Investigation on intensity of tones due to self-excited oscillation within the leading-edge slat cove at different incoming flow speeds

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\textbf{A R T I C L E  I N F O}

\begin{quote}
Article history:
Received 17 December 2018
Received in revised form 28 May 2019
Accepted 31 May 2019

Keywords:
Leading-edge slat
Aerodynamic noise characteristics
Incoming flow speed
Tones
Intensity
\end{quote}

\textbf{A B S T R A C T}

To provide further understanding of the low to mid frequency tonal noise characteristics of the leading-edge slat in the processes of take-off and landing, both experimental and numerical investigations are carried out on a two-dimensional high-lift configuration, with a stowed flap at varying incoming flow speeds (from 30 m/s to 60 m/s). The intensity variation of the low to mid frequency tonal noise is found to be closely related to the selection of the main mode of self-excited oscillation within the leading-edge slat cove. With increasing incoming flow speed, the main mode of the self-excited oscillation switches to a higher one. Meanwhile, the ratio of the self-excited oscillation period to the vortex shedding period is introduced to explain further the relationship between the main mode and incoming flow speed. As the incoming flow speed increases from 30 m/s to 60 m/s, the self-excited oscillation period is basically constant due to the flow similarity, whereas, the vortex shedding frequency is gradually increasing. The characteristic frequency of the shedding vortex near the cusp is found to be approximately proportional to $3/2$ of the incoming flow speed power law.

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1. Introduction

In recent decades, owing to the rapid development of the air-transport industry and increasingly strict airworthiness regulations, people have paid more attention to the noise radiation from large civil aircraft. The high-lift devices, as essential components for ensuring safety in the processes of take-off and landing, are big contributors to the overall radiated acoustic field from an aircraft during these two phases \cite{1,2}, especially the leading-edge slat. That is, for regional, short range jets the leading edge slat has been identified as a major airframe noise source \cite{3,4}.

More recently, leading-edge slat noise has been studied through wind-tunnel measurements \cite{5,6}, theoretical study \cite{7}, and numerical simulations \cite{8,9}. The aim has been to analyze the noise generation mechanism regarding the leading-edge slat and its noise radiation law, thereby eliciting effective noise reduction methods. Some studies on noise source mechanisms \cite{7} have identified that noise generated by the slat include low to mid frequency broadband noise \cite{10,11}, multi-discrete narrowband noise superimposed onto this type of broadband noise \cite{11,12}, and high-frequency hump noise caused by trailing edge vortex shedding \cite{13}. Among them, low to mid frequency tonal noise is a significant contributor to the overall noise, since its sound pressure level (SPL) is the highest of the three types of slat noise, and a considerable amount of research has been carried out on the noise source mechanisms in regard to this form of tonal noise \cite{14–17}. One reasonable explanation for the noise generation mechanism about tonal noise in the low mid frequency band is the self-excited oscillation within the slat cove. Based on the principle of self-excited oscillation within the slat cove, the equation \cite{16}, improved Rossiter’s original formula \cite{17}, was proposed to predict the low-mid frequency band tonal noise originating from slat cove according to noise source mechanisms of leading-edge slat. This equation has also been applied to many subsequent studies \cite{18}. The results have shown that \cite{18} the self-excited oscillation characteristic frequencies calculated from empirical formula show good agreement with the frequencies of discrete peaks on the far-field noise spectrum obtained by wind tunnel testing. In addition, in order to study further the noise characteristics of the low to mid frequency band tonal noise, the effect of the slat geometrical settings \cite{19,20} and angle of attacks (AoA) \cite{20,21} on slat noise was investigated. It was found that \cite{19} the noise in this band dramatically drop when the gap between the main wing and slat is...
almost closed, at which point the turbulence kinetic energy in the reattachment position of the mean flow streamline following the mean shear layer is reduced. Moreover, the level of the noise in the low to mid frequency is diminished and the high frequency content increases as the gap, overlap, angle of attack and slat deflection increase separately or in combination [20].

The above works have basically clarified the generation mechanism of low to mid frequency tonal noise and noise characteristics in terms of tonal frequency. To study the low to mid frequency noise intensity, a slat noise model [22] was presented and validated by itself experimental data. The amplitude of the low to mid frequency broadband noise generated by high-lift devices can be well predicted by this model. However, there has been less research on variation law of intensity of low to mid frequency band tones due to self-excited oscillation within the slat cove. Whilst previous work [14, 19, 20] has mentioned that the intensity of tonal noise generated by the slat cove is affected by the incoming flow conditions (angle of attack, incoming flow speed) and geometrical settings (overlap, gap and deflection angle), the specific reason for the intensity variation has not been further explained.

A number of studies [23–26] focusing on the intensity of tones within the conventional cavity have shown that a mode selection phenomenon exists in the self-excited oscillation within a shallow cavity. Moreover, the self-excited oscillation modes are affected by incoming flow parameters, such as the Mach number, Reynolds number, boundary layer thickness, which participate in the selection of the self-excited oscillation mode [23]. Clearly, these parameters are related to the incoming flow speed, especially the boundary layer thickness, which is extremely sensitive to this. In addition, whilst in the process of take-off and landing, the geometric parameters of the leading-edge slat and the incoming angle of attack are almost fixed, that of the incoming flow speed is gradually increasing or decreasing. Hence, in an effort to study the variation trend regarding to main mode of self-excited oscillation within the leading-edge slat cove, the low to mid frequency tonal noise characteristics of a two-dimensional, three-element high-lift configuration at the incoming flow speed range from 30 m/s to 60 m/s are analyzed. The experiments were conducted in the D5 aero-acoustic wind tunnel at Beihang University. Numerical simulations of the mean flow around the high-lift configuration were also carried out to help the interpretation of the results.

The paper is organized as follows. Section 2 describes the experimental setup, including the wind tunnel, experimental instruments, high-lift configuration model and the test case. Section 3 verifies the flow field as well as containing analysis of the relationship between tones intensity and main mode selection of self-excited oscillation within the leading-edge slat cove. The conclusions are summarized in Section 4.

2. Experimental set-up

2.1. Experimental facilities

Aero-acoustic measurements were conducted in the D5 aero-acoustic wind tunnel at Beihang University, which is a newly commissioned small-scale, closed-circuit aerospace wind tunnel. The test section is 2.5 m in length with a square cross section of 1.0 m by 1.0 m. The contraction ratio is 1:9 and the maximum operating velocity is 100 m/s in the closed test section. The free-stream has a turbulence intensity of less than 0.08% and the test section is surrounded by an anechoic chamber to provide the non-reflecting condition. The anechoic chamber is 7 m(L) × 6 m(W) × 6 m(H), with a low cut-off frequency of f = 200 Hz. [26]. For fulfillment of both aerodynamic and acoustic measurements simultaneously, the closed test section with semi-anechoic sidewalls was used in this paper. Moreover, an external absorbing plate with internal DSM cloth was used as the sidewall mode suction surface to eliminate noise interference [27], and a layer of DSM cloth was utilized as another sidewall, as shown in Fig. 1. The DSM cloth has an ultrahigh molecular weight polyethylene fiber plain weave (90 g/m²) that has good air tightness and better sound transmission than a hard wall. The sound-absorbing plate is an external 1.5 mm thick perforated plate with a porosity ratio of 30% and internal sound-absorbing cotton (10 kg/m³). When sound waves pass through the DSM cloth [28, 29] and the jet boundary layer [30] acoustic loss happens, which should be estimated to correct the measured far-field sound pressure signals. The losses have been measured, and the following results of the sound pressure level (SPL) have been corrected with the DSM cloth and boundary layer losses.

As shown in Fig. 1, a far-field microphone is used as the sound field measuring equipment. Far-field noise is measured using the Brüel & Kjær 12-channel acoustic vibration analysis system, which includes a 12-channel compact LAN-XI module and 1/2-inch free-field microphones (type 4189). The free-field microphone sensitivity is 50 mV/Pa, and dynamic range is 14.6 dB ~ 146 dB. The acoustic signal is measured over a time interval of 41.75 s at a sampling frequency of 65,536 Hz. The far-field microphone is placed 2 m away from the geometric center of the experimental model with a direction angle of 290° and located at the pressure side of model, as in a flyover configuration.

Measurements of the mean surface pressure distribution on the high-lift configuration model are carried out by three electronic pressure scanners (Type PSi8916), with 0.05% precision and every scanner can measure 128 pressure taps. A total of 318 static pressure taps populate the airfoil surface, including all three cross sections along a spanwise direction, of which 106 pressure taps are in each cross section. As shown in Fig. 2, static pressure taps are located along the mid-span cross section and the other two cross sections, namely at z/b = 0 (S2) and z/b = ±1/10 (S1 and S3), respectively. Among them, x is along the streamwise direction, y is along the vertical direction, z is along the spanwise direction and b represents the span length. The number of pressure taps on the slat, main and flap surface in each cross section is 7, 75 and 24, respectively. The reference pressure of the scanners is static free-stream pressure measured by the Pitot-static probe upstream.
2.2. Experimental model

A two-dimensional three-element high-lift model was used as the experimental model for this paper. The geometric center of the experimental model is 1 m from the nozzle, as shown in Fig. 1. The experimental model is mounted vertically between two end-plates to ensure that the flow around the airfoil is two-dimensional. The experimental model is manufactured in aluminum alloy with 0.4 m stowed chord length and 1 m span length. Among them, the leading-edge slat chord length is 17.7% of the airfoil stowed chord. In order to avoid the influence of other noise sources, such as the trailing-edge flap, the flap is in a stowed situation [16].

2.3. Test case

Far-field noise and mean surface pressure measurements were conducted at an AoA of 8° and incoming flow speeds ranging from 30 m/s to 60 m/s, with an interval of 5 m/s, corresponding to Reynolds numbers based on an airfoil stowed chord of $Re = 0.81 \times 10^6 - 1.62 \times 10^7$. In order to ensure the safety of the pressure valve, the maximum wind speed of the mean surface pressure distribution measurement was set at 50 m/s.

Hot-wire measurements were conducted for an incoming flow speed range from 10 m/s to 20 m/s, with an interval of 5 m/s, corresponding to Reynolds numbers based on an airfoil stowed chord of $Re = 2.7 \times 10^5 - 5.4 \times 10^5$. The AoA was 4°, for which the position of the hot-wire support rod was limited by the main wing, while also ensuring that the probe direction was parallel to the flow direction as much as possible. The hot wire probe was placed 0.2 mm away from the cusp, as shown in Fig. 3.

3. Results and discussion

3.1. Flow field verification

To verify the flow field similarity within the Reynolds numbers range tested in this experiment and numerical simulation reliability, model surface mean pressure measurements were carried out. Given the flow field experiment involves just mean surface pressure measurement, numerical simulation is used as a common method for predicting and analyzing the flow field, [14,16,31] for these results are needed to provide more flow field information to analyze the flow field characteristics.

Numerical simulation verification is carried out on the surface mean pressure coefficient ($C_p$), lift coefficient ($C_l$) of a 30P30P airfoil and its velocity profiles at four representative cross-section positions, which have been covered in detail by [32], but only a brief overview of them is given in this paper. The structured grid is created by the grid generation software ANSYS ICEM and the first-layer grid height of the wall is $1 \times 10^{-5}$ times the reference chord length. The computational fluid dynamics software FLUENT is applied as the solver to simulate the steady incompressible RANS equations and the S-A turbulence model. The momentum and turbulent kinetic energy in the equation are two-order upwind schemes. The pressure–velocity coupling is dealt with using the SIMPLEC algorithm.

The results of the numerical simulation are in good agreement with the experimental ones [32]. The numerical simulation reliability is also assessed by comparing $C_p$ distribution data obtained by the experiment with that obtained by the numerical simulation for the same model.

Fig. 4 shows the experimental and calculation results for $C_p$ distribution at an AoA of 8° mostly fit with the experimental results. That is, the surface pressure distribution around the slat obtained by numerical calculation shows similar flow field characteristics with that obtained by the wind tunnel experiment, which leads to similar noise characteristics [33]. Computational predictions are approximately aligned with the wind tunnel measurements.

![Fig. 4. Experimental and calculation results regarding mean surface pressure distribution at an AoA of 8°.](image-url)
in the closed test section. Moreover, within the Reynolds numbers range tested in this experiment, the surface mean pressure coefficient distribution at different incoming flow speeds have generally provided consistent results, which illustrates flow field similarity.

To verify further the flow field similarity, velocity field information in the vicinity of the slat, especially near the cusp, at the incoming flow speed range from 30 m/s to 60 m/s is compared. As shown in Fig. 5, the velocity contour maps share similar characteristics in magnitude that is normalized on the basis of incoming flow speed ($U_\text{in}$), mean flow streamlines following the mean shear layer, reattachment position of mean flow streamlines. The normalized velocity profiles following the normal direction of the separating boundary layer near the cusp, as shown in Fig. 6, further demonstrate flow field similarity. It should be noted that the cusp is regarded as the initial position of the separating boundary layer, which can be seen from Figs. 5(b) and 6.

It can also be seen from Fig. 6 that, as the incoming flow speed increases, the separating boundary layer thickness, $\delta$, clearly decreases and the maximum velocity in the separating boundary layer near the cusp, $U_{\text{max}}$, gradually increases.

To evaluate further the spanwise effect of model, measurements of the mean surface pressure and hot-wire at different spanwise cross sections were carried out. Mean surface pressure distribution measurements were conducted for an incoming flow speed of 50 m/s. As shown in Fig. 7(a), the results about pressure distribution at different spanwise cross sections have basically provided consistent results. In addition, hot-wire measurements were conducted for an incoming flow speed of 15 m/s. As shown in Fig. 7(b), hot-wire energy spectrum basically share the same amplitude characteristic in both broadband and narrowband. The
frequency error corresponding to the narrowband frequency is lower than 4 Hz.

Hence, the flow around the high-lift model can be regarded as a two-dimensional flow regime.

3.2. Effect of incoming flow speed on tones intensity

The spectra in Fig. 8 show that, as the incoming flow speed increases, the amplitude of broadband noise increases, which can be seen from the dotted lines. In addition, the fitting curves of amplitude of broadband noise, and the tonal noise frequencies shift to a higher frequency range with a gradual increase in incoming flow speed. However, it is not clear about the amplitude of tonal noise. Hence, noise characteristics regarding tones intensity at an incoming flow speed range from 30 m/s to 60 m/s are the focus of the analysis below.

Self-excited oscillation within the leading-edge slat cove is one of the explanations for tonal noise in the low to mid frequency band. The following empirical formula, derived by M. Terracol, et al. [16] was proposed to predict frequencies corresponding to this band’s tonal noise.

\[ f_n = \frac{U_{\infty}}{L} \frac{n}{(2n/K_v + Ma)} \]  

where, \( K_v = \frac{U_v}{U_{\infty}} \), \( L \) is the shear layer length between the cusp and the reattachment position, \( L \) is the distance between the separation point near the cusp and reattachment position, \( U_v \) is the average convection velocity along the shear layer, \( U_{\infty} \) is the incoming flow speed.

Table 1

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Parameter definition</th>
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<tbody>
<tr>
<td>( L_v )</td>
<td>Shear layer length between the cusp and the reattachment position</td>
</tr>
<tr>
<td>( L )</td>
<td>Distance between the separation point near the cusp and reattachment position</td>
</tr>
<tr>
<td>( U_v )</td>
<td>Average convection velocity along the shear layer</td>
</tr>
<tr>
<td>( U_{\infty} )</td>
<td>Incoming flow speed</td>
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Fig. 7. Results about pressure distribution and hot wire ((a) Mean surface pressure distribution; (b) Velocity energy spectra).

Fig. 8. The effect of incoming flow speed on the sound pressure level spectrum of far-field noise.

Fig. 9. Normalized sound pressure level spectrum at different incoming flow speeds and an AoA of 8°.
The main characteristic frequency of the self-excited oscillation within the slat cove is firstly at $f_n$ with an $n$ of 2, and then it switches to $f_n$ with an $n$ of 3, as the incoming flow speed increases. In other words, the intensity variation of the low to mid frequency tones is related to the main self-excited oscillation mode switch. The effect of the incoming flow speed on the main mode switch of self-excited oscillation within the slat cove is more obvious in Fig. 10, which shows the SPL difference between the second and third peaks. It can be seen that, Mode II is the main self-excited oscillation mode when the incoming flow speed is less than 35 m/s at an AoA of 8°. With increased incoming flow speed, the amplitudes corresponding to the two peaks are basically equal, which can be regard as the transition phase of Mode II and Mode III. With further increase in the incoming flow speed to 50 m/s, Mode III is the main self-excited oscillation mode. That is, Mode II and Mode III successively become the main mode of self-excited oscillation, and the transition phase occurs at an incoming flow speed of about 40 m/s when the angle of attack is 8°.

3.3. Analysis on the main mode selection combined with flow field information

To analyze further the relationship between the main mode of self-excited oscillation within the slat cove and the incoming flow speed, the local flow field information near the cusp is considered in this subsection. As mentioned above, the quantity of vortices, $n$, is that which can be contained simultaneously in the shear layer during a self-excited oscillation period and this is related to the characteristics of the free shear layer. The self-excited oscillation feedback loop is related to the quantity of the shedding vortex near the cusp and the vortices interacting with the solid surface of the upper trailing edge of the slat within an oscillation period [34]. Characteristic frequencies of shedding vortex near the cusp are firstly measured by hot-wire equipment to analyze the shedding vortex characteristics.

As the free-stream velocity increases, the characteristic frequency moves toward high ones, which is observed in Fig. 11(a), and the characteristic frequency of the shedding vortex is generally proportional to the $3/2$ velocity power law, as shown in Fig. 11(b). This frequency, $f_v$, can be expressed as:

$$f_v \propto U_\infty^{3/2}$$

Furthermore,

$$St = \frac{f_v \cdot D}{U_\infty} \propto U_\infty^{1/2} \cdot D$$

where, $D$ is the characteristic size of the shedding vortex. It is found that the characteristic size of the shedding vortex near the cusp is proportional to the separating boundary layer thickness in the range of the local Reynolds number. The larger the incoming flow velocity, the smaller the characteristic size and separating boundary layer thickness are and the higher the characteristic frequency of the shedding vortex. It should be noted that the relationship between the characteristic frequency of the shedding vortex and incoming flow speed is independent of the angle of attack, which only depends on the range of the Reynolds number.

Due to intermittency of the shear layer, multiple self-excited oscillation modes apparently coexist in the far-field noise spectrum [35]. The oscillation mode with the strongest noise amplitude can be considered as the primary mode. Hence, $n_p$, the number of the primary mode can be expressed as:

$$n_p \propto \frac{f_v}{f_c} \propto \frac{U_\infty^2}{K_v} \propto \frac{L_v \cdot U_\infty^2}{K_v} = \frac{L_v}{D \cdot K_v}$$

where $f_c$ is almost equal to $f_n$, with an $n$ of 1 and among which, $L/c$ is ignored for the reason that, under the tested condition, the time for sound waves traveling to the cusp is much less than that for the shedding vortex moving to the reattachment position along the shear layer.

In the previous studies on the conventional cavity self-excited oscillation [24,36], it has been mentioned that the ratio of the cavity length over the momentum thickness of the separating boundary layer, $L/\theta$, participates in the mode selection. However,
the convection velocity, $U_\infty$ within the slat cove is more easily affected by the geometric parameters compared with the conventional cavity. $K_v$ also participates in the mode selection of self-excited oscillation within the slat cove.

Due to flow field similarity, as shown in Fig. 5, the shear layer length between the cusp and the reattachment position along the mean flow streamline following the mean shear layer, $L_\alpha$, at all incoming flow speeds involved in this paper is almost equal. Moreover, the velocity distributions along the mean flow streamline following the mean shear layer at the incoming flow speed range from 30 m/s to 60 m/s are shown in Fig. 12. They depict that the mean convection velocity, $U_\infty$, approximated by the mean plateau value of the velocity, shares the same characteristics due to flow field similarity, as shown in Fig. 12(b). It should be mentioned that the horizontal and vertical coordinates in Fig. 12(b) are dimensionless, using $L_\alpha$ and $U_\infty$, respectively. Hence, at the same AoA of 8°, the $K_v$ values are almost equal.

According to Eq. (4), as the incoming flow speed increases, the main mode of self-excited oscillation switches to a higher one.

4. Conclusion

In this paper, the aero-acoustic experiments on a two-dimensional high-lift configuration model at the same angle of attack of 8° and the incoming flow speed range from 30 m/s to 60 m/s corresponding to Reynolds numbers based on an airfoil stowed chord of $Re = 1.35 \times 10^6$ were carried out in the D5 aero-acoustic wind tunnel at Beihang University. The aim was to study the influence of the incoming flow speed on the amplitude of tones generated from self-excited oscillation within the slat cove, and a numerical simulation method was used as a tool to assist the analysis of the flow field.

By analyzing the normalized far-field noise spectrum data, it was found that an increase in the incoming flow speed causes primary tones switching from mode 2 to mode 3. To analyze further the relationship between the main mode and the incoming flow speed, the shedding vortex characteristics were analyzed. The results show that the characteristic frequency of the shedding vortex is basically proportional to 3/2 of the incoming flow speed power law. The higher the incoming flow speed, the higher the characteristic frequency of the shedding vortex and the more the vortices are contained simultaneously in the shear layer during a self-excited oscillation period, which leads to a higher mode.

For a slat cove with the same geometrical setting at the same angle of attack, a higher self-excited oscillation mode is excited when the incoming flow velocity is larger. Due to the flow field similarity, the selection of the main mode depends just on the incoming flow speed. This can be used to evaluate the variation trend on main mode of self-excited oscillation within the slat cove in the process of take-off and landing, thereby further helping the aircraft designer to control the frequency band in which the main mode appears.

Declaration of Competing Interest

There is no conflict of interest.

Acknowledgements

This work was supported by the National Natural Science Foundation of China (Grant No. 11502012, 11850410440, 11772033 and 117721202).

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