Investigation of Noise Generation from Bluff Flap Side-edge of a High-Lift Wing Model

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This paper presents computational and experimental results on investigation of noise generation from the flap side-edge for high-lift device noise research models in JAXA. The main purpose of this paper is focused on investigation of the differences of the flow field between the models with and without the swept angle and taper-ratio of the wing by comparison of the computational results. In the case of wings with the swept angle and taper-ratio, the flap is deployed in a three-dimensional direction based on the wing planform. The changes of the behaviors of the vortices from the flap side-edge and resulting pressure fluctuations due to the flap deployment are shown.

Key Words: Airframe Noise, High-Lift, CFD

Nomenclature

\[ \text{AoA} \] : angle of attack
\[ b/2 \] : half span length
\[ C_p \] : pressure coefficient
\[ \Delta t \] : computational time step
\[ MAC \] : mean aerodynamic chord length
\[ Re \] : Reynolds number based on \( MAC \)
\[ SPL \] : sound pressure level
\[ T \] : total computational time
\[ U \] : velocity magnitude
\[ \eta \] : spanwise location

Subscripts

\( c \) : corrected data for tunnel wall effect
\( u \) : uncorrected data for tunnel wall effect
\( \infty \) : free stream condition

1. Introduction

In the recent development of civil aircraft, environmental performance relating to noise around airports is becoming one of the most important factors for market competitiveness. In successive efforts for engine noise reduction, airframe noise is becoming a focus in reducing overall noise level, especially during approach conditions where engines are throttled-down. Therefore, airframe noise reduction technologies are of increasing importance for future civil aircraft.

The trailing-edge flap is a high-lift device deployed during landing and take-off to increase lift at low-speed conditions. Noise from the flap side-edge is recognized to be one of the major noise sources of the airframe noise.1-5) The broadband noise is generated around the side-edge of the flap due to shear-layer instability and around the gap between the main wing and flap.

Understanding the details of the noise generation mechanism will facilitate low-noise design to effectively reduce the noise considering penalties from weight, structural restrictions and aerodynamic performance. JAXA has conducted research work on characteristics of flap side-edge noise and mechanisms of noise generation and reduction.6-12) In Refs. 6-8), the noise generation mechanism around the flap side-edge and sensitivity of the flap side-edge shapes on the far-field noise have been discussed using the far-field noise and model surface unsteady pressure data measured by a series of wind tunnel tests on a simplified three-dimensional three-element high-lift wing model with a slat and a part-span single-slotted flap. The research model, “OTOMO,” employed a rectangular wing planform to investigate the basic characteristics of noise from high-lift devices. In Ref. 9), the changes of the flow field and far-field noise according to several flap side-edge shapes such as bluff, rounded or cavity side-edges were investigated in detail by CFD/CAA and compared with the wind tunnel test results. A practical low-noise device was also investigated in Ref. 9).

The basic research model called “OTOMO” omitted the swept angle, taper and dihedral angle of the wing. On the other hand, in the case of wings with a swept angle
and a taper-ratio, the flap is deployed in a three-dimensional direction based on the wing planform. The flap deployment may change the flow structures of vortices and shear-layer generated around the flap side-edge. Toward further improvements to predict and reduce the airframe noise from actual aircraft, the influences of the omitted parameters on the noise generation mechanisms should be investigated thoroughly.

To investigate the influences, a half-span three-element high-lift wing model with a taper-ratio and a swept angle “OTOMO2” which has the same wing section with “OTOMO” was designed and fabricated in JAXA. A series of wind tunnel tests have been conducted since 2011. In Ref. 11), differences of noise generation around the flap side-edge between the models with and without the taper-ratio and swept angle were discussed using the wind tunnel test results. In Ref. 12), some noise reduction devices were evaluated using the model.

In this paper, the flow field around the basic bluff flap side-edge shape with a rectangular cross-section for OTOMO2 is investigated mainly using CFD/CAA. The differences of the flow fields between the models with and without the taper-ratio and swept angle are discussed by qualitative comparison with our previous computational results for OTOMO. Based on the computations and wind tunnel tests, mechanisms of the noise generation from the flap side-edge are discussed.

2. Research Models for High-Lift Device Noise Research

In order to investigate the flow field around the flap side-edges with and without a taper-ratio and a swept angle of the wing, high-lift wing noise research models in JAXA, OTOMO8) and OTOMO2,10) are used. Figures 1 and 2 show the model configurations with both slat and flap deployed. The models are generic high-lift wing models with a full-span slat and a part-span flap. The models were designed to investigate the detail flow field and noise around the slat and flap-edge for the purpose of high-lift device noise research in JAXA.

OTOMO has a rectangular wing planform with the aspect ratio of 4.5, while the swept angle of the leading edge, aspect ratio and taper-ratio of OTOMO2 are 33°, 4.11 and 0.646, respectively. The planform of OTOMO2 is extracted from a high-lift aerodynamic research aircraft model “JSM”13,14) in JAXA. It assumes an outer wing of a 100-passenger-class civil jet aircraft. The wing section of OTOMO2 is the same as that of OTOMO, but the size of the model is reduced to an 85% scale of OTOMO to reduce the wind tunnel wall interferences. b/2 of OTOMO and OTOMO2 are 1.35 m and 1.2 m, respectively.

To eliminate undesirable excessive noise sources which are peculiar to these simplified models and not essential for the research of slat and flap noise from realistic aircrafts, the slot at the slat root and tip is partially filled up when the slat is deployed and a simple tip fence is attached to the wing tip. For OTOMO2, furry materials are also attached to the tip fence and slat supports to reduce the excessive noise as shown in Fig. 3.

3. Experimental Facilities and Measurements

In this research, two different wind tunnel facilities shown in Fig. 4 are used. The JAXA-LWT2 Lowspeed Wind Tunnel is used for the aerodynamics and flow field measurements. The noise source identification by a phased-microphone array is also conducted in the JAXA-LWT2. It is an atmospheric pressure closed-circuit tunnel with a closed solid wall square test section or a closed anechoic test section with the Kevlar wall.15,16) The size of the test section is 2 m in height, 2 m in width, and 4 m in length. The far-field noise is measured using the Large-Scale Anechoic Wind Tunnel in the Railway Technical Research Institute (RTRI).17) The tunnel has an open-jet nozzle with a rectangular cross-section. The size of the test section is 3 m in width, 2.5 m in height, and 8 m in length. A spacer with sufficient height is installed below the body-pod, to avoid interference between the model and the boundary layer growing on the tunnel wall.
4. Computational Method

For unsteady aeroacoustics computations, CFD/CAA software, PowerFLOW, is used. The computational method is based on a Lattice Boltzmann Method. The system of equations is solved on a Cartesian mesh using a renormalization group-based VLES two-equation turbulence model with an extended turbulent wall model to simulate the wall boundary layer with much less grid resolution near the wall. The far-field results are obtained with the Ffowcs Williams and Hawking's method using model surface pressure including the ground plane whose size is the same as the one used in the wind tunnel test.

Figure 5 shows the computational grids for OTOMO2. For OTOMO2, the configuration which deployed the flap but retracted the slat (flap-only-deployed configuration) is computed to focus on the flap noise. The computational grid consists of 14 levels of variable resolution. The finest level is set to 0.1 mm only near the flap side-edge where the shortest distance between the flap side-edge and main wing is approximately 0.6 mm. The total number of voxels is 165 million for OTOMO2. Computations are conducted at \( \alpha = 8^\circ \), which is almost equivalent to the experimental condition of 10\(^\circ\) in the open-jet wind tunnel test at RTRI. \( U_\infty \) and \( Re \) are 67 m/s and 2.6 \( \times 10^6 \). \( \Delta t \) is set to 1.7\( \times 10^{-7} \) sec. The total number of time steps is approximately 3 million steps, which corresponds to computations for 0.5 sec. The required CPU time for the computation is approximately 17,500 CPU hours using 128 cores in a Xeon E5-2665 PC-cluster system.

The computational conditions of the results for OTOMO in Ref. 9) are slightly different from those for OTOMO2, but they are comparable for the qualitative comparisons. The comparison of computational conditions is shown in Table 1.

5. Results

Figures 6 and 7 show the noise source maps for OTOMO2 at \( \alpha = 6^\circ \) and 8.5\(^\circ\) (\( \alpha = 8^\circ \) and 10.4\(^\circ\)) measured using a microphone array in the hard wall test section of the JAXA-LWT2. \( U_\infty \) is 53 m/s. The noise source maps for six different 1/3-octave band center frequencies are shown in Figs. 6 and 7. The dominant noise sources at the center frequency of 1 kHz are ambiguous due to the high background noise in the JAXA-LWT2. Over the frequency of 2.5 kHz, only the flap edge appears to be the dominant noise source for both \( \alpha \) conditions. In the frequency range from 2.5 to 8 kHz, the center of the noise source is located after the middle of the flap edge. Over the frequency of 16 kHz, two noise sources are found after the middle of the flap edge and near the leading-edge of the flap edge.

Figure 8 shows narrow-band spectra of the far-field SPL measured at a polar angle of 90\(^\circ\) at several angles of attack from \( \alpha = 2.8^\circ \) to \( \alpha = 14.2^\circ \). No outstanding peak is observed in the spectra for all results. In the frequency range from 3 to 5 kHz, the noise levels are the same level of SPL for all angles of attack. Over the frequency of 5 kHz, the noise levels increase with increasing \( \alpha \). Especially at \( \alpha = 14.2^\circ \), the change of SPL is large in the frequency ranges under 3 kHz and over 5 kHz.
discontinuities of \( C_p \) distributions are due to the pressure taps on the stowed slat.

The computational result assuming fully-turbulent flow shows fair agreement with experimental results in RTRI except for the suction peak level on the leading-edge of the flap and the size of the flow separation near the trailing-edge of the flap. The computational result exhibits slightly larger flow separation over the flap. One of the reasons for the difference seems to come from boundary layer transition. In Ref. 9), the computational result considering the boundary layer transition improves the prediction of \( C_p \) for OTOMO. On the other hand, consideration of the transition does not cause significant difference especially for the flap-noise in the computation. Therefore, all computations are conducted with fully turbulent assumption hereafter.

Figure 9 compares the time-averaged surface \( C_p \) distributions at \( \eta = 50\% \) between experimental and computational results. The computational result considering the boundary layer transition improves the prediction of \( C_p \) for OTOMO. On the other hand, consideration of the transition does not cause significant difference especially for the flap-noise in the computation. Therefore, all computations are conducted with fully turbulent assumption hereafter.

Figure 10 compares the narrow-band spectra of \( \text{SPL} \) between the experimental and computational results for OTOMO2. The background noise measured without the model is subtracted in the experimental data for the comparison with the computational results. \( \text{SPL} \) computed by the integration of the whole model surface shows several outstanding peaks in the spectra, while no outstanding peak is observed in the wind tunnel results. Figure 11 shows the time-averaged \( C_p \) distribution and surface restricted streamlines. Figure 12 shows the bandpass-filtered pressure fluctuation level in dB for the frequency range from 0.7 to 1.4 kHz. In Fig. 11, the flow separation near the wing-tip is observed in the computation. Figure 12 indicates a high pressure fluctuation level in the regions with the flow separation. As shown in Fig. 3, furry materials are attached to the tip fence to reduce undesirable excessive noise on the wind tunnel testing model, while they are not modeled in the computations. \( \text{SPL} \) computed by the integration without the wing-tip region in Fig. 10 shows no outstanding peaks and fair agreement with the experimental data.
Fig. 10. Comparison of narrow-band spectra of far-field SPL between the experimental and computational results for OTOMO2 at $AoA = 8.0^\circ$.

Fig. 11. Time-averaged $C_p$ distribution and surface restricted streamlines for OTOMO2 at $AoA = 8.0^\circ$.

Fig. 12. Bandpass-filtered pressure fluctuation level in dB for OTOMO2 at $AoA = 8.0^\circ$ (0.7 and 1.4 kHz).

Figure 13 compares the time-averaged computational results of the vorticity magnitude and streamlines passing through the center of the major longitudinal vortex for OTOMO and OTOMO2. For both cases, two major vortex structures are observed: (A) side-vortex rolled-up from the lower edge near the leading-edge and (B) upper-vortex rolled-up from the upper edge near the leading-edge. The vorticity magnitude of the side-vortex is much higher than that of the upper-side vortex. The two vortices merge at the upper surface after the middle flap-chord. Figure 14 compares the time-averaged computational results of the vorticity component in the free-stream direction. The rotation directions of the vortex with positive and negative values are counter-clockwise and clockwise viewing forward, respectively. For both cases, a vortex structure with clockwise rotation is generated around the edge in the cove of the main wing near the leading-edge of the flap-edge as shown in Fig. 14(i). An upper-vortex with counter-clockwise rotation is rolled-up from the upper edge near the leading-edge, while the pair vortex with clockwise rotation is rolled-up from the lower edge of the side of the main wing as shown in Figs. 14(i) - 14(ii).

In the case of OTOMO, the upper-vortex and side-vortex rolled-up from the flap side-edge merge near the 60% flap-chord (Fig.13(a), Fig.14(iv) and Fig.14(v)), then the merged vortices move to inboard on the upper surface of the flap and separate away from the upper surface (Fig.13(a) and Fig.14(vi)). In the case of OTOMO2, the upper-vortex passes through further inboard on the upper surface of the flap due to the flap deployment in an oblique direction (Fig.13(b), Fig.14(iv) and Fig.14(v)). It delays the merging point of the two vortices and the merged vortices are located closer to the flap upper surface near the trailing-edge than those of OTOMO (Fig.13(b) and Fig.14(vi)).
Figures 15 and 16 show the bandpass-filtered pressure fluctuation level in dB on the model surface for the frequency ranges of 2 - 3 kHz and 5.6 - 7.1 kHz for OTOMO and 1.4 - 2.8 kHz and 5.7 - 11.3 kHz for OTOMO2. Figures 17 and 18 show the bandpass-filtered pressure fluctuation level in space for the frequency ranges of 2 - 3 kHz and 5.6 - 7.1 kHz.

(a) Flap-tip from upper side.

(b) Flap-tip from lower front.

(i) 2 - 3 kHz.
(ii) 5.6 - 7.1 kHz.

(i) 1.4 - 2.8 kHz.
(ii) 5.7 - 11.3 kHz.

(a) Flap-tip from upper side.

(b) Flap-tip from lower front.

(i) 2 - 3 kHz.
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(i) 1.4 - 2.8 kHz.
(ii) 5.7 - 11.3 kHz.

(i) 5.6 - 7.1 kHz

(ii) 5.6 - 7.1 kHz

Fig. 17. Bandpass-filtered pressure fluctuation level in space for OTOMO at $\alpha_o = 10.0^\circ$.

Fig. 18. Bandpass-filtered pressure fluctuation level in space for OTOMO2 at $\alpha_o = 8.0^\circ$.

Regions with a high pressure fluctuation level are found along the paths of the upper and side vortices. The regions with a high pressure fluctuation level are also found on the upper surface of the flap near the side-edge around the 5 - 25% flap-chord location where the upper-vortex fluctuates with the interferences of the wake from the main wing, flows from the cove and gap between the main wing and flap. The regions with a high pressure fluctuation level are spreading in the spanwise direction near the flap trailing-edge especially at a lower frequency range. The grown upper vortex near the flap trailing-edge engulfs the wake from the trailing-edges and causes the high pressure fluctuation level on the surface as shown in
Figs. 17(iv) and 18(iv).

In the case of OTOMO, the highest level is found on the side-edge and the upper-surface of the flap around the 60% flap-chord location where the side and upper vortices merge for all frequency ranges as shown in Figs. 15 and 17(iii). In the case of OTOMO2, the regions with the highest pressure fluctuation level are located on the side-edge and the upper surface of the flap near the leading-edge and around the 75% flap-chord location especially at higher frequency range as is also shown in the noise source maps measured in JAXA-LWT2. In addition, the area with a high pressure fluctuation level is wider than that of OTOMO. In the case of OTOMO2, the upper-vortex passes through further inboard on the upper surface of the flap due to the way of the flap deployment and the merging point of the upper and side vortices locates around the 75% flap-chord location. They increase the area with a high pressure fluctuation level in the spanwise direction and around the 75% flap-chord location.

6. Conclusions

In this study, the flow fields around the flap side-edge were investigated by numerical simulations for high-lift device noise research wind tunnel models in JAXA. The differences of the flow fields between the models with and without the taper-ratio and swept angle were investigated by qualitative comparison of the computational results. For both models, the bluff flap side-edge shapes generated two major vortex structures: side-vortex rolled-up from the lower edge near the leading-edge and upper-vortex rolled-up from the upper edge near the leading-edge. Regions with a high pressure fluctuation level were found along the paths of the upper and side vortices. One of the regions with the highest pressure fluctuation levels was found at the upper surface after the middle flap-chord where the two vortices merged. Regions with a high pressure fluctuation level were also found on the upper surface of the flap near the side-edge around the 5 - 25% flap-chord location where the upper-vortex fluctuates with the interferences of flows from the cove and gap between the main wing and flap. The regions with a high pressure fluctuation level were spreading in the spanwise direction near the flap trailing-edge especially at lower frequency range due to the grown upper vortex near the flap trailing-edge engulfing the wake from the trailing-edges of the main wing.

The model with the swept angle and taper-ratio indicated two noise sources with a high pressure fluctuation level on the upper surface of the flap near the leading-edge and around the 75% flap-chord, especially at higher frequency range. It also showed a wider area with a high pressure fluctuation level. The basic noise generation mechanism was similar between the two models, while the differences were mainly found in the behavior of the upper vortex. In the case of wings with a swept angle and a taper-ratio, the flap was deployed in a three-dimensional direction based on the wing planform. The upper-vortex passed through further inboard on the upper surface of the flap due to the flap deployment. It delayed the merging point of the two vortices and the merged vortices were located closer to the flap upper surface near the trailing-edge. Therefore, the area with a high pressure fluctuation level was increased in the spanwise direction and around the 75% flap-chord location. In this study, the flow field at a single angle of attack was investigated. The wind tunnel test results for OTOMO2 indicated a slight dependency on the angle of attack especially at higher angles of attack. On the other hand, the results for OTOMO indicated less dependency. The difference will be numerically investigated in the future.

References


