of 3.3m (length) × 3.1m (width) × 2.0m (height) and a cut-off frequency of 200Hz.

The test model was a wing with a constant span of 399mm and a NACA 0012 airfoil with a chord of 100mm. The span was 1mm shorter than the side length of the tunnel nozzle so that it would not scratch the end-plates during oscillation. The heaving motion of the wing model was driven by the voice coil motor OWS25-445-03 produced by VCM Tech Co., Ltd., which was able to produce a peak force of 445N and a continuous force of 167N, with a maximum linear stroke of 25.6mm. The trailing edge of the wing was placed 350mm downstream the wind tunnel nozzle exit plane. As shown in Figure 1(a), the wing heaved along the Z-coordinate.

2.2 Acoustic measurements

A planar microphone array was utilized to detect the position as well as the strength of the noise source on the wing. As shown in Figure 1(a), the array was placed 0.73m away from the central axis of the tunnel. The array has an aperture of 0.68m, and it consists of eight isobrachial spirals with seven flash-mounted 1/4” Brüel & Kjær type 4957 microphones on each arm (see Figure 1(b)). The origin of the spatial coordinate is set on the centre point of the airfoil trailing edge, corresponding to a distance of 0.025m downstream the centre of the array, and the positive direction of X-coordinate follows the wind direction.

A camera was used to record the position of the heaving airfoil at a sampling frequency of 400Hz. The camera and the microphone array were synchronized and triggered together at the beginning of each measurement. The instantaneous phase positions were obtained from the photos captured by the camera.

![Figure 1: The experimental setup. (a) The layout of the experimental facilities. (b) An illustration of the relative position of the microphone array and the wing model.](image-url)
2.3 Test conditions

In the present study, the tests conducted under the flow speed of 30m/s are discussed, which corresponds to a Reynolds number of $1.98 \times 10^5$. The geometric angle of attack $\alpha_0$ was fixed at $0^\circ$. The heaving motion of the wing could be described as a function of time, which followed the sinusoidal function

$$h(t) = A \sin (2\pi f_h t),$$

where $h$ is the instantaneous position of the airfoil and $t$ is the time. Since the heaving motion provides a velocity component perpendicular with the flow direction, the effective airfoil angle of attack $\alpha_e$ varies from the incident angle $\alpha_0$. In this study, since $\alpha_0 = 0^\circ$, the effective angle of attack can be expressed by

$$\alpha_e = \arctan \frac{dh/dt}{U_\infty} = \arctan \frac{2\pi A f_h \cos (2\pi f_h t)}{U_\infty}.$$

In the experiment, the heaving amplitude $h_A$ was fixed at 10mm, and the heaving frequency $f_h$ was 8Hz, corresponding to a reduced frequency and a Strouhal number of $k = 0.08$ and $St = 0.008$, respectively.

3. Results and analysis

3.1 The stationary wing

For the stationary case, the trailing edge noise spectrum acquired by microphone #1 in the array (as marked in Figure 1(b)) is presented in Figure 2. The spectrum includes the dominant discrete tone at $f = 1641$Hz and a series of harmonics. According to the previous studies [22], the tonal noise from the trailing edge is attributed to the laminar boundary layer separation, while the broadband noise is caused by the convection of the small-scale turbulence.

To get higher beam-forming resolution, the analysis was performed in the high-frequency region. Figure 3 illustrates the beam-forming results at three frequencies: one corresponds to the fourth harmonic tone at the frequency of $f = 6583$Hz (Figure 3(b)), and the other two correspond to the broadband region (Figures 3(a) and (c)). The source strength of the broadband noise, as reported in previous literature [23], is evenly distributed over almost the whole span of the wing. While for the tonal noise, its source pattern appears as two spanwise cells that are approximately symmetric about the centre of the wing span.

3.2 The heaving wing

For the case studied in this work, the effective angle of attack varied from $0^\circ$ to $0.97^\circ$. Therefore, the flow pattern near the airfoil surface, as well as the acoustic characteristics was time-dependent. The short-time Fourier transform (STFT) method was utilized to reveal the variation of the sound spectra in one heaving period. As shown in Figure 4, the heaving motion does not change the frequencies of the tones. Similar to the spectrogram of a pitching airfoil [21], the SPL of the primary peak varies in time in a range of 6dB. The high-level discrete noise always appears while the airfoil passing over the mean position where the airfoil has the highest velocity as well as the largest effective angle of attack.

Using the wavelet transformation, the variation of the sound source pattern at a given frequency can be obtained. Figure 5 presents the time history of the sound source at the fourth harmonic in one heaving period. The changing trend of the source strength corresponds to the variation of the tone level in time. From $0.35T_h$ to $0.79T_h$, as shown in Figure 5(d), the source strength is too low to be detected, corresponding to the low tone level shown in the spectrogram at the same time. Other than that, as shown
Figure 2: Trailing-edge noise spectra from one of the array microphones at the flow speed of 30m/s and \( \alpha = 0^\circ \).

Figure 3: Trailing-edge discrete noise source from the stationary wing at the flow speed of 30m/s and \( \alpha = 0^\circ \). (a) 6000Hz. (b) 6583Hz. (c) 7000Hz. The contour map is colored by SPL (dB). The blue lines refer to the outline of the wing.

in Figures 5(a), (b), (c), (e) and (f), the strength of the sound source increases and it leads to higher SPL presented in the spectrogram. It suggests that the level variation of the tones in the field is attributed to the strength variation of the sound source at the corresponding frequency.

When the sound source is strong enough to be observed in the contour map, it always appears as spanwise cells. In one heaving period, the position of the sound source varies along the wing span. From \( 0.17T_h \) to \( 0.24T_h \), as shown in Figures 5(a), (e) and (f), the two cells are centred at \( Y = 0.13m \) and \(-0.06m \), respectively. While, from \( 0.86T_h \) to \( 1.17T_h \), the centres of two source cells appear at \( Y = 0.05m \) and \(-0.07m \). As shown in Figures 5(b) and (c), that are the positions where the cells present for the stationary case (see Figure 3(b)). The variation of the source position can be explained by the change of the effective angle of attack in a heaving cycle. Although the effective angle of attack varies continuously, the source cells only appear at the aforementioned positions. An investigation of the flow field near the trailing edge is required to gain a better understanding of this issue.
4. Conclusion

In this study, the beam-forming technique was used to investigate the acoustic features of a heaving wing with a constant NACA 0012 airfoil section. The measurements were conducted at a Reynolds number of $1.98 \times 10^5$, and the geometric angle of the airfoil was fixed at $0^\circ$. The short-time Fourier transform and a real-time beam-forming algorithm were used to reveal the time-dependent variation of the sound spectra and source pattern during the heaving motion, respectively. The following conclusions can be achieved:

- Being different from the broadband noise, the source pattern of the discrete tone appears as a pair of spanwise cells shown near the centre of the wing span.
- SPL of the discrete tone varies as the wing heaves. The high-level tone always appears while the airfoil passing over the mean position, which corresponds to the effective angle of attack of about $0.97^\circ$.
- The change of the tone level in a heaving period is attributed to the strength variation of the sound source at the corresponding frequency.
Figure 5: Variation of the source pattern at $f = 6583\text{Hz}$ in one heaving period. (a) 0.15$T_h$. (b) 0.24$T_h$. (c) 0.32$T_h$. (d) 0.43$T_h$. (e) 0.90$T_h$. (f) 1.0$T_h$. All six time slots are indicated in Figure 4.

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