

Acoustic Response of Fully Passive Airfoil under Gust [†]

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Abstract: Acoustic response from a freely responding symmetric airfoil subjected to gust is investigated in a two-dimensional numerical environment. Gust model is superimposed on the inlet velocity up till the critical flutter velocity. Second order transient formulation, $k - \omega$ turbulence model and dynamic meshing technique were adopted. By employing the Ffowcs Williams and Hawkins (FW-H) acoustic methodology, the acoustic signature generated by the airfoil for the range of velocities ($0.85 \leq U/U_c \leq 1$ near the critical flutter velocity) is quantified over a range of acoustic receivers in the surrounding of the airfoil. Sound pressure levels (SPLs) are determined, and directionalities have been studied. It is revealed that the distribution of sound pressure level at the exciting frequency is affected by the gust profile. Scales of these sound pressure levels, however, relied on the Reynolds number and the dynamics of the system.

Keywords: gust response; flow noise; aeroacoustics; fully passive airfoil



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1. Introduction

The interior noise and airframe noise have been explored extensively in the recent past. There is an ever-increasing urgency to mitigate the influence of aerospace productions on the environment with the European commission calling for noise reduction [1], which has resulted in the development of systems capable of meeting noise certification needs.

The flow of fluid over stiffened structures is known to yield sound, as well as disturbs and sustains vibrations in the structure. When a body moves in a nonuniform fluid flow, the contact between the body and the unsteady fluid harvests pressure fluctuations on the body surface resulting in the noise propagated to the far-field. This investigation has numerous applications in the design and mitigation of microaerial vehicles (MAVs) as well as aircraft structural noise.

Métivier et al. [2] performed a series of investigations experimentally on an unrestricted pitching wing (chord length = 0.156 m) at Reynolds numbers of 5.10^4 – 1.10^5 and revealed that the airfoil became unstable, exhibiting limit-cycle oscillations. Wind tunnel studies using a pitching and plunging airfoil in the previous Reynolds number range have also been performed [3]. The consequence of laminar separation on the flapping airfoil has been considered experimentally and numerically by [2,4]. These research studies confirm that the separation of the boundary layer in the laminar region at the trailing edge is accountable for pitching oscillations.

2. Governing Equations

The current effort utilised the two-dimensional unsteady Reynolds averaged Navier–Stokes (URANS) methodology improved with a transitional turbulent solver for the flow calculations ($k - \omega$ Shear Stress Transport). Moreover, the Ffowcs Williams and Hawkins's (FW-H) method was employed for the aeroacoustics calculations. The model was selected as it was not computationally expensive and was apt for predicting the tonal noise from the flow and the interface of the flow with nonpermeable contours.

2.1. Aeroelastic Model

An airfoil able to move in pitching and heaving degrees of freedom is placed on a pivot point passing through the pitching axis (z) (Figure 1). The equations of motion [5] for such an airfoil can be given as (Equations (1) and (2)):

$$F = m_h \ddot{y} + D_h \dot{y} + k_h y + S(\dot{\theta}^2 \sin \theta - \ddot{\theta} \cos \theta) \quad (1)$$

$$M = I_\theta \ddot{\theta} + D_\theta \dot{\theta} + k_\theta \theta - S \ddot{y} \cos \theta \quad (2)$$

where m_h is the heaving mass (kg), D is the damping (kg s^{-1} and $\text{kg m}^2 \text{s}^{-1} \text{rad}^{-1}$ for pitching and heaving, respectively) and k is the stiffness coefficient (Nm^{-1} and $\text{Nm} \cdot \text{rad}^{-1}$ for pitching and heaving, respectively). I_θ (kg m^2) is the moment of inertia around the angular axis. The subscripts h and θ denote heaving and pitching. Plugging $S = m_p x_\theta$ (where m_p is the pitching mass (kg) and x_θ the centre of gravity location (m)), an inertial coupling exists in both degrees of freedom.

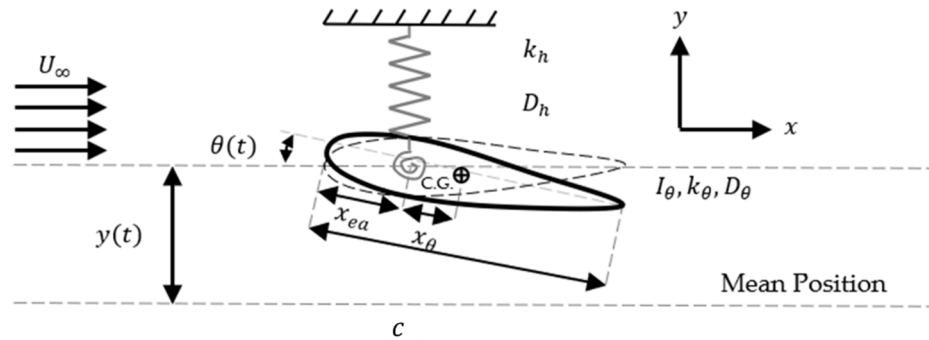


Figure 1. Basic representation of an inflexible, elastically mounted, symmetrical airfoil through figurative illustration of main parameters.

2.2. Oncoming Gust Shape

The gust shape presented in this work comprises two components [5], i.e., vertical and horizontal. The horizontal and vertical components (Equations (3) and (4)) were modelled by using the symmetric Gaussian distribution function:

$$u = a \times e^{[-(\frac{x-d}{n})^2]} \quad (3)$$

$$w = -a_0 \times e^{[-(\frac{x-d_0}{n_0})^2]} + a_1 \times e^{[-(\frac{x-d_1}{n_1})^2]} \quad (4)$$

where d (m) denotes the centroid position, a (m) denotes the amplitude and n (sec) denotes the time throughout which the components have a value above 50% of their peak amplitude, i.e., full duration at half maximum.

3. Numerical Procedure

The flow solution was performed on a numerical set of 143,416 structured cells consisting of NACA 0015 airfoil with a chord length of 0.12 m. The domain size was equal to $160c$.

For the URANS solution, the pressure-based solver was utilised with the SIMPLE algorithm. The gust model was overlapped on the inlet velocity up till the critical flutter velocity. Numerical simulations for the velocity range of $(0.85 \leq U/U_c \leq 1)$ near the critical flutter velocity were performed (where U_c is critical velocity).

Acoustic data were acquired for 20,000 time steps along with a time step size duration of 10^{-5} s after the URANS model achieved steady state. The pressure was noted by the placement of acoustic receivers as described in the literature [6].

Model Validation

In order to validate the model, the coefficients of lift, drag and sound pressure levels were compared (Table 1) with those stated by experimental [7] and numerical setups [8,9]. Lastly, the sound pressure level in the one-third octave bands ($SPL_{1/3}$) were established and further related with the validation cases along with the mesh convergence study (Figure 2). The current model replicated the position of the main tone (~ 1.6 kHz) and sound pressure level (75 dB), which was in perfect harmony with the published data [7,10,11].

Table 1. Comparison of time averaged aerodynamic coefficients.

Coefficient	URANS (Existing Study)	Experimental [7]	% Difference	Numerical [8]	Numerical [9]
C_L	0.43	0.44	2.32%	0.45	0.46
C_D	0.0084	0.0083	1.20%	0.0075	0.0071

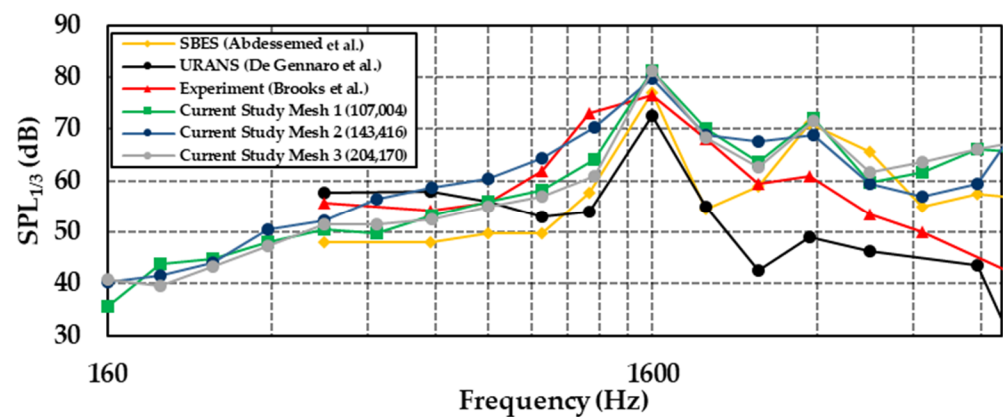


Figure 2. One-third octave band SPL showing SBES, URANS and experimental comparison for M2 along with mesh convergence study.

4. Results and Discussion

A fast Fourier transform (FFT) method was employed to determine the frequencies from the acoustic pressure signals. Here, the role of velocity (U/U_c), and the excitation frequency was investigated for the production of aerodynamic noise.

Production of Sound Waves

The current numerical simulations were performed for $Re = 80,000$ – $120,000$ while varying U/U_c from 0.85 to 1. Figure 3 depicts a magnified schematic at $U = 0.85U_c$ for one of the 38 receivers at the circle ($x = 5c$). The forcing frequency (10.54 Hz) and its even harmonic (21.08 Hz) has a significant role in the production of the flow noise as the oncoming gust influences these signals for the lift and drag. This tendency is palpably seen for all receivers.

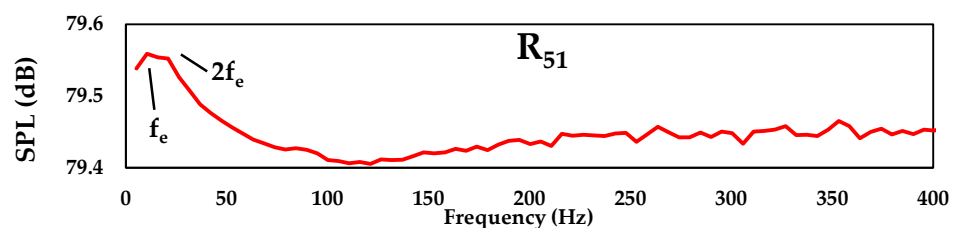


Figure 3. Frequency configuration of SPL about the flapping hydrofoil at one of the receiver locations in the middle circle.

An evaluation for the SPL for microphones positioned at the circles ($x = 5c, 8c$) is shown in Figure 4. The setting where the incoming velocity is equal to the critical velocity represents the highest perturbations in the flow media in terms of frequency and oscillation amplitude. With a growing (U/U_C), the SPL increases for the excitation frequencies. While traveling away from the airfoil, the amplitudes of SPL decrease.

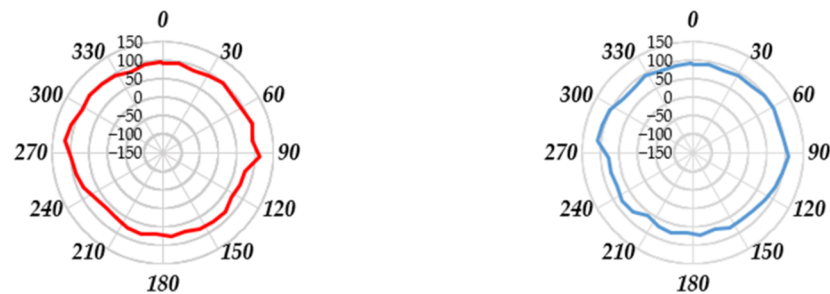


Figure 4. Polar plots showing the spread of SPL: the row expresses data for $\frac{U}{U_c} = 1$; columns 1 and 2 characterize measurements at the middle ($x = 5c$) and outer circles ($x = 8c$), respectively.

5. Conclusions

In this research work, the acoustic response of a passively moving airfoil subjected to a specific gust profile for a range of flow velocities was investigated numerically. The dependency of the sound pressure level magnitude on various parameters was explored. The flow velocity was one of the significant factors to control the change in the sound pressure level magnitudes. For the whole range of velocities (U/U_C), the sound pressure levels depicted the tonal noise on the excitation frequencies. The oscillation frequencies were a function of the force coefficients, which were basically reliant on the gust shape. The oscillation frequencies governed the whole spectrum of sound pressure levels. This aspect was the crux of this study and can be the pioneer phase to control the sound levels at will in real-world applications.

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