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Discrete Tonal Noise of NACA0015 Airfoil at Low Reynolds Number

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ABSTRACT

This paper is a pilot study of the effect of external forcing and passive control on the generation of airfoil whistle noise. Interaction between instability travelling inside laminar boundary layer with the airfoil trailing edge produces discrete tonal noise. This phenomenon commonly found at low-to-moderate Reynolds numbers. The characteristics and behavior of tonal emissions at low Reynolds number differs from that at higher Reynolds number. Therefore, the purpose of this work is to study the discrete tonal noise generated by laminar boundary layer instability at low Reynolds number as well as at a variation of angle of attack. Experimental testing on NACA0015 was done in the anechoic wind tunnel to measure the sound spectrum at Reynolds number of $Re{\sim}10^4$ and angle of attack of $0°\leq\alpha\leq5°$. This work is intended to provide additional information to the tonal behavior of NACA series airfoil. Flow separation without reattachment occurs on the suction side within the selected Reynolds number and angle of attack. No tonal sound was found if f_s falls below 40dB. At low Reynolds number, airfoil discrete tone consists of high intensity f_s accompanied by more pronounced f_n as freestream velocity increases. Airfoil tonal noise gradually decreases as angle of attack increases from α=0^° before disappearing beyond α=5°. Moreover, previously proposed empirical models to predict f_s were found to have limitation in predicting tonal frequency at low Reynolds number at a variation of angle of attack. In addition, general observation shows f_n has a velocity dependency of $\sim U^{0.8}$ while f_s is prone to exhibit ladder structure behavior with velocity dependency of $\sim U^{1.3}$.

Keywords:
Discrete tonal noise, flow Instabilities, anechoic wind tunnel

1. Introduction

Airfoils operating within low to moderate Reynolds numbers were found to generate whistle-like tonal noise. This noise is usually distinct and can be irritable to an observer and may be encountered in everyday life on any airfoil-shaped structures, fan, turbines, and etc. It is of importance to understand the behavior and the conditions at which this tonal noise is generated. This paper aims to investigate discrete tonal noise generated by NACA0015 airfoil at low Reynolds numbers at a variation of angle of attack. It is hope that experimental investigation on NACA0015 will provide

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additional information to the tonal noise behavior of the NACA series airfoil.

1.1 Previous Study on Airfoil Tonal Noise Characteristics

It has been established that the tonal noise is generated due to the instability travelling inside the laminar boundary layer known as the Tollmien-Schlichting waves (TS-waves) and is exponentially growing in nature. When these instabilities arrive at a discontinuity such as an airfoil trailing edge, their interaction radiated high intensity sound [1]. However, the existence of the TS-waves alone is not sufficient in generating high intensity tonal noises. The naturally amplified TS-waves must undergo massive amplification at separated flow region where laminar separation bubble must remain close to the trailing edge [2]. Since laminar separation bubble is a must criterion in airfoil tonal emission, Nash *et al.,* [2] further stated that the adverse pressure gradient near the trailing edge must not be too strong which will inhibit flow reattachment leading to no laminar bubble.

Laminar boundary layer on the pressure side was found to be a major contributor in the tonal emission. Forced transitions using tripping method on the airfoil suction and pressure sides as a flow control to suppress the tonal noise were done to investigate airfoil tonal noise characteristics [3-6]. Little changes on the tonal noise when tripped on the airfoil suction side whereas, tonal suppression was found when tripped on the airfoil pressure side.

Intensive research has been directed to investigate the causes of airfoil tonal emission since Clark [7] first discovered it. The airfoil tonal noise is composed of both broadband noise with centered frequency f_s as well as a superposition of secondary discrete tonal noise of frequency f_n, where n refers to the tone group of each individual frequency. The discrete frequency consists of a primary frequency with the highest intensity f_{n-max}, which later was found to be closed to f_s. Past works have defined f_s differently, in the current study, f_s is regarded to be equal to f_{n-max}, which is the primary frequency with the highest intensity in the sound pressure level spectrum.

An empirical model to predict f_s obtained from experimental tests on NACA0012 at a range of freestream velocities at a single angle of attack of $\alpha = 0^{\circ}$ is as shown in Eq. 1 [8]. The displacement thickness at the trailing edge is denoted as $\delta^*{}_{TE}$ whereas St_s is determined as 0.048.

$$f_s = \frac{St_s U}{\delta^*{}_{TE}} \tag{1}$$

In a different experimental study, airfoil noise due to laminar boundary layer vortex shedding of NACA0012 was investigated at a wide range of angle of attack from 0° to 25.2°. A prediction model was proposed to calculate the primary tonal noise as shown Eq. 2 [9].

$$f_s = \frac{St' U}{\delta_P} \tag{2}$$

This empirical model considered the blockage effect due to the deflection of an open jet boundaries during testing in the open jet anechoic wind tunnel. It was argued that the pressure distribution around an airfoil at a specific condition might differ from another and this will directly affects the measured tonal noise emission. Therefore, effective angle of attack was considered in order to match the lift coefficients (hence, the pressure distributions) in true flight with the experimental conditions [10]. Moreau and Hanner [11] numerically shows the pressure distribution of NACA0012 reasonably match an infinite domain at the effective angle of attack. Nonetheless, the blockage effect is assume to be negligible and is not considered in the present work. In addition, in Eq. 2, the Strouhal number St' as well as the boundary layer height on the pressure side δ_P is associated with the effective angle of attack α_* as well as the Reynolds number. Nonetheless, the Strouhal number St' was drawn to approximate the data at angle of attack $\alpha = 0^\circ$. Early speculation expects a deviation in the measured peak tonal noise as angle of attack varies when compared with this empirical model. Moreau *et al.,* [12] has shown that the empirical model able to predict well the trailing edge noise from a wall-mounted finite airfoil. However, the trailing edge noise calculated from the empirical model deviates from the measured trailing edge noise as the angle of attack increases.

Paterson *et al.,* [4] proposed an empirical model to predict the primary frequency as shown in Eq. 3.

$$f_s = KU^{1.5}/(cv)^{0.5} \tag{3}$$

This prediction model is anticipated to give noticeable deviation in predicting the peak frequency at a variation of angle of attack as it only considers the mean behavior of f_s. Moreover, Tam [13] estimated the discrete frequency as shown in Eq. 4 considering the tone group n to describe the phase condition. However, the work by Tam [13] has been further modified. It has been shown that the discrete frequency obeys the power law of $\sim U^m$ where m is found to be in the range of $0.8 \leq m \leq 0.85$ [8].

$$f_n = 6.85nU^{0.8} \tag{4}$$

The generated discrete tonal noise as observed by Paterson *et al.,* [4] and its ladder structure behavior has received unusual attention. Paterson *et al.,* [4] associated the generation of tonal noise with vortex shedding. It was considered that to base the tonal noise on only vortex shedding, as explained by Paterson *et al.,* [4], is not sufficient. However, it also involves with acoustic feedback mechanism [13-15]. The existence of laminar separation bubble was found on the pressure side of a flat plate [16]. A feedback loop concept was proposed to exist between the laminar boundary layer instabilities and the sound source generated near the trailing edge. The concept stated that the noise generated near the trailing edge radiates back upstream to the point of maximum velocity to create feedback loop. Arbey and Bataille [8] confirmed the proposed concept in their work, stating that the discrete tonal noise is associated with acoustic feedback mechanism.

1.2 Acoustic Feedback Mechanism

In a much recent study, stability analysis study employing direct numerical simulation was carried out to study airfoil tonal noise emission [17-19]. Jones and Sandberg [17] confirmed the present of tonal noise as well as acoustic feedback loop is associated with airfoil trailing edge. However, acoustic feedback was not found in the work of Tam and Ju [18] although the tonal noise is present. DNS as well as experimental study by Desquesnes *et al.,* [19] showed that the primary tonal frequency was found to be due to the most amplified TS-wave passing the trailing edge. Bubble separation near the trailing edge region was discovered to provide further amplification to the naturally amplified TS-wave consequently, inducing vortex shedding which generates tonal noise as it passes through the trailing edge. This interaction is said to generate dipole noise and will be radiated back upstream as acoustic waves. Desquesnes *et al.,* [19] further stated that the boundary layer on the suction side is found to be highly receptive to the main tonal noise generated on the pressure side. Thus explaining the acoustic feedback mechanism where laminar boundary layer instability on the suction side is further amplified and interacts with the trailing edge to generate discrete tonal noise which is different from the primary tonal frequency resulting in the observed discrete tonal noise.

1.3 Present Study on Airfoil at Low Reynolds Number

Previous research studying airfoil tonal emission were mostly directed at moderate Reynolds numbers in the range of $\sim 10^5$ and $\sim 10^6$. Current study focuses on the characteristics of airfoil tonal noise at low Reynolds number. In order to study the airfoil tonal noise at low Reynolds numbers, it is first necessary to understand the flow structure as well as the laminar boundary layer instability that exists in this flow regime. The flow over airfoils at low Reynolds numbers differs from that found at higher Reynolds numbers. At low Reynolds number, the TS-waves travelling inside the laminar boundary layer are amplify in the separated shear layer as the adverse pressure gradient builds on the airfoil surface [20-21]. The laminar boundary layer separates from the airfoil surface and rapidly transits to turbulence by generating unsteady vortex structures [20-22]. The separated flow separated and reattaches as turbulent flow provided adequate adverse pressure gradient, forming laminar separation bubble on the airfoil surface. However, there is a possibility of boundary layer separation without flow reattachment; thus, no laminar separation bubble is formed [23].

Tripping method may be used to investigate the existence of the separation bubble on airfoil surface. Forced transition was done on NACA0015 by employing tripping method at a range of angle of attack of $0^{\circ} \leq \alpha \leq 5^{\circ}$ and at low Reynolds number [5]. Insignificant changes on the airfoil noise were measured when tripped at the suction side at all angle of attack. In a different study, numerical and experimental study on NACA0015 airfoil at a range of low Reynolds numbers found that separation starts to take place on the suction side from the trailing edge as angle of attack increases from $\alpha = 0^{\circ}$ [24]. Therefore, Lee *et al.,* [5] deduced that flow separation occurs without reattachment on the suction side. On the other hand, tripping the pressure side up to 75% chord was able to suppress tonal emission. Tripping the airfoil at which the separation bubble present known to deteriorate the airfoil noise. Therefore, it was concluded that that separation bubble exist approximately beyond 75% of the airfoil chord.

2. Methodology

Measurements of airfoil noise were made in KAIST anechoic wind tunnel with anechoic chamber size of $4.8 \ \times 5.8 \ \times 4.0^{(H)}$. The schematic of the wind tunnel is as shown in Figure 1. In order to minimize wall reflection in the chamber, the walls are acoustically treated with foam wedges. The chamber has background noise lower than 30 dB and a cut-off frequency is found to be 180 Hz. The background noise magnitude is considered relatively small in the frequency range of interest. The generated airfoil tonal noise is expected to be in the high frequency range <1000 Hz therefore, the background noise is adequate for airfoil noise assessment. The wind tunnel is an open circuit suction type with a test section size of $0.35 \ \times 0.35 \ \times 1.1^{(L)} \ m$. The test section has an open-jet test section and a maximum speed of 62.8 m/s with turbulent intensity lower than 0.1%. Experiment was conducted at a range of speed of 20 m/s < U < 30 m/s as well as at angle of attack ranges from $0^{\circ} \leq \alpha \leq 5^{\circ}$.

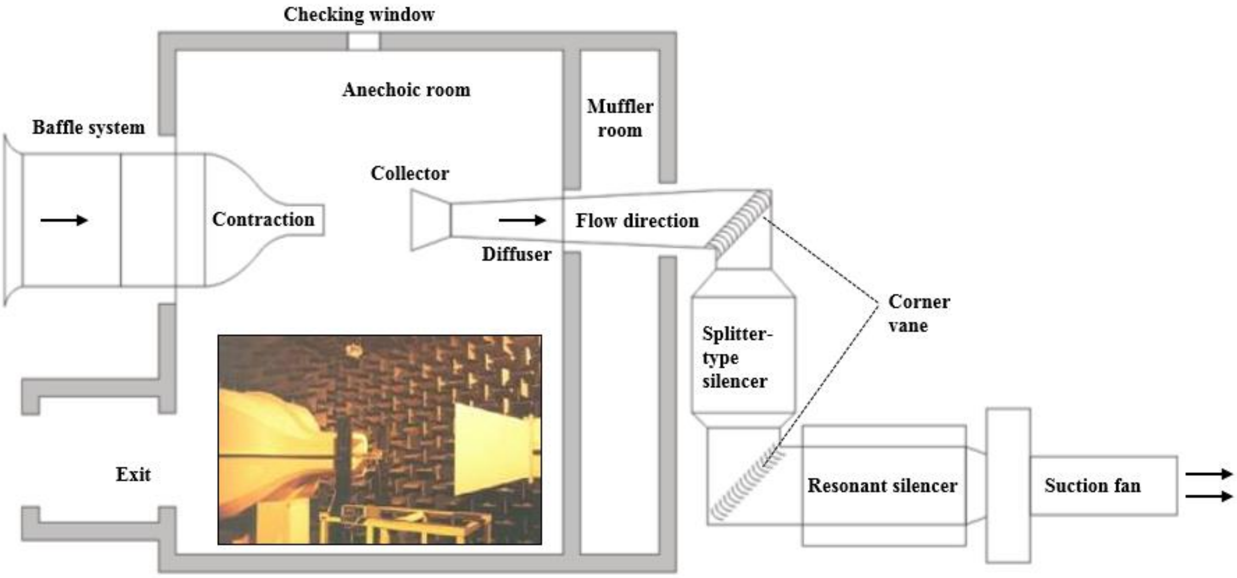


Fig. 1. Schematic of KAIST anechoic wind tunnel

The airfoil under investigation is NACA0015 with chord length of 50 mm and a span of 350 mm. The airfoil is placed horizontally in the test section and is held by an acrylic panel at both sides. The airfoil noise spectrum was measured using a single microphone measurement. The microphone is a half-inch B&K microphone with nominal sensitivity of 50 mV/Pa as well as flat frequency response up to 20 kHz. Its sensitivity was calibrated using B&K 4231 sound calibrator before measurement was carried out. The microphone was mounted at the mid-span of the airfoil directly 0.9m above it, at this distant, it is sufficient to avoid flow disturbance. The schematic for the acoustic measurement is as shown in Figure 2.

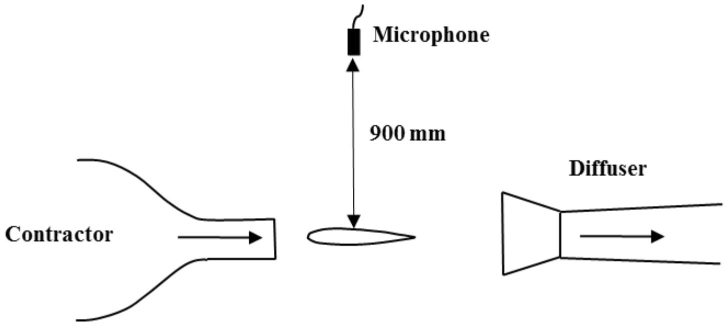
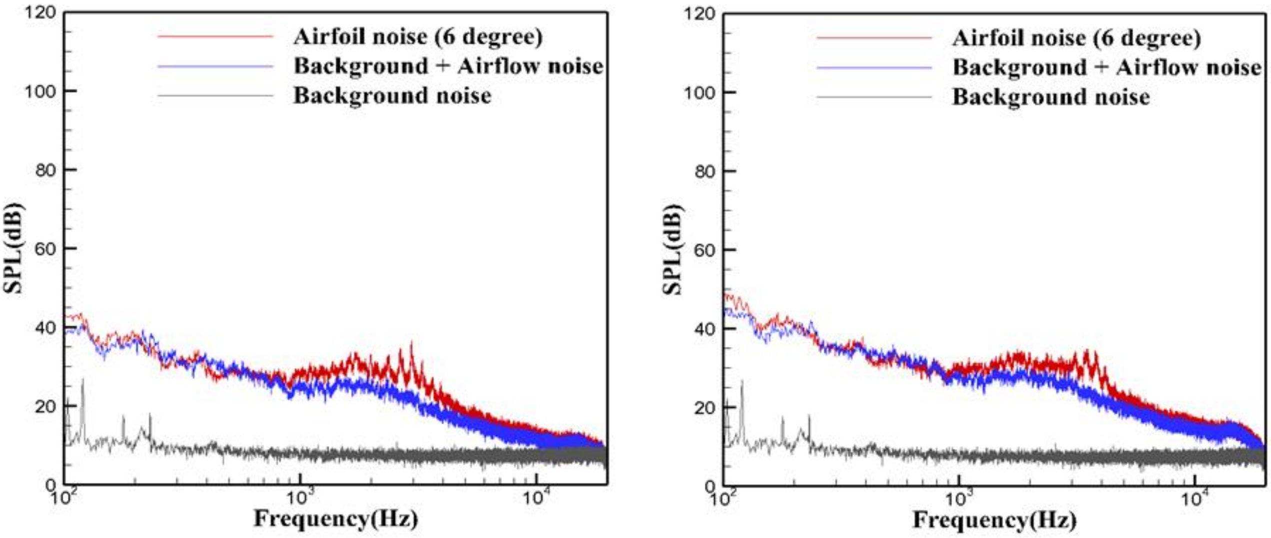


Fig. 2. Side view schematic of acoustic measurement (not drawn to scale)

3. Results

Previous research mostly directed in the study of airfoil tonal noise of NACA0012 airfoil whereas; current study is intended for NACA0015 airfoil. These airfoils are anticipated to give similar trend and behavior even though direct comparison is not possible. The measured noise characteristic does not represent the general trend of behavior for the airfoil tonal noise and is only valid for the measured range of freestream velocity. As it is known that, the tonal emission is highly dependent on both Reynolds number and angle of attack. The noise spectra of the airfoil noise in the present study are measured within a range of Reynolds numbers of $7.0 \times 10^4 \leq Re \leq 9.5 \times 10^4$ and at angle of attack from 0^0 to 5°. Multiple peaks at low frequency range was found in the measurement of chamber background noise, the worst case of background noise magnitude is 27 dB at frequency of 120 Hz. this magnitude is considered relatively small in the frequency range of interest. The measured tonal noise is of high frequency range of $1000\ Hz < f_n$. Thus, the chamber background noise is adequate for airfoil noise measurement.

It was found that the peak frequency needs to be at least 40dB in order to produce noticeable tonal noise. Tonal peak fall less than 40 dB will be considered as 'no tone'. No tonal emission was found beyond $\alpha = 5^{\circ}$ at all freestream velocity. The measured sound spectrum at $\alpha = 6^{\circ}$ is as shown Figure 3. The chamber background noise is indicated by the greyscale line, the blue line represent the airflow noise without airfoil installed in the test section. The red line indicated the measurement with airfoil mounted in the airflow. Although small steady peak is still present in the sound spectrum, however, no distinguishable tonal sound audible during testing.



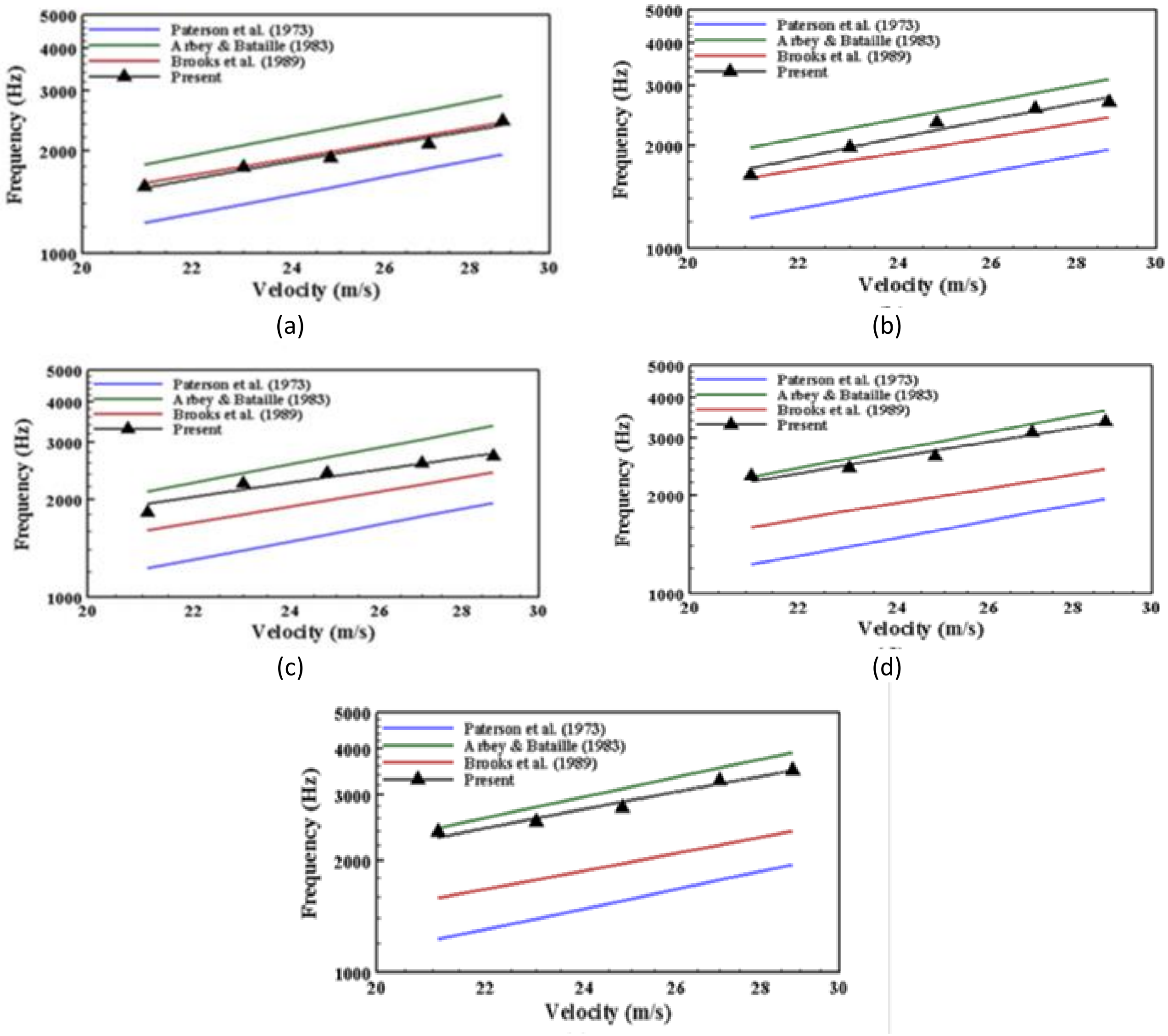
(a) (b)

Fig. 3. Sound spectrum at $\alpha = 6^{\circ}$ at freestream velocity (a) 24.8 m/s and (b) 28.8 m/s

3.1 Validation of Peak Frequency f_s

Peak frequency f_s as compared with existing prediction models are as shown in Figure 4. The tonal noise produced at $\alpha = 5^{\circ}$ is relatively low; discussion at this angle of attack will be overlook for the time being. It is worth mentioning that the tonal behaviour at this angle still obeys the characteristics of tonal noise at low Reynolds number airfoil. Measured tonal noise was found to be at higher frequencies at all angle of attack compared to the prediction model suggested by Paterson *et al.* [4]. The deviation is expected because this prediction model considered the mean behavior of the primary frequency.

The measured peak frequency is in good agreement with prediction model of Brooks *et al.,* [9] at low angle of attack specifically at $\alpha = 0^{\circ}$(Figure 4(a)). However, the empirical model was found unable to predict well the primary frequency f_s at higher angle of attack; this is similar as observed by Moreau *et al*., [12]. Airfoil boundary layer prediction at low Reynolds number may be the cause of the deviation. The measured peak frequency was found to gradually shifting upward and is in reasonable agreement with prediction model of Arbey and Bataille [8] specifically at $\alpha = 3^{\circ}$in Figure 4(d) and $\alpha = 4^{\circ}$ (Figure 4(e)). The suggested Strouhal number by Arbey and Bataille [8] was found relatively too high to give good prediction at lower angle of attack. Although these prediction models were empirical models drawn from NACA0012, in general, they were found to predict well the value of f_s for NACA0015 operating at low Reynolds number.



(a)

(b)

(c)

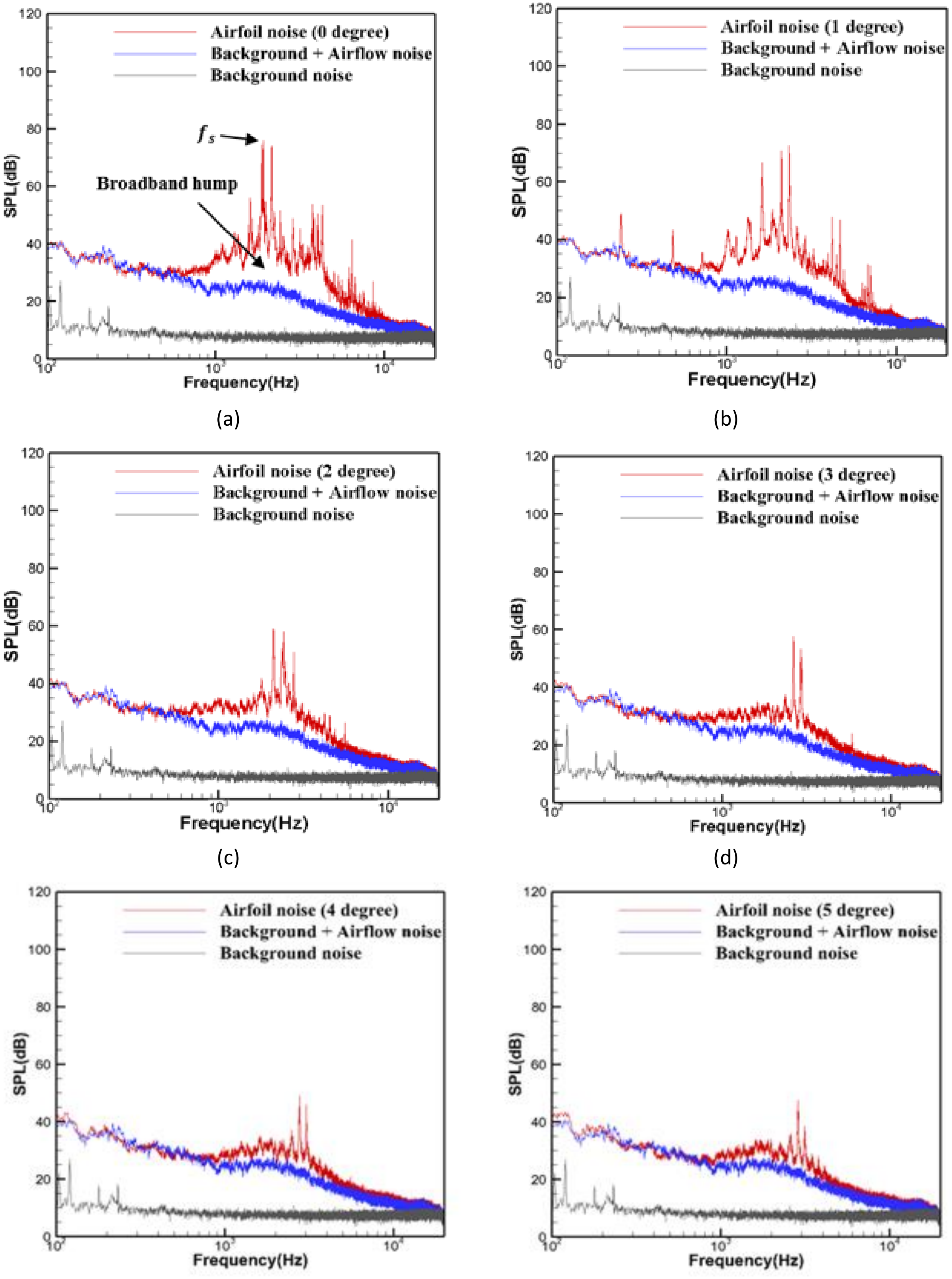
(d)

(e)

Fig. 4. Comparison of measured peak frequency f_s at (a) $\alpha = 0^{\circ}$ (b) $\alpha = 1^{\circ}$ (c) $\alpha = 2^{\circ}$ (d) $\alpha = 3^{\circ}$ (e) $\alpha = 4^{\circ}$

3.2 Airfoil Sound Spectrum with Respect to Angle of Attack

Sound spectrum with respect to angle of attack at freestream velocity 24.8 m/s and 28.8 m/s are as shown in Figure 5 and Figure 6 respectively. The strength of the tonal noise, both f_s and f_n is the highest at $\alpha = 0^{\circ}$ as shown (Figure 5(a)) and (Figure 6(a)) respectively. The tonal noise diminishes in strength as the angle of attack increases at all tested freestream velocities. In addition, the broadband hump loses its strength as angle of attack increases. The broadband hump barely exceeds the background noise at $\alpha = 5^{\circ}$ (Figure 5(f)). Only weak traces of tonal noise are present at this angle of attack. Moreover, the tonal noise was found to fall below 40 dB and no tonal noise found at 28.8 m/s (Figure 6(f)).

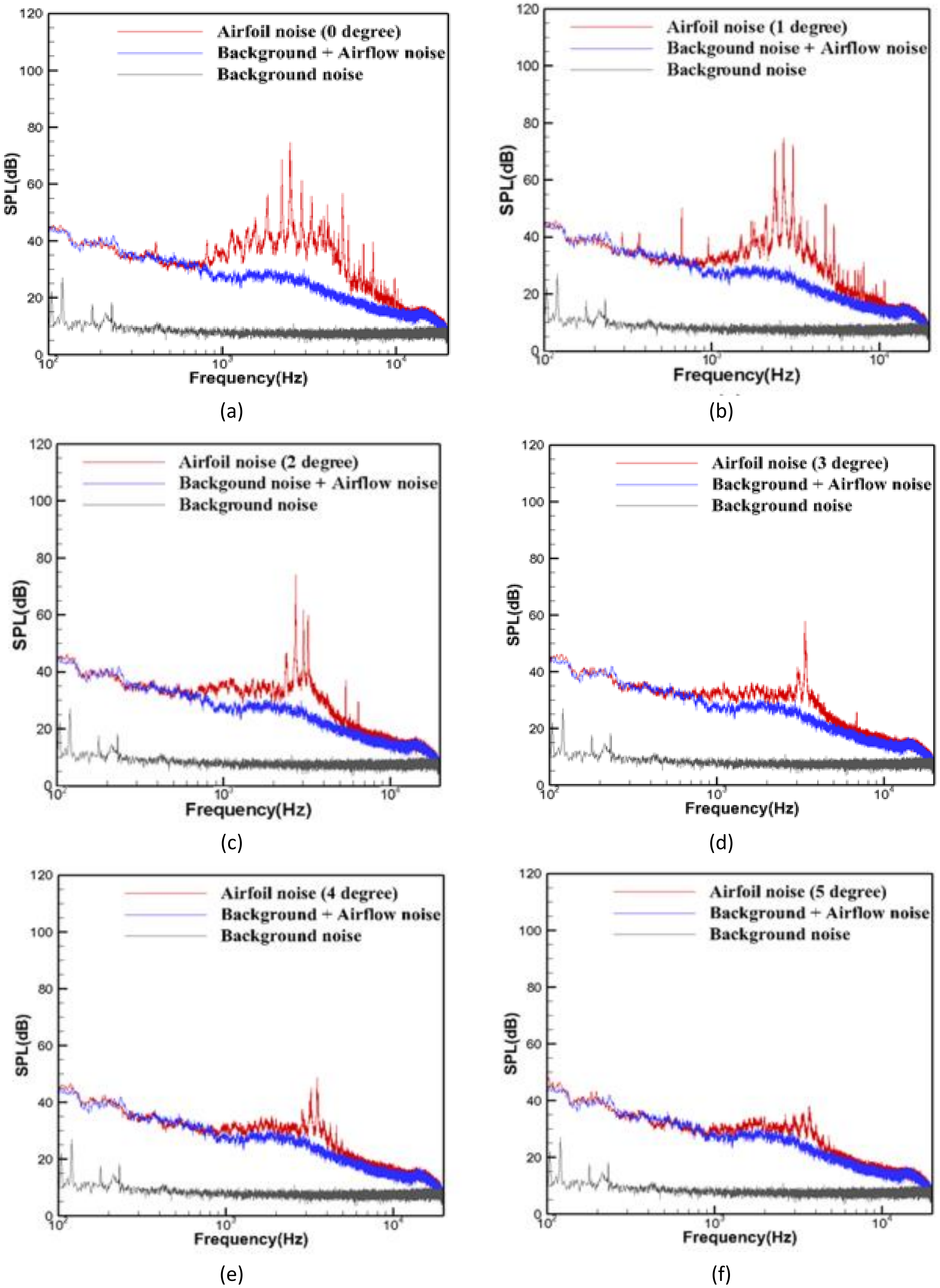


(a) (b)

(c) (d)

(e) (f)

Fig. 5. Measured sound spectrum at velocity 24.8 m/s at (a) $\alpha = 0^{\circ}$ (b) $\alpha = 1^{\circ}$(c) $\alpha = 2^{\circ}$ (d) $\alpha = 3^{\circ}$ (e) $\alpha = 4^{\circ}$and (f) $\alpha = 5^{\circ}$



(a) (b) (c) (d) (e) (f)

Fig. 6. Measured sound spectrum at velocity 28.8 m/s at (a) $\alpha = 0^\circ$ (b) $\alpha = 1^\circ$ (c) $\alpha = 2^\circ$ (d) $\alpha = 3^\circ$ (e) $\alpha = 4^\circ$ and (f) $\alpha = 5^\circ$

Primary tones with high intensity as well as secondary tones are present at $\alpha = 0^\circ$. The transition of the primary frequency from one tone group to another was found as freestream velocity increases. This is similar to the observation made by Arbey and Bataille [8], however, in contrast with the observation made by Tam and Ju [18] as well as Probsting *et al.,* [25]. No observation was made on the transition of the primary tone when tested at $\alpha = 0^\circ$ and it was stated that the geometric angle of attack $\alpha = 0^\circ$ is sensitive to the asymmetry in the experimental setup [25]. Current study did not consider the effective angle of attack which might be a plausible cause leading to the difference.

The primary tone as well as the secondary tone was found to gradually decrease in strength as angle of attack increase. Varying the angle of attack shows the airfoil tonal noise consists of a primary tone f_s with weaker secondary tones f_n. Desquenes *et al.,* [19] stated that the phase of the hydrodynamic fluctuations on both pressure and suction sides plays an important role on the amplitude of tonal emission. It was shown that counter rotating vortices from airfoil suction and pressure side meets at the trailing edge to produce high intensity noise whereas weak noise is associated with vortices having the same phase. Relating with current results, the fluctuations at lower angle of attack consists of high amplitude tones. It may indicate that the hydrodynamic vortices on both sides of the airfoil moves with opposite phase. Weaker tones may suggest that the fluctuations gradually moving at the same phase as angle of attack increases. Unquestionably, the hydrodynamic fluctuations are correlated with the naturally amplified disturbance as well as the existence of the laminar separation inside the flow.

A marked distinction in the measured sound spectrum as the angle of attack changes to $\alpha = 2^\circ$ (Fig. 5(c) and Fig, 6(c)). Obvious reduction in the broadband hump is observed. The tonal noise gradually becomes more broadband forming steady peak starting from this angle of attack. The onset of transition occurs further upstream on the suction side of the airfoil as angle of attack increases whereas transition shifts further downstream on the pressure side [6]. As angle of attack increases, pressure side experience late transition and early separation on the suction side causes the flow to be dominated by turbulent flow, which explains the reduction in tonal noise. As mentioned before, it has been shown from previous measurements; the suction side of the airfoil under investigation does not undergo reattachment after separation, which ensures the flow remains turbulent after transition [5]. This explains the gradual disappearance of the airfoil tonal noise.

The pressure distributions over the airfoil are identical over the two sides of the airfoil at $\alpha = 0^\circ$ for symmetrical airfoil. The pressure distribution on the pressure side is consistently becomes higher compared to the suction side for every increment in angle of attack for airfoil operating at low Reynolds number [24]. This forces the flow to separate starting from the trailing edge on the suction side. Concurrently the boundary layer on the pressure side becomes stable which causes insufficient amplification on the TS-wave in order to produce tonal noise [26]. It is expected that operating the airfoil at higher freestream velocity may further generate tonal sound.

As depicted in Fig. 5 and Fig. 6, general behavior observed as angle of attack increases, f_s was seen to be gradually shifting to a higher frequency, agreeing with the experimental work done on airfoil operating at low-to-moderate Reynolds number [27]. The sound level of f_s decreases as angle of attack increases which confirms the work done by Probsting *et al.,* [25] pertaining to airfoil operating at low Reynolds number, however, differ from the work done by Arcoundoulis *et al.,* [27] and Chong *et al.,* [28]. A study on NACA0012 airfoil at Reynolds numbers 5.0×10^5 at angle of attack 0°, 1.4° and 4.2° shows that as angle of attack increases, the sound level of the primary tone at all Reynolds number increases [28]. Present result contradicts with this observation; nonetheless, the deviation is expected due to the different regime considered between these studies. The difference in observation implies that the tonal noise is dependence not only on angle of attack but also Reynolds number.

3.3 Airfoil Sound Spectrum with Respect to Freestream Velocity

The influence of freestream velocity on the noise level at $\alpha = 1^{\circ}$ and $\alpha = 3^{\circ}$ are as shown in Figure 7 and Figure 8 respectively. Broadband hump ranges approximately between 300 Hz to 5000 Hz formed at velocity 21.1 m/s at $\alpha = 1^{\circ}$ (Figure 7). At a slightly higher freestream velocity of 28.8 m/s, the broadband hump was found to be located at approximately between 1000 Hz and 6000 Hz, however, closer to the background noise. Similar behaviour was found at $\alpha = 3^{\circ}$ (Figure 8), broadband hump shifted from lower frequency range to higher frequency range. Arbey and Bataille [8] relate the airfoil broadband noise with the diffraction of pressure sound waves at the trailing edge. In addition, since flow separation takes place and reattaches as turbulent flow near the trailing edge, the scattering of the surface fluctuations due to the turbulent boundary layer at the trailing edge contributes to the broadband noise [29]. This is in line with the observation made on a loaded fan blades, intensity tonal noise was shown to be generated by the unstable laminar boundary layer with TS-waves whilst the turbulent boundary layer and the turbulent vortex shedding contributes to broadband noise [30].

Furthermore, noticeable reduction in broadband hump was found as freestream velocity increases confirming the work done by Padois *et al.,* [31]. Acoustic measurements on NACA0012 airfoil at low Reynolds number shows the broadband hump reduces closed to the background noise as freestream velocity increases [31]. Moreover, slight change in the intensity of f_s was observed as velocity increases. This is true at all angle of attack under consideration. In addition, as f_s falls below 60dB, the associated f_n was found to be mostly distributed at sound level below 40dB and the tonal noise resembles the first regime. This was seen at $\alpha = 3^{\circ}$ at all freestream velocity as shown in Figure 8. In addition, Padois *et al.,* [31] suggests three different tonal noise regimes for airfoil operating at low Reynolds number. The first regime composed of primary tone accompanied by several secondary tones. The second regime consists of two unsteady primary tones followed by secondary tones; whereas, the last tonal regime is a hump with small steady peaks. All three tonal regimes suggested may be found in the present measurements, however, depending on angle of attack and freestream velocities. The second tonal regime was found at lower angle of attack between $\alpha = 0^{\circ}$ and $\alpha = 2^{\circ}$, the tonal noise gradually resembles the first regime as freestream velocity increases. Steady peak can be found at $\alpha = 3^{\circ}$ and $\alpha = 4^{\circ}$ (Figure 5(e) and Figure 6(e)) over broadband hump close to the background noise. The sound characteristics resembled that of the third regime at higher angle of attack of $\alpha = 5^{\circ}$ (Figure 6(f)) where the airfoil tonal noise is more broadband with low intensity peak.

The peak frequency f_s was found to shift to a higher frequency as freestream velocity increases that confirm the observation made in other studies [27-28]. The tonal noise is said to decrease in strength as freestream velocity and turbulence increases [9]. However, this behaviour cannot be observed at the selected range of freestream velocity, operating the airfoil at fairly higher freestream velocity is required in order for the tonal noise to subside. The observation made in this study resemble the one made by Probsting *et al.,* [25], strong primary tone is present with less pronounced secondary tones were observed as freestream velocity increases. However, measured sound spectrum does not show pronounced decrement as shown by Arcondoulis *et al.,* [27], only weaker secondary tones associated with high intensity primary tone is found as velocity increases.

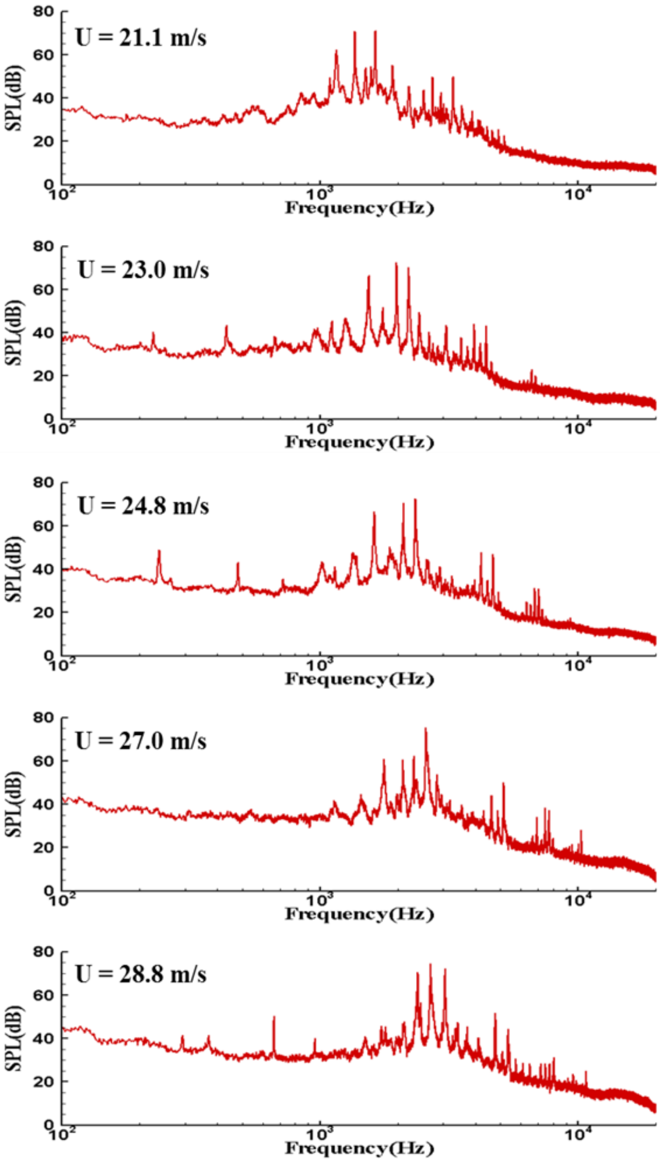


Fig. 7. Measured sound spectrum at angle of attack $\alpha = 1^{\circ}$

3.4 Discrete Frequency and Ladder Structure

The associated frequency f_n in the noise spectra belongs to a specific tone group. Extracting and plotting each frequency according to its tone group with respect to freestream velocity reveals its dependency. Figure 9 shows the development of a selected tonal frequency as freestream velocity varies at angle of attack $\alpha = 1^{\circ}$. The individual frequency belongs to the tone group 1 to 6 at every freestream velocity were extracted and plotted in Figure 10(b). The measured individual frequency in the present research shows reasonable agreement at all angle of attack as observed by previous research [8,13,28].

The ladder structure as observed by Paterson *et al.,* [4] is still noticeable although the range of freestream velocity under consideration in this work is limited. Generally, the tonal noise has more than one transition as freestream velocity increases, which inferred to as the rung of a ladder structure. It was found that f_s has a sudden jump to a different tone group. The tone transition at $\alpha = 1^{\circ}$ in Figure 9 shows f_s has a sudden transit from tone 1 in Figure 9(a) to tone 6 in Figure 9(b).

The sudden transition in primary frequency results in different dependency of f_s with freestream velocity as compared to f_n resulting in the ladder structure behavior. Results show that as freestream velocity increases, the development of additional side tones appears as can be seen in Figure 9(c).

The dependency of f_s with freestream velocity found to be slightly lower than that found by Paterson *et al.*, [4] as shown in Figure 10.

The primary peak dependency was found to be approximately $\sim U^{1.3}$ except for $\alpha = 1^{\circ}$ in Figure 10(b) and $\alpha = 2^{\circ}$ Figure 10(c). There is almost no tone jump found at $\alpha = 2^{\circ}$ although, there is a sudden jump in the tone group found between 21.1 m/s and 23.0 m/s. It is believed that further increment in velocity is required for further tone jump at this angle of attack. Nonetheless, overall results are still in good agreement with past work [6]. General observation shows that the dependency of f_s for airfoil at low Reynolds numbers was seen to be slightly lower than those at higher Reynolds numbers.

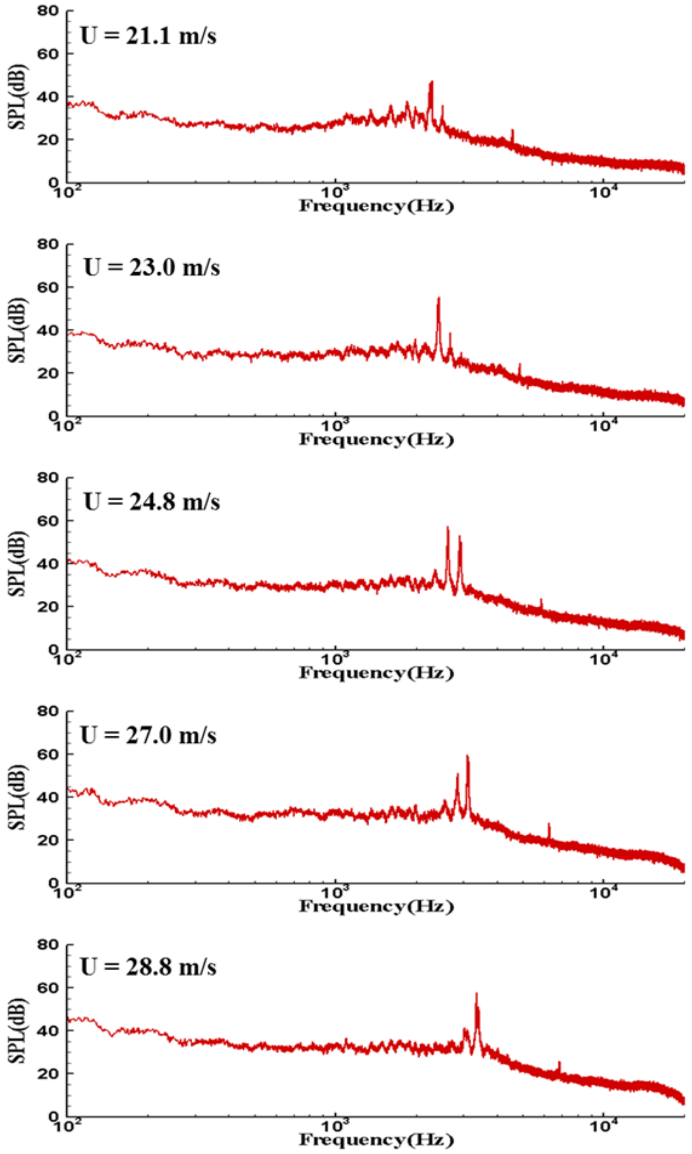
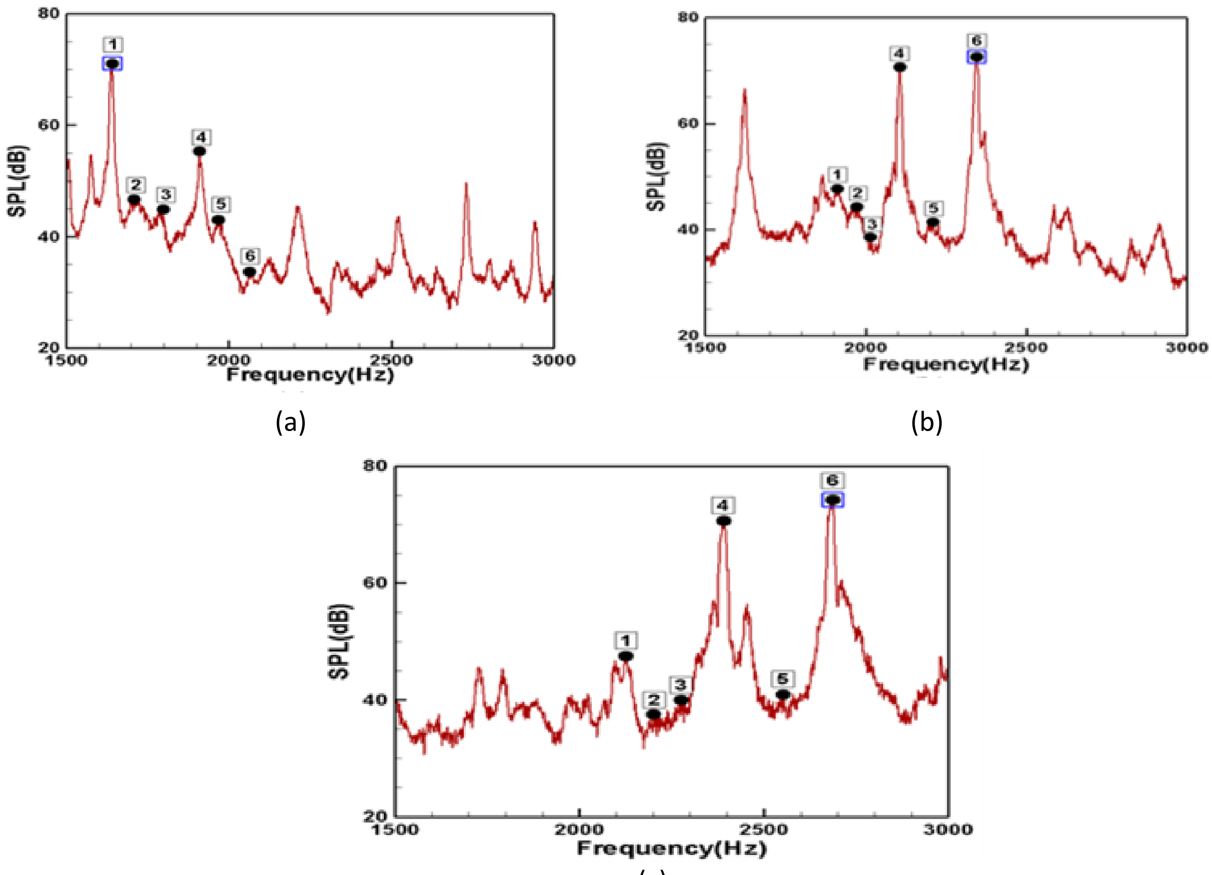


Fig. 8. Measured sound spectrum at angle of attack $\alpha = 3^{\circ}$

Tam and Ju [18] suggested that different ladder structures might be associated with different mechanisms. The tonal behavior by both suction and pressure sides through tripping method was investigated [6]. The study reported that the overall trend of airfoil peak frequency was found to have a dependency of $\sim U^{1.5}$ which agrees with the present data at $\alpha = 1^{\circ}$ in Figure 10(b). They found that tripping the suction side of the airfoil, thus, eliminating the suction side contribution to tonal noise leads to a ladder structure with dependency of $\sim U^{1.3}$. The study postulated that the tonal emission behaviour most probably governed by the shear layer vortices passing the trailing edge on the pressure side leading to sound generation.

The ladder structure measured in the present study, in general, gives a power law of approximately $\sim U^{1.3}$ in Figure 10(a), 10(d) and 10(e); it may be imply that the airfoil within the considered range of low Reynolds number governed by the periodic shedding of vortices at the trailing edge on the pressure side. Since the flow on the suction side assumed to undergo separation without reattachment as angle of attack increases, this may explain the dominancy of the pressure side in producing the tonal sound. Thus, the interaction of the naturally amplified laminar instability with the laminar bubble of the pressure side said to produce shear layer vortices, which generates tonal sound of frequency f_s as it passes through the trailing edge. Since the airfoil suction side is highly receptive to disturbance, the tonal sound propagates upstream affecting the flow on the suction side, which leads to shear layer shedding resulting in the formation of associate discrete frequency.

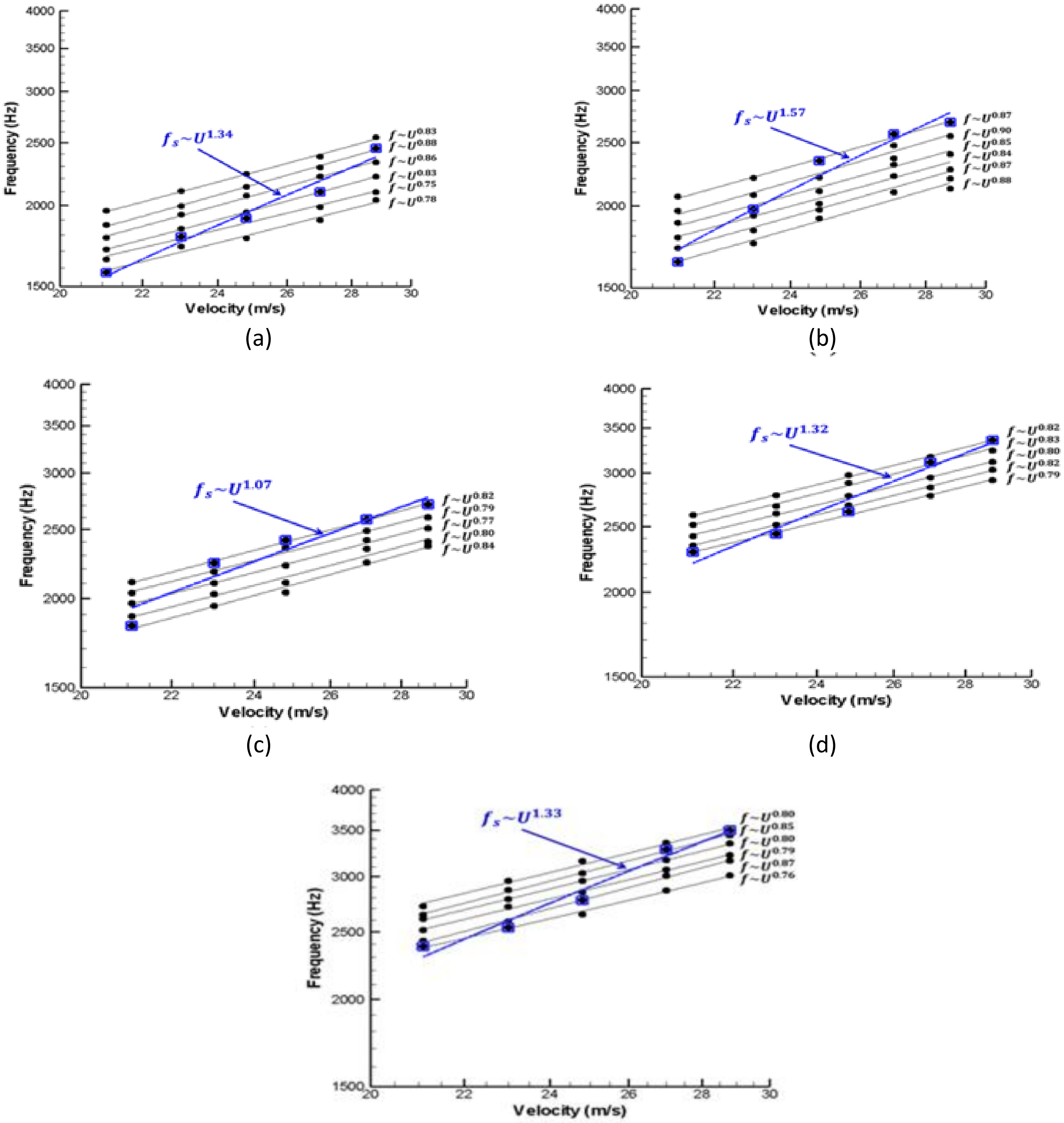


(a)

(b)

(c)

Fig. 9. Peak frequency transition at $\alpha = 1^{\circ}$



(a) (b) (c) (d) (e)

Fig. 10. Ladder jump in primary frequency (□) and individual frequency (●) at angle of attack (a) $\alpha = 0^{\circ}$ (b) $\alpha = 1^{\circ}$(c) $\alpha = 2^{\circ}$ (d) $\alpha = 3^{\circ}$(e) $\alpha = 4^{\circ}$

4. Conclusions

Experimental investigation was done on NACA0015 airfoil in order to study airfoil tonal emission from instabilities travelling inside the laminar boundary layer at a variation of angle of attack of $0^{\circ} \leq \alpha \leq 5^{\circ}$ and Reynolds number of $7.0 \times 10^4 \leq Re \leq 9.5 \times 10^4$. At these conditions, the airfoil under investigation undergoes separation without reattachment on the suction side. The airfoil noise was found to be composed of both tonal and broadband type noise. Laminar separation bubble on the pressure side is a must criterion in order to produce high intensity tones. Moreover, each of the existing prediction model described in this paper was found to have limitation in predicting airfoil tonal noise at a variation of angle of attack at low Reynolds number. Airfoil tonal noise is highly dependent on both freestream velocities as well as angle of attack. Its tonal emission at low Reynolds number differs from that at high Reynolds number. No significant reduction in the primary frequency observed as freestream velocity increases due to the limited range considered in present study whereas, the broadband noise approaches background noise as freestream velocity increases. At low Reynolds number, airfoil discrete tone consists of high intensity primary frequency accompanied by more pronounced secondary tones, as freestream, velocity increases, lesser secondary tones were observed. This is obvious at low angle of attack of $\alpha = 0^{\circ}$ and $\alpha = 1^{\circ}$. Airfoil tonal noise gradually decreases as angle of attack increases and no tonal sound was found beyond $\alpha = 5^{\circ}$ at all tested freestream velocity. In addition, no tonal noise was generated if f_s falls below 40dB, also, the associated f_n was found to be mostly distributed at sound level below 40dB if f_s falls below 60dB. Moreover, the airfoil has a strong preference in the selection of the discrete tones. The individual frequency dependency with freestream velocity was found to be $f_n \sim U^{0.8}$. General observation made on the primary frequency f_s was found to have one or multiple jump as velocity increases. The primary frequency dependency at $\alpha = 1^{\circ}$ is $f_s \sim U^{1.57}$ and only a single jump in tone found at $\alpha = 2^{\circ}$. Nonetheless, the ladder structure at low Reynolds number for airfoil experiencing no reattachment on the suction side is prone to have a dependency of $f_s \sim U^{1.3}$ which was suggested to be governed by the shear layer vortices interaction with the trailing edge generating sound on the pressure side. The pilot study have covered the characteristics of airfoil discrete tonal noise. Future work will incorporate external forcing and its effects to the generation of airfoil tonal noise.

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