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The effect of a cavity on airfoil tones

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ABSTRACT

The presence of a cavity in the pressure surface of an airfoil has been found via experiment to play a role in the production of airfoil tones, which was attributed to the presence of an acoustic feedback loop. The cavity length was sufficiently small that cavity oscillation modes did not occur for most of the investigated chord-based Reynolds number range of 70,000–320,000. The airfoil tonal noise frequencies varied as the position of the cavity was moved along a parallel section at the airfoil's maximum thickness: specifically, for a given velocity, the frequency spacing of the tones was inversely proportional to the geometric distance between the cavity and the trailing edge. The boundary layer instability waves considered responsible for the airfoil tones were only detected downstream of the cavity. This may be the first experimental verification of these aspects of the feedback loop model for airfoil tonal noise.

1. Introduction

Tones may be produced by airfoils under some conditions. The spectral characteristics of the tones have been found to vary. Tonal noise may be produced for chord-based Reynolds numbers up to approximately 600,000 [1,3]; where the Reynolds number is defined as $Re_C = UC/\nu$ where U is the freestream velocity, C is the chord and ν is the kinematic viscosity. The present study concerns the production of such tones from an airfoil with a spanwise cavity.

Differing components of the airfoil tonal noise have been identified. A central frequency, f_s, has been associated with the most amplified boundary layer Tollmien–Schlichting (T–S) wave over the airfoil [13]. Furthermore, some authors have found the presence of a series of discrete tonal frequencies, f_n, with approximately even frequency spacing, Δf, while other authors have found a single tone.

In the first comprehensive study on the topic, Paterson et al. [24] attributed the noise produced by NACA 0012 and NACA 0018 airfoils to vortex shedding and provided an empirical $U^{1.5}$ scaling relation for the mean behaviour of the tones which is given in Eq. (1). Arbey and Bataille [1] later showed this to be equivalent to a scaling relation for the central frequency, f_s, based on an approximately constant boundary layer displacement-thickness-based Strouhal number of 0.048:

$$f_s = \frac{0.011U^{1.5}}{(C\nu)^{1/2}} \tag{1}$$

Tam [29] disagreed with the suggestion of the tones being due to vortex shedding and was the first to identify that the previously observed tonal frequencies were within the region of unstable frequencies of the laminar boundary layer,

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proposing the existence of an aeroacoustic feedback loop which would better describe the ‘ladder structure’ that had been observed. This feedback loop model, which was furthered by numerous authors including Archibald [2], Longhouse [16], and Arbey and Bataille [1], described the series of discrete tones found at a given set of flow conditions. The model contains three components [1,16]: (1) the initiation of laminar boundary layer instability waves (T–S waves) at a neutral stability point on the pressure surface; (2) the convection of these waves past the trailing edge where strong acoustic waves are radiated due to diffraction of the sources in the boundary layer by the sharp trailing edge; and (3) propagation of these acoustic waves upstream to this point where they cause the initiation of further instability waves in the boundary layer such that reinforcement occurs at certain frequencies (the receptivity of the laminar-transitional boundary layer around airfoils to acoustic waves was well known [4]).

The possible frequencies of the discrete tones (f_n) were derived by Arbey and Bataille [1]. Here, L is the characteristic length of the feedback loop, U_c is the convection velocity of disturbances, c is the speed of sound, U is the free-stream velocity and n is the mode number. For reinforcement ‘nothing should change by going around the loop once’ [29] and this requires a total phase change around the feedback loop of $2\pi(n+1/2)$, where the addition of 1/2 accounted for a 180° phase shift at the trailing edge [1]. Substituting $f_n = \omega_n/(2\pi)$, where ω_n is the angular frequency of the tone, gives [1]

$$\frac{f_n L}{U_c}\left(1+\frac{U_c}{c-U}\right) = n+\frac{1}{2} \tag{2}$$

Some recent studies have questioned the necessity or form of this feedback loop in the production of the noise, while other studies claim to support its existence. McAlpine et al. [17] found that the presence of a laminar separation bubble near the trailing edge of NACA 0012 and FX79 W151 airfoils played a role in the generation of noise. They identified that amplification of the airfoil tonal frequency was controlled by inflectional velocity profiles due to the presence of a laminar separation bubble which was detected near the trailing edge. It was found that most of the amplification occurs near the trailing edge. Furthermore, McAlpine et al. [17] did not find a ‘ladder structure’, and they believed that a feedback loop was not necessary for the production of airfoil self-noise, although ‘there will be some feedback about the separation bubble’ [17, p. 777]. In a related study Nash et al. [21] eliminated the ladder structure of the tones by fitting acoustic lining to the ceiling and floor of the working section of their wind tunnel and claimed that previous researchers may have been ‘misled’ by spurious feedback loops peculiar to the experimental rigs used.

Moreau et al. [19] found that the noise produced by an airfoil (a slender flat plate profile with asymmetric wedge-shaped trailing edge) was due to vortex shedding. Although tones with approximately equal frequency spacing were found, boundary layer instability waves at these frequencies were not detected and the frequencies were outside the instability envelope of the boundary layer according to linear stability theory, therefore the authors did not believe that there was a feedback loop involved. The tonal noise produced by this airfoil was attributed by the authors to vortex shedding over a separation bubble detected near the trailing edge, with no boundary layer instability waves involved.

Tam and Ju [30] attributed the basic tone generation mechanism of a NACA 0012 airfoil to the near-wake Kelvin–Helmholtz (K–H) instability at zero angle of attack. They believed that the instability initiated at this part of the wake ‘is ultimately responsible for the generation of the aerofoil tones’ [30, p. 559]. Tam and Ju deduced a rationale for simulating the airfoil in order to investigate the mechanism of a truly isolated airfoil both without a separation bubble (owing to the zero angle of attack) and also avoiding the ‘acoustic feedback anchored to laboratory equipment or built-in hardware’ that could be found in a physical experiment [30, p. 566]. Tam and Ju agree with Nash et al. [21] that the feedback tones are facility related and ‘are not genuine tones’ of a truly isolated airfoil [30, p. 567].

On the other hand, some other recent studies have suggested that an acoustic feedback mechanism plays a role in the production of the noise. Takagi and Konishi [28] investigated the role of artificial feedback on the noise produced by flow over a NACA 0012 airfoil. The addition of a splitter plate disturbed the formation of a discrete frequency vortex street, so that only a broadband T–S contribution remained, however the addition of artificial feedback from external acoustic forcing was found to excite a discrete frequency. The authors claimed that this demonstrated the role of an acoustic feedback loop in the frequency selection of trailing edge noise. Ikeda et al. [11] numerically found that a NACA 0012 at zero angle of attack was governed by the wake instability only, yet for non-zero angle of attack instability waves were present in the suction side boundary layer which were attributed to an acoustic feedback mechanism. Jones et al. [12] performed a numerical simulation of the flow around a NACA 0012 airfoil. A ‘wavepacket’ perturbation was applied to the flow field, and this was found to be sufficient to set up a self-sustaining oscillation.

In summary, a number of different findings have been made regarding the mechanisms involved in the generation of the noise. Further experimental or numerical avenues in the investigation of airfoil tonal noise would be helpful towards clarifying the mechanisms. To this end, a variation in trailing edge noise tonal frequency produced by the flow when a circular cavity was present in a NACA 0018 compared to the same airfoil without a cavity was identified by van Osch [22], however no explanation for the behaviour was provided by the author. It should be expected that the tone generation mechanisms for airfoils with cavities will be similar to closed profile airfoils as a laminar boundary layer will re-form downstream of a cavity in the surface of an airfoil given a sufficiently low Reynolds number.

This paper discusses trailing edge noise produced by a nominally two-dimensional airfoil with a rectangular cavity. This airfoil profile was designed for the investigation of cavity noise, however at Reynolds numbers below the onset of cavity oscillations [26] the profile was found to produce airfoil tones whose frequencies varied with cavity position. In the paper, the general characteristics of the noise are first shown to be consistent with previous observations for airfoil tonal noise.