A REVIEW OF TRAILING EDGE NOISE GENERATED BY AIRFOILS AT LOW TO MODERATE REYNOLDS NUMBER

E.J.G. Arcondoulis, C.J. Doolan, A.C. Zander and L.A. Brooks
School of Mechanical Engineering, University of Adelaide, SA 5005

This paper contains a detailed literature review of research findings regarding the cause of flow-induced noise created by airfoils operating at low to moderate Reynolds numbers. There are many important engineering applications that operate at these conditions. More investigation is required to understand why airfoils in this range of Reynolds numbers produce high levels of tonal noise. As discussed in this paper, there are still many uncertainties surrounding the nature of the source.

INTRODUCTION

Airfoils produce tonal and broadband noise at low to moderate Reynolds number flow conditions (50,000 < Re < 200,000; Re = UL/v, where U is the freestream velocity, L is the airfoil chord and v is the kinematic viscosity of the fluid). Many important engineering applications (including micro-wind turbines, compressor and cooling fans, small unmanned air vehicles and submarines) operate at this flow condition and hence it is important to understand and control this undesired noise.

The tonal and broadband noise is produced in the vicinity of the trailing edge of an airfoil [1]. Although there is no consensus, various explanations for the trailing edge noise mechanism have been proposed. Quadrupole noise sources in the boundary layer and near wake are made more efficient through a diffraction process at the sharp trailing edge, forming a cardioid directivity pattern [1], [2]. Sound at certain acoustic frequencies is thought to be amplified, via an acoustic feedback mechanism near the trailing edge [3], [4], [5], [6]. There exists some disparity in the explanations for this mechanism and where the origin of the feedback loop is located. A schematic diagram illustrating the fluid flow and cardioid directivity pattern is provided in Figure 1.

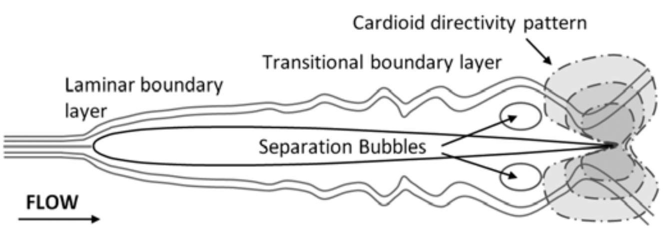

Figure 1: Schematic diagram of low to moderate Reynolds number and 0° angle of attack airfoil fluid flow and cardioid directivity pattern.

This aim of this paper is to provide a review of airfoil trailing edge noise mechanisms at low to moderate Reynolds number. The flow structure around an airfoil in this flow regime is described, followed by an explanation of the diffraction and acoustic scattering observed at the trailing edge and the nature of the trailing edge noise. The postulated feedback mechanisms causing this trailing edge noise are then discussed and summarised.

FLOW STRUCTURE

At low Reynolds number, the flow about airfoils has different characteristics from that found at high Reynolds number. Sandberg et al. [2] show that at Re = 50,000 and 0° angle of attack, laminar boundary layers form initially on the airfoil surfaces but unsteady disturbances appear (Tollmein Schlicting or T-S waves) that are the first stages of transition to a turbulent state. Depending on local flow conditions, the boundary layer may also separate, creating an oscillating shear layer. These unsteady flow fields are on each side of the airfoil and interact at the trailing edge, forming a complex wake [7].

At non-zero angles of attack, the flow structure is asymmetric about the airfoil chord. The boundary layers on each side of the airfoil grow and become more unstable at different rates relative to the distance from the airfoil leading edge. The boundary layer on the suction side of the airfoil becomes highly unsteady and generally separates from the airfoil, forming an unstable shear layer. The separation takes place further upstream than the 0° case, resulting in a turbulent shear layer at the trailing edge. The pressure side boundary layer generally remains laminar along the entire chord for relatively low angles of attack.

DIFFRACTION AND ACOUSTIC SCATTERING

A more complete description of the edge diffraction process is given in Figure 2, which replaces the airfoil with a semi-infinite half plane. The noise sources in the boundary layer are now represented as quadrupoles [8] that can be considered as a pair of dipoles whose major axes are orthogonal. Five quadrupoles are drawn so that the major axis of one of the dipole pairs is oriented towards the sharp edge. When a wave from a dipole encounters the edge, a diffracted wave is produced that travels back towards the quadrupole with opposite phase. This diffracted wave combines with outgoing waves from the other side of the dipole (that has similar phase to the diffracted wave) to create an efficient source of sound. In this way, one side of the quadrupole is made an efficient radiator of sound and results in the cardioid directivity pattern commonly associated with trailing edge noise [1], [9].

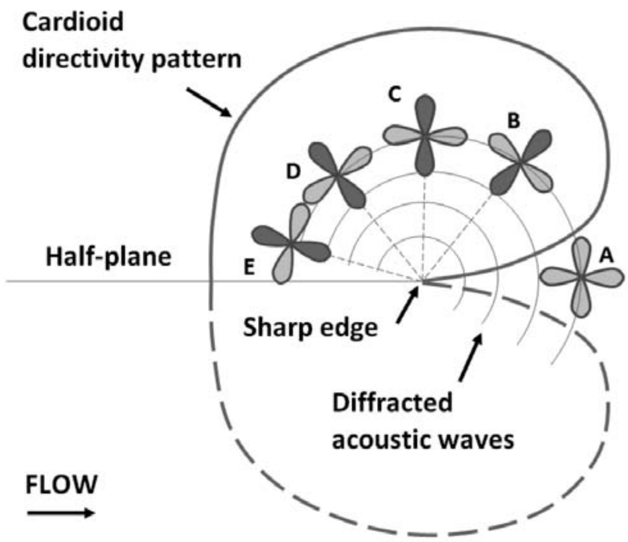

Figure 2: Cardioid directivity pattern of the noise emitted from eddies in various locations relative to a sharp edge.

THE NATURE OF TRAILING EDGE NOISE

The noise generated by airfoils at low to moderate Reynolds number can be generally classified as either tonal or broadband. The noise is observed to contain a superposition of discrete tones on a broadband hump [3], [10]. This is demonstrated in Figure 3 which presents the noise spectra generated by a NACA0012 airfoil at a Reynolds number of 75,000 and 0° angle of attack. Figure 3 shows a primary tone (*fn,max*) and a series of secondary tones (*fn*) [3]. The broadband hump (*fs*) is also evident in Figure 3 and is defined as the centre frequency of the broadband noise component.

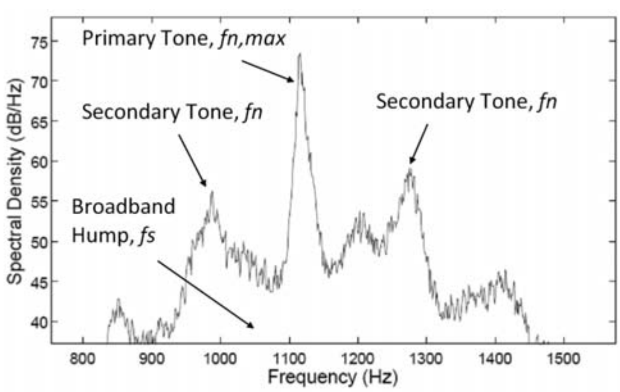

Figure 3: Noise Spectra for a NACA0012 airfoil at a Reynolds number of 75,000 and 0° angle of attack [10].

Broadband noise is due to a large number of incoherent eddies with a variety of sizes and strengths. The tonal noise however is due to reasonably coherent and strong eddies in the trailing edge region. The questions of how tonal noise is generated and why some eddies are more coherent and stronger than others remain unsolved. Many studies have attempted to answer these and other related questions regarding low Reynolds number trailing edge noise.

The first comprehensive study of airfoil self-noise at low to moderate Reynolds numbers was performed by Paterson et al. [11]. They presented the measured tonal noise frequency for each flow velocity case and observed that for a small increase in flow velocity, *U*, the primary tonal noise frequency (*fn,max*) would increase by $U^{0.8}$. At certain flow velocities, the tonal frequency was seen to instantly "jump" to a higher frequency, forming a new 0.8 power relationship with velocity. This overall pattern of increasing frequency with respect to $U^{0.8}$ for a given velocity range forms a "ladder structure" [3], [12], [13]. Looking at a range of Reynolds numbers and angles of attack, there are many $U^{0.8}$ power curves. If a line is fitted through all these data points, the overall frequency dependency will fit a $U^{1.5}$ curve, given by

$$f = \frac{0.011U^{1.5}}{\sqrt{Cv}} \tag{1}$$

where f is the frequency of the primary tone, U is the fluid freestream velocity, C is the airfoil chord length and v is the kinematic fluid viscosity. Figure 4 shows the results of Arbey and Bataille [3], displaying this ladder structure.

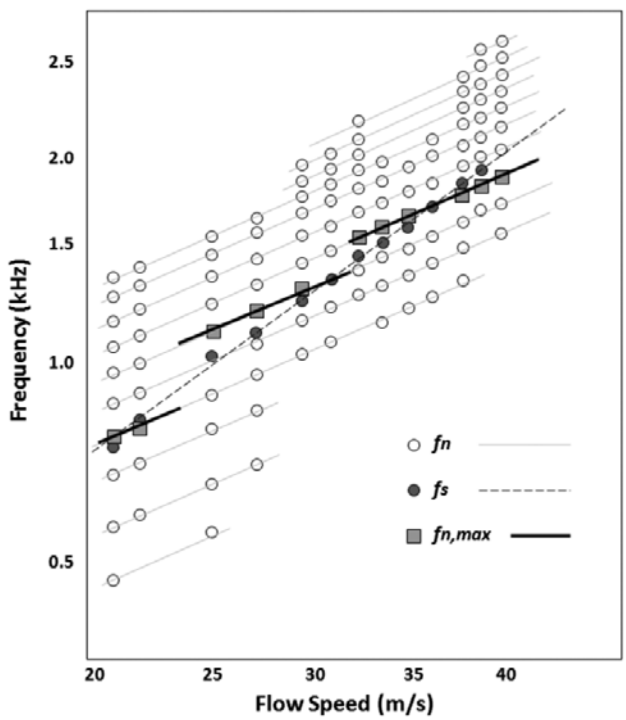

Figure 4: Ladder-type evolution of the dominant discrete frequency, *fn,max*, for a NACA0012 airfoil with 160mm chord. Adapted from [3].

Arbey and Bataille [3] show that for the same airfoil profile at 0° angle of attack, increasing the Reynolds number (by increasing the freestream flow speed and/or airfoil chord) results in a decrease in the primary tonal noise amplitude

($f_{n,max}$). This implies that there exists a Reynolds number for a given airfoil and angle of attack that results in the greatest tonal noise amplitude. Note that the quantity and amplitude of the secondary tones (f_n) are also influenced by the increase in Reynolds number. The main frequency (f_s) was observed to have a Strouhal number dependence, based on the boundary-layer thickness at the trailing edge. Arbey and Bataille [3] also confirmed that the broadband contribution is a result of the diffraction of pressure waves at the trailing edge.

Preliminary investigations show that the primary tonal noise frequency can be estimated using a parametric fit to empirical data [11], but there is still no formal method for determining which angle of attack and Reynolds number causes the greatest tonal sound pressure level for an airfoil under low to moderate Reynolds number flow conditions.

FEEDBACK MECHANISM

Although there have been many investigations into the causes responsible for the trailing edge noise of airfoils in low Reynolds number flow regimes, there is no general consensus amongst the acoustic community for the cause of tonal trailing edge noise. Further, insufficient experimental measurements have been performed to confirm the mechanisms proposed in the literature. The following is a discussion of the various proposed causes of tonal noise.

Paterson et al. [11] postulated that the observed ladder structure behaviour was due to a vortex shedding phenomenon, located at a distance downstream of the trailing edge. Tam [12] disputed Paterson et al.'s [11] explanation of the cause of the tonal noise, arguing that vortex shedding noise is Strouhal number dependent, which is inconsistent with the data of [11]. Tam [12] recognised the $U^{1.5}$ increase of the tonal noise frequency; however, he claimed that this was only an empirical fit over a large frequency range and did not capture the detail of the ladder structure.

Tam [12] proposed that the ladder structure of tonal noise was due to a self-excited feedback loop of aerodynamic origin. Acoustic disturbances originating at the sharp trailing edge propagate downstream along the airfoil wake. When these disturbances are of sufficient magnitude they induce lateral oscillations in the wake, resulting in the emission of acoustic waves. A portion of the acoustic wave energy is propagated upstream to the pressure side of the airfoil near the trailing edge, forcing the boundary layer to oscillate, thereby completing a feedback loop.

Arbey and Bataille [3] agree in some aspects with Tam [12], in that the existence of regularly spaced discrete tonal frequencies is linked with an aeroacoustic feedback mechanism. However, they propose that hydrodynamic fluctuations (which generate acoustic waves as they are diffracted at the trailing edge) propagate upstream to a point on the airfoil where the hydrodynamic instabilities are formed. This explanation differs from that of Tam [12] in both the location at which the acoustic feedback loop closes and the distance from which the acoustic source is located relative to the trailing edge.

Arbey and Bataille [3] suggest that the location of the hydrodynamic instabilities is the point of maximum flow velocity in the laminar boundary layer. If both the acoustic wave and the hydrodynamic fluctuation frequency are in phase at this location, the hydrodynamic fluctuation will become amplified [12], [14]. This fluctuation then propagates downstream, thus closing the feedback loop.

Nash et al. [13] disagreed with others ([3] and [12]) and proposed that the feedback mechanism responsible for the tones is based on a vortex shedding process. As the unstable boundary layer forms, T-S waves continue to grow as they propagate toward the trailing edge of the airfoil and begin to roll up into a vortex. The interaction of this vortex with the trailing edge generates a scattered oscillating field around the airfoil which oscillates at the same frequency as the T-S wave. This oscillating field extends upstream to approximately half the chord which is close to the point at which the boundary layer becomes unstable.

Nash et al. [13] hypothesise that the oscillating mean flow provides an upstream feedback mechanism for the most amplified instability, resulting in the narrow-band acoustic tones observed. However, McAlpine et al. [15] suggest that the vortex shedding at the pressure side owing to the separation bubble acts in a similar way to the vortex shedding behind a cylinder. They propose that there is a small region of instability close to the body, which explains why the vortex shedding is a self excited mechanism. Nash et al. [13] also identify that previous work has neglected the influence of a laminar separation bubble near the trailing edge and its influence on the tonal noise generating mechanism.

Nash et al. [13] agree with Arbey and Bataille [3] in that there exists a point upstream of the trailing edge which is responsible for the activation of an acoustic instability via the amplification of T-S waves. While Arbey and Bataille [3] identify this location as the maximum boundary layer velocity on the airfoil, Nash et al. [13] do not refer to the maximum boundary layer velocity and estimate its location as half the airfoil chord.

Nakano et al. [4] indicate from their experimental results of a NACA0018 airfoil that the tonal noise source is distributed on the trailing edge region of the pressure surface. The periodic variations of the velocity field are observed in the separating region on the pressure surface, which is followed by upwash and downwash motion at the trailing edge of the airfoil. This separating region is also observed by Nash et al. [13] for a NACA0012 airfoil. These flow phenomena over the airfoil surface result in the periodic formation of vortex streets in the wake of the airfoil. The tonal noise appears when the adverse pressure gradient on the pressure surface is sufficiently small to allow instability waves to grow slowly along the surface. They then scatter as sound when they travel past the trailing edge and propagate upstream toward the point of boundary layer instability, initiating a feedback loop.

Nakano et al. [4] and Desquesnes et al. [16] observed that a separation bubble forms near the airfoil trailing edge on the pressure side of the airfoil under non-zero angle of attack flow conditions. The existence of this recirculation bubble had already been identified as a necessary condition for the tonal noise phenomenon to occur [17]. This periodical oscillation is amplified as it approaches the trailing edge, due to the upwash and downwash motion in the downstream of the airfoil.

Desquesnes et al. [16] propose that a secondary feedback loop exists. They explain that a laminar boundary layer is formed near the leading edge of an airfoil when the flow is steady and continues along the airfoil chord until boundary layer separation occurs, leading to an unstable shear layer with T-S instability waves. The T-S waves interact with the trailing edge, forming a dipolar acoustic source. They suggest that the acoustic waves then travel upstream along the airfoil chord and generate an acoustic feedback loop, as depicted in Figure 5.

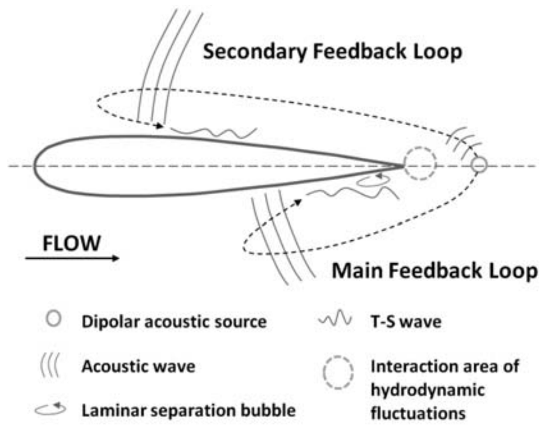

Figure 5: Schematic of the tonal noise mechanisms proposed by [16].

Desquesnes et al. [16] further explain that if the flow onto an airfoil is fast enough, or if the airfoil is located at a sufficient angle of attack, a turbulent boundary layer may form on the airfoil surface. The acoustic waves generated within the turbulent boundary layer are diffracted at the trailing edge, similar to the laminar boundary layer case, forming a dipole-like acoustic source with cardioid directivity [1]. Due to the hydrodynamic fluctuations in the immediate vicinity of the trailing edge and the turbulent nature of the flow, the noise emission is broadband. If the flow onto the airfoil is sufficient to generate a turbulent boundary layer, then the tonal noise is not observed.

The secondary feedback loop proposed by Desquesnes et al. [16] does not contradict the work of Arbey and Bataille [3]. Arbey and Bataille [3] only investigated airfoils at 0° angle of attack and Desquesnes et al. [16] only investigated non-zero angle of attack cases. It is possible that the secondary feedback loop exists in conjunction with the model proposed by Arbey and Bataille [3] at angles of attack greater than zero. It is also possible that Arbey and Bataille's [3] model could be the secondary loop shown by Desquesnes et al. [16]. A comparison of each model and their ability to predict the discrete tones of airfoil self noise for varying angles of attack has not been investigated.

Chong and Joseph [6] investigated a NACA0012 airfoil for both zero and non-zero degree angles of attack. Similar to others ([3] and [16]), they show that acoustic waves travel upstream to complete a hydrodynamic and acoustic feedback loop. They do, however, disagree with others ([3],[5],[12],[13] and [16]) and argue that the location which "closes" the feedback loop is the point at which the boundary layer instabilities on the airfoil profile originate (consistent with Nakano et al. [4]). This may not coincide with the location of maximum velocity on the airfoil profile [3] or half the airfoil chord length [13].

It should be noted that differences in the experimental results discussed may be due to varying testing conditions, such as freestream turbulence, vibration of the airfoil or other factors that can influence boundary layer transition at low to moderate Reynolds number.

OCCURENCE OF TONES

Desquesnes et al. [16] furthered previous work [3], [11], [13], [17] and generated plots of angle of attack against Reynolds number, identifying regions of the plot surface which exhibited tones or no tones. Some of these results, including some results from Arcondoulis et al. [10] are provided in Figure 6. The proposed tonal noise envelope [17] shown in Figure 6 conflicts with some of the presented data. Charts of this type for other NACA airfoil profiles are not known to the authors.

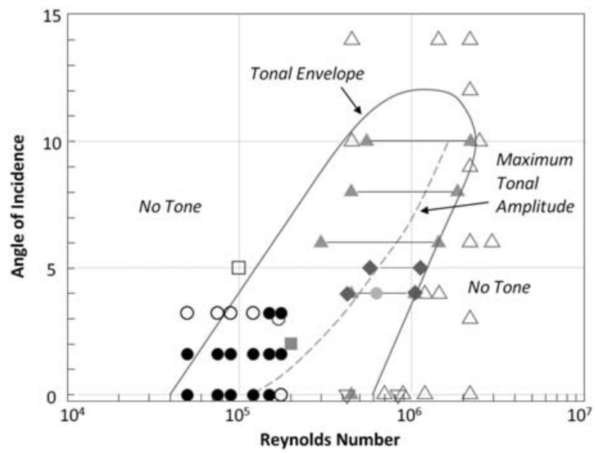

Figure 6: Pattern showing where tonal noise is likely to occur for a NACA0012 airfoil (adapted from [17]). Filled markers represent that a tone was present, whilst unfilled markers represent that a tone was not present. Data sources: shaded/unshaded circles [10], shaded/ unshaded triangles [11], unshaded inverted triangles [3], shaded/ unshaded squares [16], shaded diamonds [17]. The tonal envelope and the maximum tonal amplitude lines are from [17].

INFLUENCE OF AIRFOIL PROFILE

The aforementioned research provides a detailed investigation of specific airfoil sections with varying flow conditions. Sandberg et al. [2] identified a reverse flow region for the NACA0012 airfoil which is not displayed by the thinner airfoils. They explain that the flow oscillates around the trailing edge at the wake frequency; however they are unclear as to why there is a unique behavioural flow pattern for the NACA0012 airfoil profile. This finding suggests that the airfoil profile has a significant effect on the flow in the wake. Many of the theories suggest that the hydrodynamic instabilities in the wake are important in the structure and physics of the acoustic feedback loop. Thus it can be deduced that the airfoil profile influences the nature of the acoustic feedback mechanism.

SUMMARY

This paper has reviewed previous work on trailing edge noise generated by airfoils at low to moderate Reynolds number. The flow structure around an airfoil is reasonably well established; however, the physics of the feedback mechanism which results in the production of tonal noise is still unclear. Understanding the processes which cause this tonal noise is important, as this will allow advancements in quieter designs of engineering applications involving airfoils. There are many unresolved areas in this field of research, which are summarised in the text below and where appropriate, in Figures 7 and 8.

- There are limited mean and unsteady velocity data for various NACA airfoil profiles, for various angles of attack and at low Reynolds number.
- A comprehensive understanding of tonal noise production at various Reynolds numbers, angles of attack and for different airfoil profiles (obtained in an anechoic environment) has not yet been obtained.
- The effect of the airfoil profile on the tonal and broadband noise components for various Reynolds numbers and angles of attack has not been comprehensively investigated.
- There is no consensus on the location and physics of the activation of the acoustic feedback loop(s). Also, the position on the airfoil chord where the acoustic feedback loop(s) is (are) closed on the airfoil chord is not resolved. These require investigation.
- There does not yet exist an accurate model which predicts the magnitudes of the primary and secondary tones and the broadband noise.

FUTURE WORK

It is the intention of the authors to further pursue this ongoing study at the University of Adelaide, via the use of more refined experimental methods, including the use of aeroacoustic beamforming in conjunction with hot-wire anemometry. It is anticipated that a greater understanding of the acoustic feedback mechanism for the trailing edge noise of airfoils at low to moderate Reynolds number will be obtained.

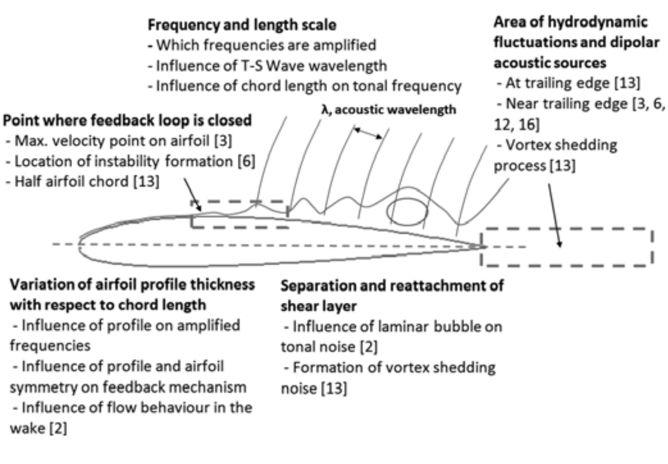

Figure 7: Summary of some of the unresolved flow features and acoustic feedback mechanism characteristics of an airfoil at 0° angle of attack.

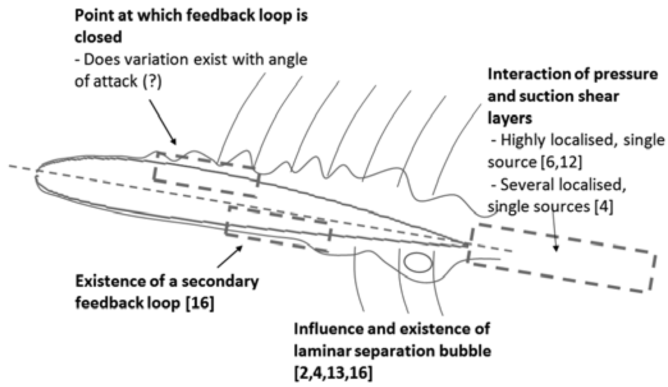

Figure 8: Summary of some of the unresolved flow features and acoustic feedback mechanism characteristics of an airfoil at non-zero angles of attack.

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