

Computational Study of Noise Characteristics for 30P30N Leading-edge Slat and Krueger Flap

Mitsuhiro Murayama,¹ Kazuomi Yamamoto,² and Yasushi Ito³
Japan Aerospace Exploration Agency (JAXA), Mitaka, Tokyo, 181-0015, Japan

Ryutaro Furuya⁴
Ryoyu Systems Co., Ltd., Minato-ku, Nagoya, Aichi 455-0024, Japan

Meelan M. Choudhari,⁵ and David P. Lockard⁶
NASA Langley Research Center, Hampton, VA 23681, USA

In this study, numerical simulations are performed to investigate the flowfield, the noise sources, and their detailed characteristics around high-lift configurations featuring either a conventional leading-edge slat or a Krueger flap. While the flowfields and potential noise sources are similar for the two types of configurations, the noise directivity patterns exhibit some differences. The influence of the cavity where the Krueger flap is stowed on the lower surface is also examined via numerical simulations with and without the cavity. Results show that the cavity does not have a significant influence on the flowfield around the Krueger flap and the gap region. However, when the cavity is present, additional noise sources are observed around its rear part, although they are not as significant as the noise sources on the lower side of the Krueger flap. These additional noise sources contribute to the directivity of high noise levels, especially in the upstream direction.

Nomenclature

c	=	stowed chord length
C_p	=	time averaged surface pressure coefficient
SD	=	power spectral density

Abbreviations

CAA	=	computational aeroacoustics
CFD	=	computational fluid dynamics
DNW	=	German-Dutch Wind Tunnels
LBM	=	Lattice Boltzmann Method
NBP	=	narrow-band peak
RNG	=	renormalization group
SPL	=	sound pressure level
TKE	=	turbulent kinetic energy
VLES	=	very large eddy simulation
VR	=	variable resolution

I. Introduction

In recent years, there has been a growing demand to mitigate the negative environmental impact of rising air traffic. Consequently, the importance of fuel efficiency and noise reduction has increased accordingly. One approach to enhance the fuel efficiency involves aerodynamic drag reduction via natural laminar flow wings¹⁻².

¹ Senior Researcher, Aviation Technology Directorate. Senior Member AIAA.

² Senior Expert, Aviation Technology Directorate. Senior Member AIAA.

³ Associate Senior Researcher, Aviation Technology Directorate. Senior Member AIAA.

⁴ Research Engineer, Aerospace Engineering Solution Division.

⁵ Aerospace Technologist, Computational AeroSciences Branch. Fellow AIAA.

⁶ Aerospace Technologist, Computational AeroSciences Branch. Associate Fellow AIAA.

The delay in laminar-turbulent transition of the boundary layer over the wing surface can yield substantial reductions in the frictional drag, which can account for up to one half of the overall drag for a conventional, subsonic aircraft. However, to realize the benefits of natural laminar flow in practice, it is crucial to maintain a smooth wing surface by avoiding surface roughness that could precipitate an earlier onset of transition. Even if the manufactured wing surface is perfectly smooth, the accumulation of insect debris in the course of flight operations can also lead to a loss of laminar flow near the leading edge of the wing³. These considerations must be taken into account in designing a high-lift system that is compatible with laminar flow technology. Leading-edge slats are commonly employed on conventional aircraft to delay potential onset of stall during the take-off and landing phases of flight. However, slats are susceptible to insect contamination. Furthermore, when the slat is in the retracted position during cruise, the boundary-layer flow is likely to encounter a step excrescence between the slat trailing-edge and the adjacent portion of the wing upper surface. Either of these surface imperfections can lead to premature transition in the wing boundary layer.

The Krueger flap denotes an alternate form of high-lift devices near the leading edge that can address the above-mentioned problems, making it easier to realize the drag reduction due to natural laminar flow wings.⁴⁻⁸ Krueger flaps are retracted from the lower surface of the wing, thereby eliminating any step on the upper surface. Moreover, it provides shielding for the wing leading edge when the aircraft is at lower altitudes, reducing the potential for insect contamination. For hybrid laminar flow configurations that utilize surface suction near the leading edge to achieve much larger drag reduction in comparison with natural laminar flow alone, the Krueger flap also reduces the risk of blocked perforations across the region of suction.

Leading-edge slats are known to be one of the major sources of airframe noise, and a number of studies have already been carried out to investigate the associated noise generation mechanisms as well as the characteristics of the radiated noise.⁹⁻¹⁸ To compare the noise characteristics of a conventional slat and a Krueger flap, Bahr et al. conducted extensive aeroacoustic measurements for a canonical, two-dimensional 30P30N airfoil configuration in the NASA Langley Quiet Flow Facility (NASA-QFF).⁷ To avoid the extreme flow turning typical of three-element airfoils in a laboratory scale open jet facility, they stowed the flap and adjusted the angle of attack to mimic the effects of flap on the flow around the slat. The Krueger flap was designed for an equivalent mission as the leading-edge slat⁶, and the NASA-QFF experiments provided aeroacoustic measurements of both the baseline 30P30N configuration with a leading-edge slat and the modified design with a Krueger flap. While the experimental findings indicated differences in spectral details of the noise field radiated from the slat and the Krueger flap, their scaling behavior with respect to significant flow parameters, such as the Mach number, and the respective sensitivities to the slat gap setting were similar to each other. The results also showed that the Krueger cavity had a detectable effect on the level and directivity of the noise field, but the influence was not as pronounced as originally anticipated.

Pott-Pollenske and Delfs¹⁹ have extended the comparison between the noise characteristics of Krueger flap and leading-edge slat to a conventional (i.e., non-laminar), three-dimensional wing that was tested in the acoustic test section of DNW's low speed wind tunnel in Braunschweig. The effects of Krueger settings such as deflection angle and gap were also measured and, in all cases, the Krueger device was found to be the dominant noise source associated with the high-lift system. At reference settings, the noise characteristics of the Krueger device were similar to those of the slat, with the Krueger configuration resulting in slightly enhanced noise level. They also found the effect of the Krueger cavity to be small and, similar to the effects of slat gap, reduction in the Krueger gap led to lower levels of noise.

The experimental comparisons in Refs. [7, 19] focused on acoustic measurements, and no measurements of off-body flowfields were carried out for either configuration. However, a companion study to Ref. [7] focused on numerical simulations of both the unsteady flow and the aeroacoustics.²⁰ In Ref. [21], a reduced order prediction model was applied to Krueger flap noise on both conventional aircraft and hybrid-wing-body configurations. This model attributed the Krueger device noise to four distinct components associated with the unsteady flow in the cove underneath the Krueger flap, the gap region, the brackets, and the cavity underneath the wind leading edge. Numerical simulations were used in Ref. [22] to investigate potential noise reduction via geometric changes to the Krueger flap contour. An aerodynamically optimized, longer chord Krueger flap was found to yield significant noise reduction over the reference Krueger with a shorter chord length and the conventional slat. Furthermore, sealing the cavity for Krueger flap stowage was shown to yield an additional modest reduction in the Krueger flap noise.

In the present study, numerical simulations are performed to investigate the flowfield, the noise sources, and their detailed characteristics around the 30P30N multi-element airfoil configuration with either a conventional slat or the Krueger flap, as discussed in Ref. 7. The influence of the Krueger cavity is also investigated by comparing the predicted noise with and without the cavity.

II. Computational Geometries

Figure 1 shows the computational geometries of the effectively two-element airfoil configuration that was comprised of either a conventional slat or a Krueger flap and a main wing with the trailing-edge flap in a retracted state, as discussed in Ref. 7. The 30P30N slat is used as the reference conventional slat, while the slat in the wind tunnel test in the NASA-QFF has some differences when compared to the baseline slat from the BANC Workshop series.^{23,24} Differences are observed in the outer mold line of the slat, specifically in the cove geometry. The present computations employ the same slat geometry as the slat tested in the NASA-QFF. Configurations with three different slat angles of 10, 20, and 30 degrees, respectively, were defined in Ref. [7]. For this study, only a single configuration with a slat angle of 30 degrees is employed. The deployment setting of the Krueger flap was designed to match the overall model lift, as discussed in Refs. [6,7]. As depicted in Fig. 1, the overall configuration can include a simplified cavity on the lower side of the main wing to stow the Krueger flap. However, the configuration without the cavity opening is considered as the baseline Krueger flap configuration in this study.



Fig.1 Computational airfoil geometries. Black: configuration with a conventional slat, red: configuration with a Krueger flap with an exposed cavity.

III. Computational Method and Conditions

The unsteady flow of high-lift configurations of interest and the resulting aeroacoustics are simulated using a commercial CFD/CAA software based on the Lattice Boltzmann Method (LBM), SIMULIA Powerflow.²⁵⁻²⁶ The LBM simulation employs a Cartesian mesh, and the simulation methodology amounts to a renormalization group (RNG)-based Very Large Eddy Simulation (VLES) with an extended turbulent wall model that allows the effects of the wall boundary layer to be captured without resolving the near wall dynamics in the viscous sublayer and the buffer layer.

Based on Ref. [7], the following conditions are employed for the numerical simulations: The freestream Mach number is set equal to 0.17, corresponding to a freestream speed of 58.6 m/s and a reference temperature of 295.56 K. The Reynolds number based on the stowed chord length of 16.7 inches is equal to 1.59 million. The angle of attack in the effectively free-air computation is set to 12 degrees to match the surface pressure distribution around the slat at the angle of attack of 27 degrees in the NASA-QFF wind tunnel test.

Figures 2 and 3 show cross-sectional views of the computational grids superimposed on the computed distribution of time-averaged velocity magnitude for the configuration with a conventional slat (Fig. 2) and a Krueger flap with an exposed cavity (Fig. 3). The spanwise extent of the simulation domain is 5% of the stowed chord length, c , and periodic boundary conditions are enforced at both edges. The size of the outer boundary is $100c \times 100c$. The computational grid consists of a total of eight levels of variable resolution (VR) from $VR0$ to $VR7$, with the minimum spacing of 0.0831 mm in $VR7$ regions around the slat trailing-edge and the slat cusp as shown in Fig. 2(b). The cove region was set to $VR6$, and the wake regions behind the slat and the Krueger flap were set to $VR4$. The same gridding strategies were applied to both the slat and Krueger flap as shown in Fig. 3. The total number of voxels is around 42 million. The initial transient time is 0.05 seconds (i.e., nearly 7 flow-through times based on the reference chord length and freestream speed), followed by a sampling duration of 0.025 seconds for estimating the flow statistics including the frequency spectra.

The far field noise spectra were obtained with the FfowcsWilliams-Hawkings (FW-H) method by using pressure fluctuations on a permeable surface constructed on the outer surface of the $VR2$ region.

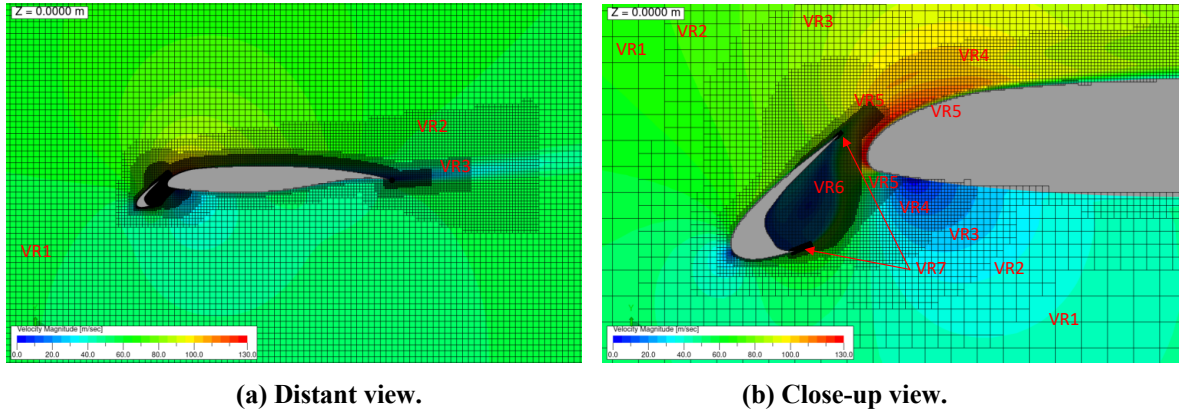


Fig. 2 Cross-sectional views of the computational grid along with velocity magnitude contours for the configuration with a conventional slat.

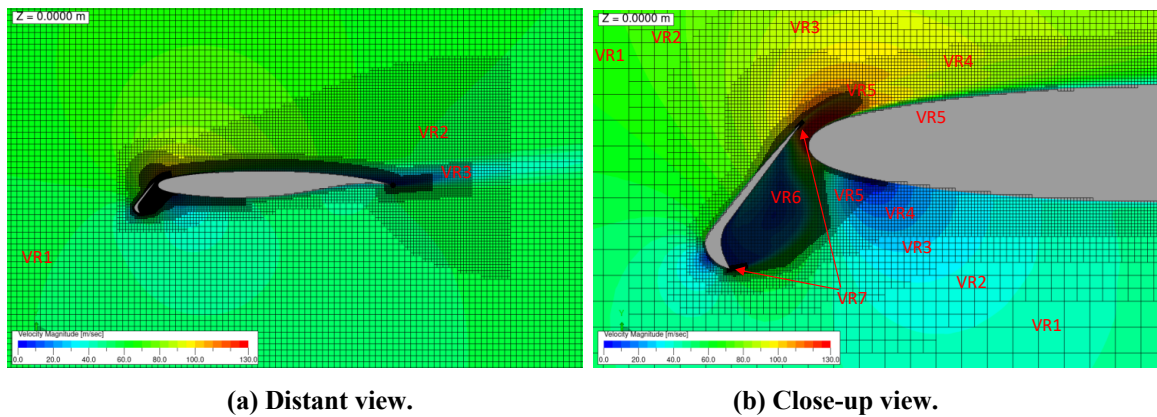


Fig. 3 Cross-sectional views of the computational grid and velocity magnitude contours for the configuration with a Krueger flap with cavity.

IV. Computational Results

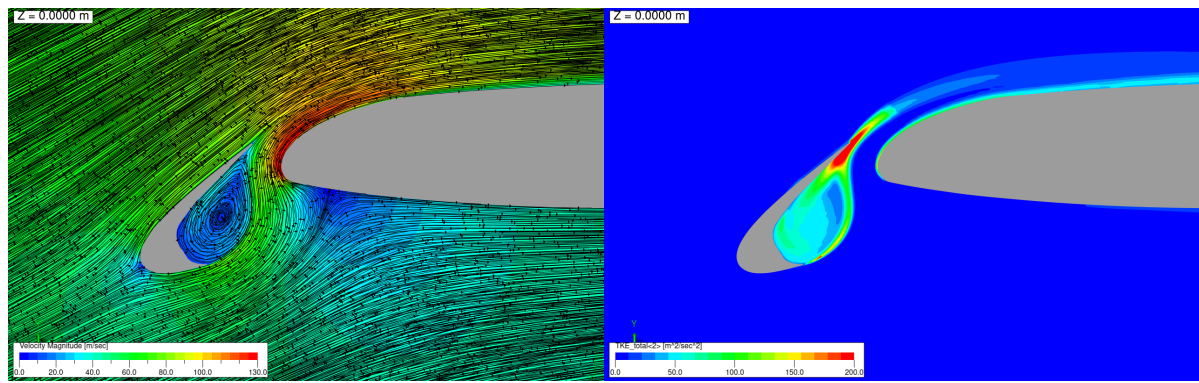
A. Comparison of configurations with a conventional slat and a Krueger flap

Figures 4 and 5 show the time-averaged computational results for the configuration with a conventional slat and a Krueger flap without cavity, respectively. Contours of velocity magnitude and the turbulent kinetic energy (TKE) are shown in the figures along with the streamlines in the $Z = 0$ plane. Figure 6 compares chordwise variations in time-averaged surface C_p between the configurations with the slat and the Krueger flap. Figure 7 compares the narrowband acoustic spectra at three microphone locations corresponding to emission angles of 70, 90, and 110 degrees, respectively. The microphone at 90 degrees is located beneath the model, while the one at 70 degrees is on the upstream side. All microphones are located 10 feet away from the center span point of the leading edge corresponding to the equivalent cruise configuration.

The unsteadiness associated with flow separation in the slat cove region is known to be a dominant component of the overall slat noise.¹²⁻¹³ The shear layer emanating from the slat cusp and its reattachment upstream of the slat trailing edge as shown in Fig. 4 lead to a primarily broadband noise spectrum. A region with high TKE is found around the reattachment point. Several Narrowband peaks (NBPs) are also observed in the predicted slat-noise spectrum at frequencies of 1.6 kHz, 2.5 kHz, 3.2 kHz, 4.3 kHz, and 5kHz, respectively, as seen from Fig. 7. A hump around 20 kHz is also observed in this noise spectrum.

The general flowfield around the Krueger flap is shown in Fig. 5 and it bears significant resemblance to the flow around the slat in Fig. 4. Again, the flow separates from the cusp and generates a recirculating flow in the cove region. The shear layer emanates from the cusp and reattaches on the cove surface upstream of the trailing edge. The deflection angle of the Krueger flap is higher than that of slat, which is accompanied by a larger height of the recirculating flow region. Additionally, the gap between the trailing edge of the Krueger flap and the leading-edge of the main wing is narrower than the slat gap, causing a stronger acceleration of the flow passing through the gap, which is manifested in the higher suction peak as seen from the C_p distributions in Fig. 6. A

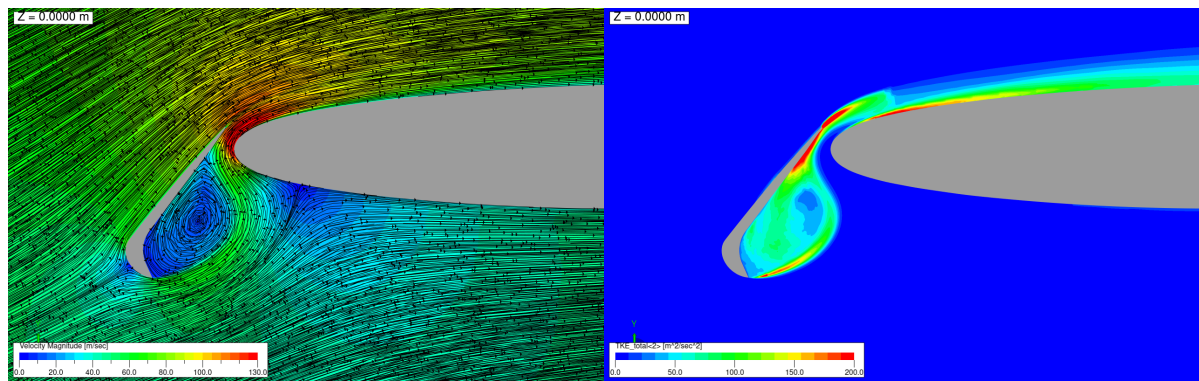
larger region with elevated TKE is observed around the reattachment point and in the wake after the trailing edge. In Fig. 7, the underlying broadband spectrum (i.e., the spectrum underneath the spectral humps at frequencies above 10 kHz) associated with the Krueger flap appears to be higher than that of the slat at sufficiently larger frequencies at the 70-degree and 90-degree locations. The noise spectrum for the Krueger flap indicates a strong spectral hump near 40 kHz. This hump is produced by the vortex shedding from the trailing edge, caused by the finite thickness of the Krueger trailing edge. The trailing edge of the slat is much thinner, which results in this peak shifting to a significantly higher range of frequencies. Consequently, the spectral hump associated with the trailing-edge vortex shedding is not prominent within the slat noise spectrum. Regarding the NBPs in the lower frequency range, the frequency of each tone varies slightly between the slat and the Krueger-flap configurations. This difference may be attributed to the variations in the chord lengths of the slat and the Krueger flap, as well as the differences in the sizes of the recirculation regions the relevant characteristics of the cove mixing layer. In the noise spectrum for the 70-degrees emission angle, the levels of Krueger-flap NBPs below 3 kHz are higher than those of the slat at 70 degrees, but they are comparable to or less than those of the slat for the other two emission angles of 90 degrees and 110 degrees, respectively.



(a) Velocity magnitude and streamlines.

(b) TKE.

Fig. 4 Time-averaged computational results for the configuration with a conventional slat.



(a) Velocity magnitude and streamlines.

(b) TKE.

Fig. 5 Time-averaged computational results for the configuration with a Krueger flap without cavity.

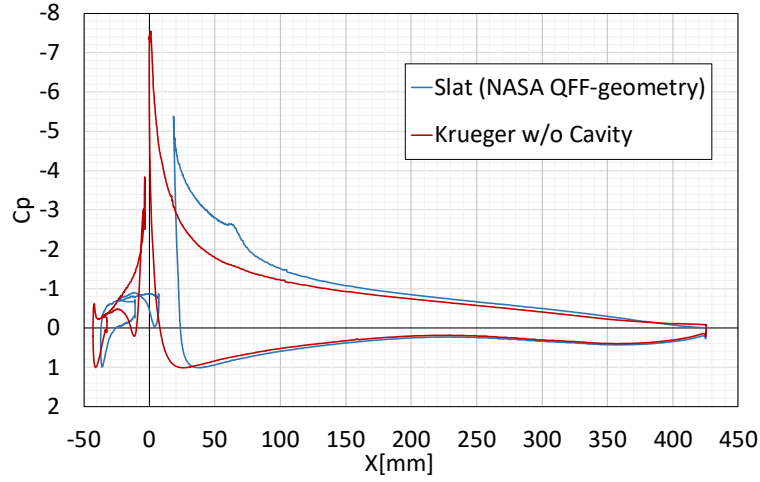


Fig. 6 Comparison of time-averaged surface C_p between the configurations with a conventional slat and with a Krueger flap without cavity.

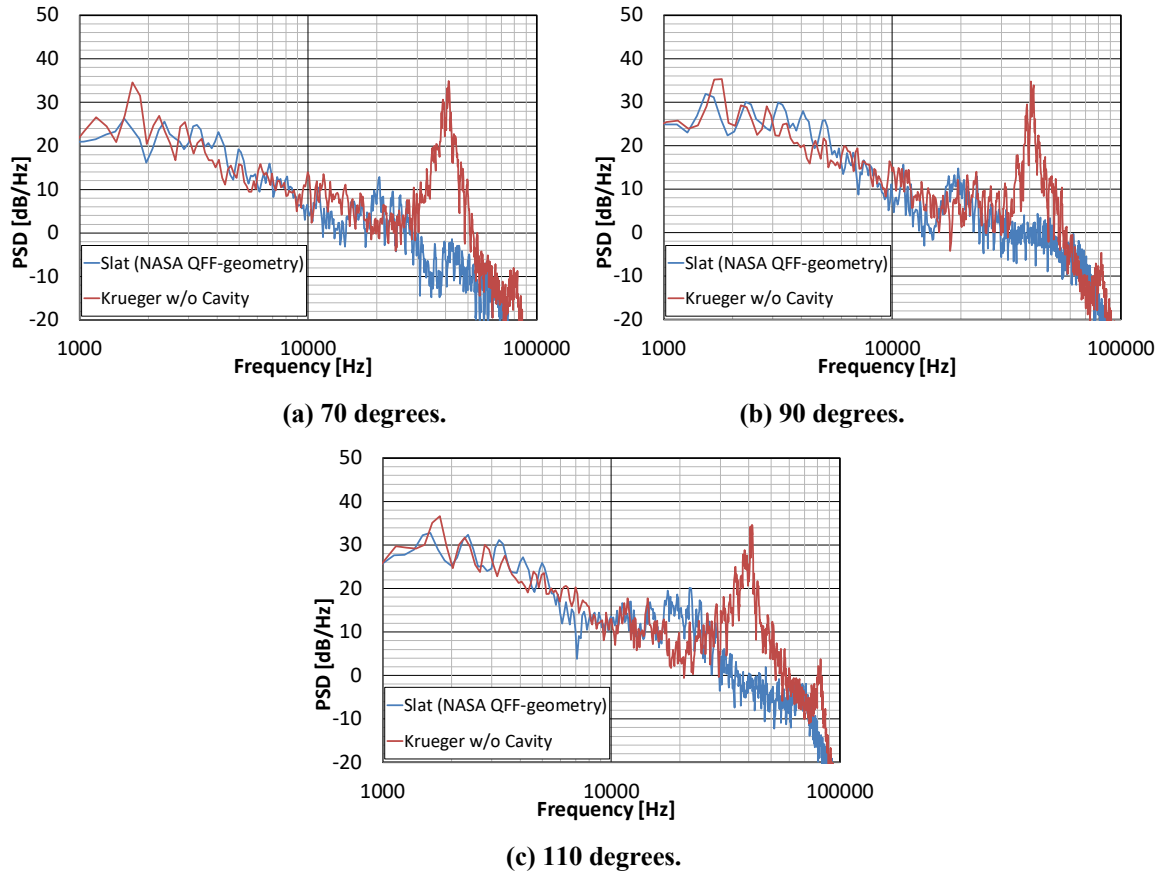
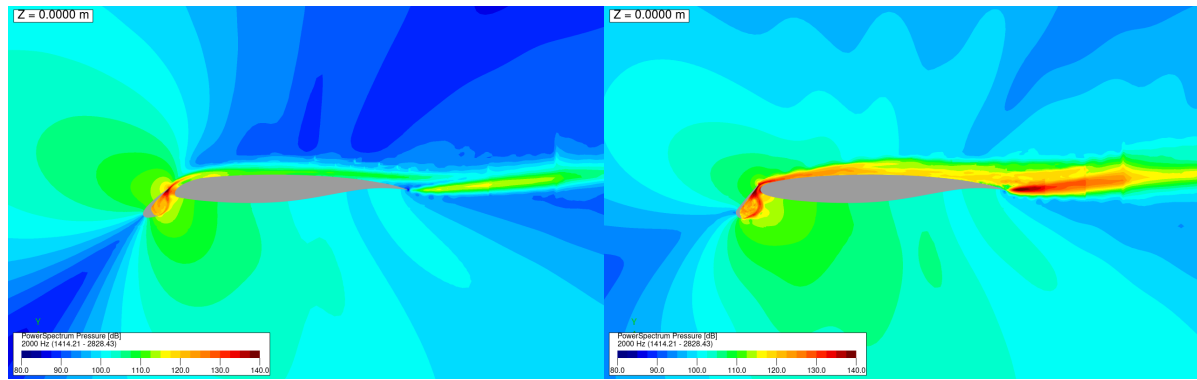


Fig. 7 Comparison of narrowband spectra between the configurations with a conventional slat and with a Krueger flap without cavity at three microphone locations corresponding to emission angles of 70, 90, and 110 degrees with respect to the flow direction (spectral bin width = 131 Hz).

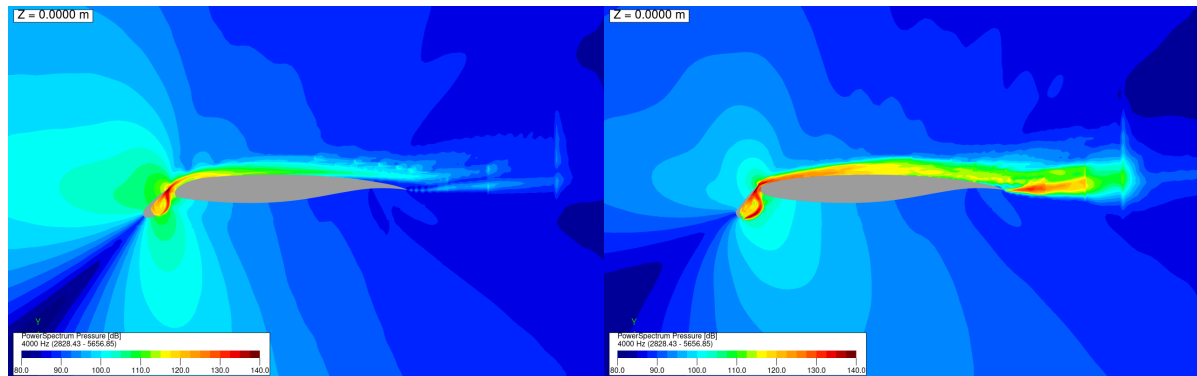
Figure 8 compares bandpass-filtered pressure fluctuation levels in three different frequency bands that are centered at 2 kHz, 4 kHz, and 16 kHz for the slat and the Krueger configurations. The resulting directivity patterns indicate relatively small differences between the two configurations. For the Krueger flap, the directivity of high noise levels has a slightly greater downstream inclination, especially in the frequency bands centered on 2 kHz and 4 kHz. While the overall flowfields and the potential noise sources are generally similar between the two, one of the main reasons behind the above trends could be related to the difference in deflection angles of the slat and

the Krueger flap. In particular, the Krueger flap has a higher deflection angle, leading to higher noise levels in the downstream direction. We also observe that the directivity of low noise levels in the lower arc is approximately orthogonal to the direction of peak directivity, and hence, it is shifted in the upstream direction for the Krueger flap, especially in the frequency band centered on 2 kHz, which may account for the higher NBP levels at 70 degrees.

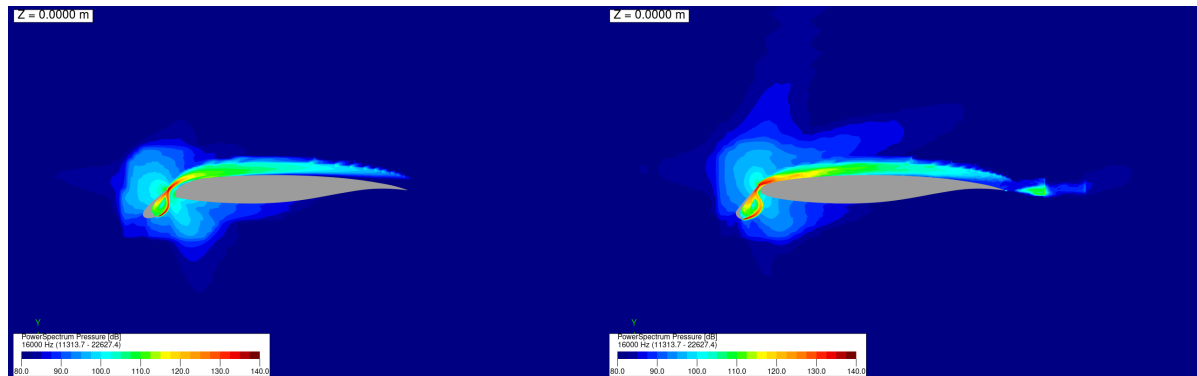
Figure 9 compares close-up views of bandpass-filtered pressure fluctuation levels around the leading-edge device for the configurations with the slat (left half in Fig. 9) and the Krueger flap (right half), respectively. The results are shown in two distinct frequency ranges centered on 16 kHz and 31.5 kHz, which correspond to the pronounced humps in the noise spectrum of the slat and the Krueger flap, respectively. The result for the slat configuration in the frequency range of 16 kHz shows high pressure fluctuations around the entire gap between the trailing-edge of the slat and the leading-edge of the main wing. The gap size coincides with approximately one half of the acoustic wavelength at the peak frequency, implying that a resonant tone due to the gap could have contributed to this peak. On the other hand, the simulation for the Krueger flap in the frequency range of 31.5 kHz shows high pressure fluctuations from the (thicker) trailing edge of the Krueger.



(a) 2 kHz (1.4 kHz–2.8 kHz).



(b) 4 kHz (2.8 kHz–5.6 kHz).



(c) 16 kHz (11.3 kHz–22.6 kHz).

Fig. 8 Comparison of bandpass-filtered pressure fluctuation levels. CFD results are shown for the configurations with a conventional slat (left) and with a Krueger flap without cavity (right).

B. Comparison of configurations with the Krueger flap configurations with and without a cavity

Figure 10 shows time-averaged computational results for the Krueger flap configuration with a cavity on the lower surface that would be used to stow the Krueger flap. The velocity magnitude, surface streamlines, and the TKE are shown in the figure. At this angle of attack, the stagnation point on the lower surface of the main wing is located just upstream of the cavity. When compared to the result without the cavity in Fig. 5, the flowfield around the Krueger flap and the gap in Fig. 10 seems to be rather similar to that in Fig. 5. Due to the shallow depth of the cavity and the stagnation point just upstream of it, the flow around the cavity differs from an open cavity flow, wherein the flow recirculates within the cavity and the shear layer oscillates over it, causing a Rossiter tone. On the other hand, the mean flow in Fig. 10 is more analogous to that over a closed cavity wherein the shear layer reattaches on the cavity floor. Furthermore, when the flow comes up from inside the cavity toward the rear corner, it undergoes separation, which leads to high levels of TKE just downstream of the cavity opening. Figure 11 compares the chordwise distributions of time-averaged surface C_p between the configurations with and without the cavity. Differences are found only around the cavity, and the C_p distributions around the Krueger flap are almost the same in both cases.

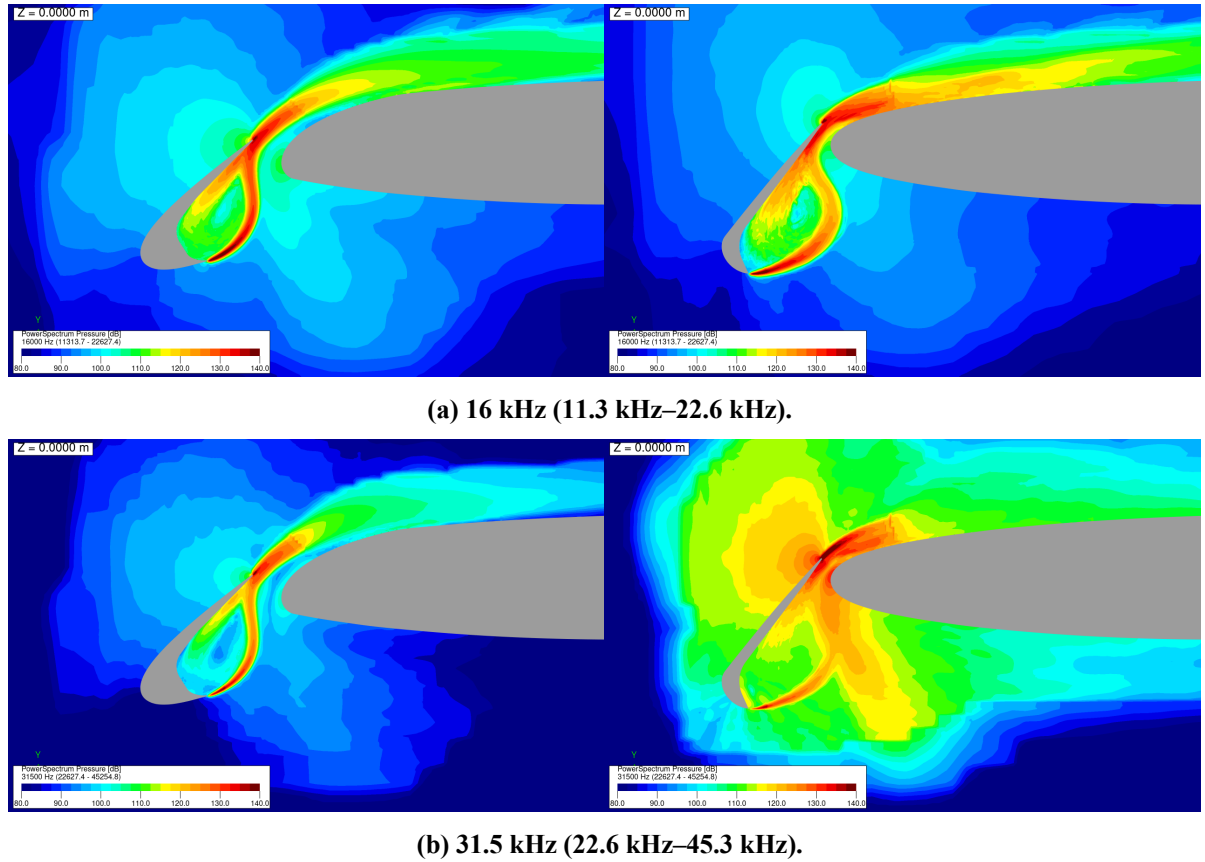


Fig. 9 Comparison of bandpass-filtered pressure fluctuation levels. Close-up views around the slat and the Krueger flap. CFD results are shown for the configurations with a conventional slat (left) and with a Krueger flap without cavity (right).

Figure 12 compares the narrowband spectra at three microphone locations corresponding to emission angles of 70, 90, and 110 degrees, respectively. Figure 13 compares the one-third octave-band spectra. The results with the cavity show generally higher noise levels below 4 kHz, especially along 70 and 90 degrees, except for the NBP at frequencies of 1.6 kHz. Figure 14 compares bandpass-filtered pressure fluctuation levels with and without the cavity for three different frequency bands centered on 2 kHz, 4 kHz and 8 kHz, respectively. In the presence of the cavity, additional noise sources are observed around the rear part of the cavity, although they are not as significant as the noise sources on the lower side of the Krueger flap (i.e., similar noise source as the cove region of the slat configuration). The additional noise sources contribute to a secondary peak in the overall directivity that is inclined slightly upstream with respect to the overhead direction, especially in the frequency bands near 2 kHz and 4 kHz. These results support the observed differences in the farfield acoustic spectra indicating the cavity-induced enhancement in noise levels below 4 kHz, especially at emission angles of 70 degrees and 90 degrees.

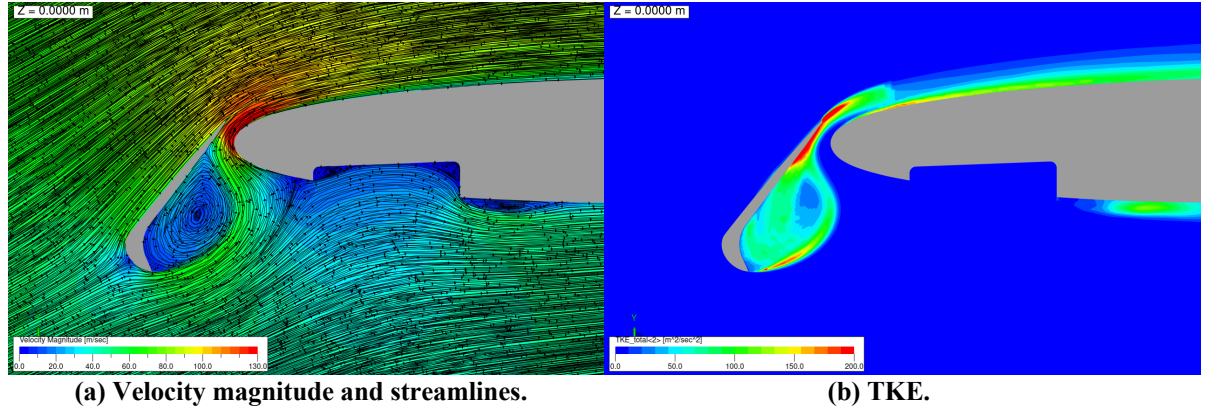


Fig. 10 Time-averaged computational results for Krueger flap configuration with an exposed cavity.

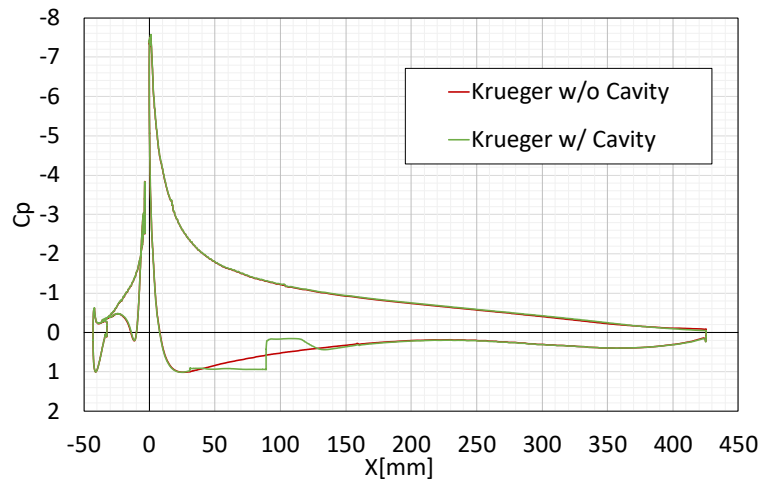


Fig. 11 Comparison of time-averaged surface C_p between the configurations with and without cavity.

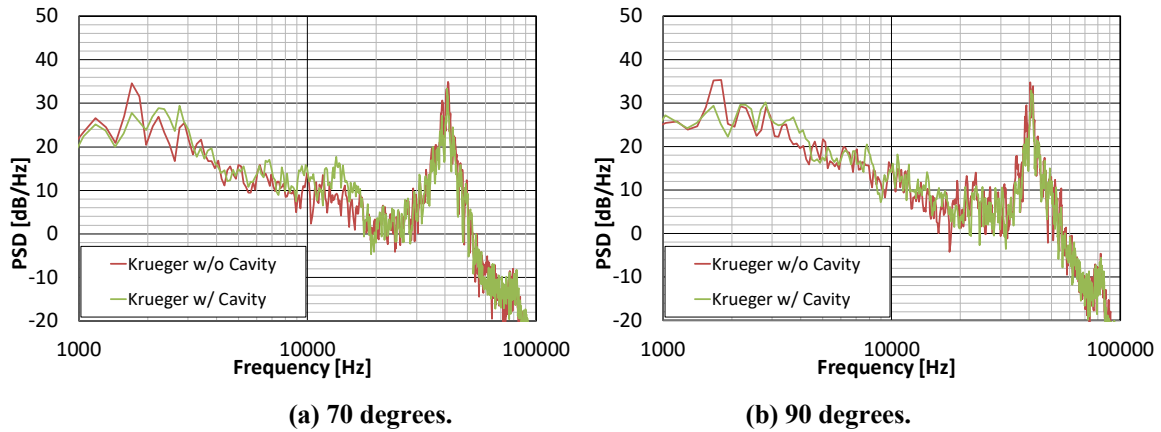
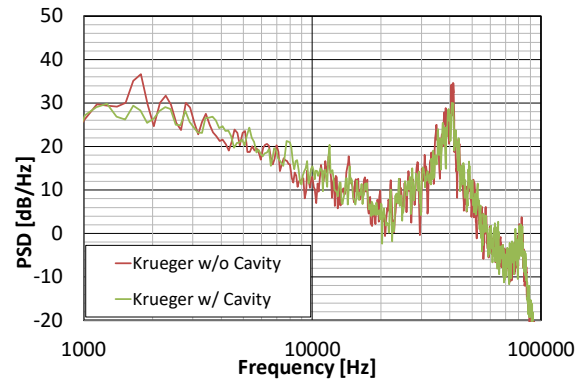
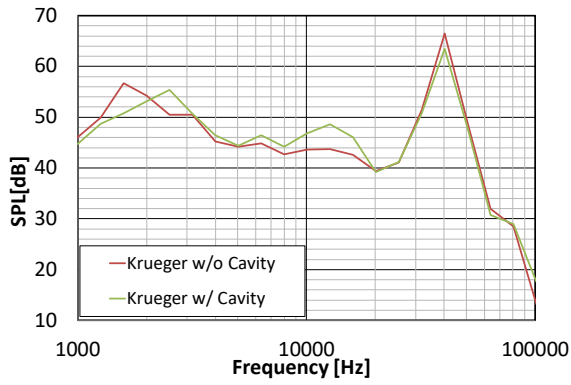


Fig. 12 Comparison of narrowband spectra between the Krueger flap configurations with and without cavity at three microphone locations corresponding to emission angles of 70, 90, and 110 degrees with respect to the flow direction (spectral bin width = 131 Hz).

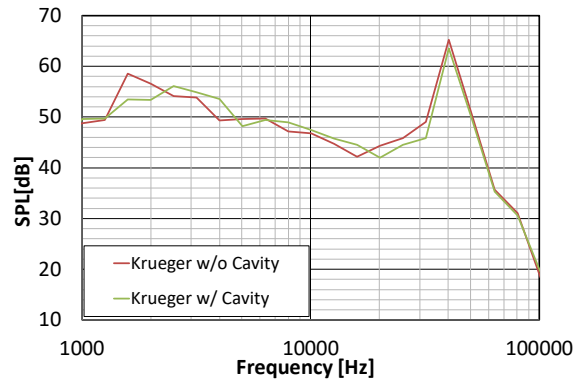


(c) 110 degrees.

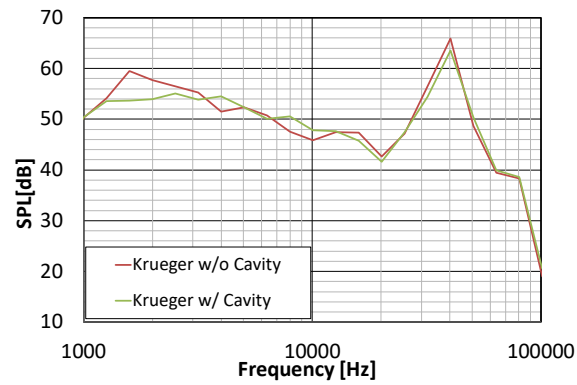
Fig. 12 (Continued)



(a) 70 degrees.

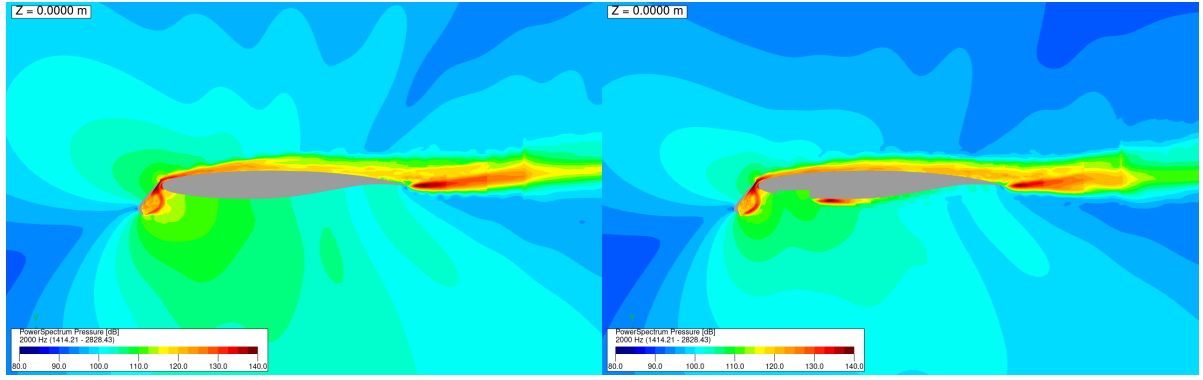


(b) 90 degrees.

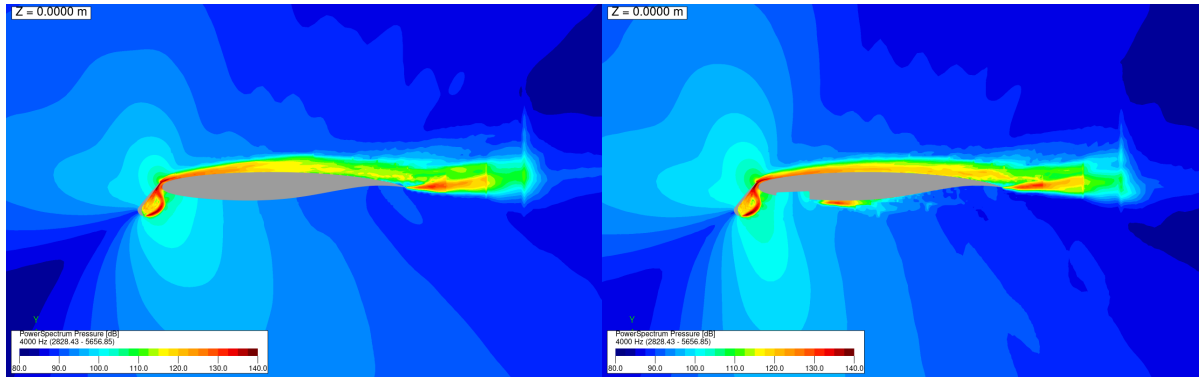


(c) 110 degrees.

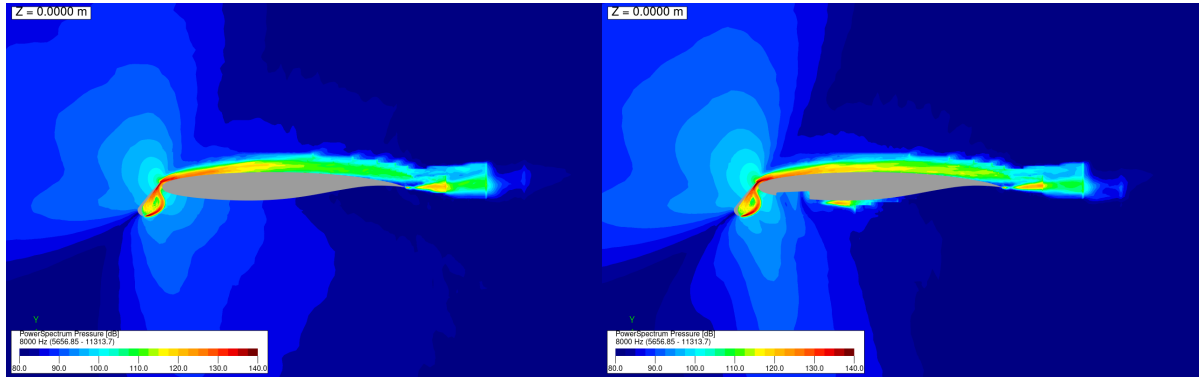
Fig. 13 Comparison of one-third octave-band spectra between the Krueger flap configurations with and without cavity at three microphone locations corresponding to emission angles of 70, 90, and 110 degrees with respect to the flow direction.



(a) 2 kHz (1.4 kHz–2.8 kHz).



(b) 4 kHz (2.8 kHz–5.6 kHz).



(c) 8 kHz (5.6 kHz–11.3 kHz).

Fig. 14 Effects of cavity on bandpass-filtered pressure fluctuation levels. CFD results for the Krueger flap configurations without a cavity are shown in the left column, whereas those with a cavity are plotted on the right.

V. Concluding Remarks

In this study, numerical simulations were performed to investigate the unsteady flowfield and the associated noise sources around high-lift configurations with a conventional leading-edge slat or a Krueger flap. While the flowfields and potential noise sources for both leading-edge devices were similar, the noise directivity patterns displayed small yet noteworthy differences between the two types of configurations. For the Krueger flap, the directivity pattern in the lower half plane was inclined more downstream, potentially as a result of the higher deflection angle of the Krueger flap. For the same reason perhaps, the directivity of low noise levels was shifted toward the upstream direction, especially in the lower frequency range near 2 kHz. This change in the directivity pattern could also be the result of the higher NBP level at the 70-degrees observer location.

The influence of the Krueger cavity was assessed via numerical simulations with and without the cavity. The flowfield around the Krueger flap and the gap region was not significantly influenced by the cavity. Due to the shallow depth of the cavity and the stagnation point just upstream of the cavity, the flow around the cavity resembles that of a closed cavity. Thus, it is rather different from an open cavity flow in the slat cove region, wherein the flow recirculates within the cavity and the shear layer oscillates over it, causing resonant cavity oscillations. On the other hand, in the case of the Krueger flap with cavity, the flow undergoes separation as it approaches the rear corner of the cavity, creating a region of high TKE just downstream of the cavity opening. In terms of the cavity influence on the noise spectra, results with the cavity show a higher noise level at frequencies of less than about 4 kHz, especially for the observer locations at 70 degrees and 90 degrees. When the cavity exists, additional noise sources are observed around the rear part of the cavity, although they are not as significant as the noise sources on the lower side of the Krueger flap. The additional noise sources contribute to enhanced noise levels toward the upstream direction, especially in the frequency bands centered on 2 kHz and 4 kHz.

In summary, the results of the numerical simulations are qualitatively consistent with the experimental measurements and provide further confidence in employing such high fidelity methods for parameter studies involving the noise sources associated with the Krueger flap. The effects of nonzero sweep and slat brackets were not investigated here, but would provide excellent topics for follow-on studies.

Acknowledgements

The authors gratefully acknowledge the generous help from Dr. Christopher J. Bahr in sharing and discussing the NASA LaRC Kreuger flap data.

References

- [1] Tokugawa, N., Osada, T., Ueda, Y. and Ishikawa, H., "Natural Laminar Flow Design of Fuselage Nose for Small Supersonic Civil Transport," 29th Congress of the International Council of the Aeronautical Sciences, St. Petersburg, Russia, 2014.
- [2] Tokugawa, N., Toyoda, K., Kuroda, F., Ueda, Y. and Ishida, T., "Natural Laminar Flow Design for Highly Swept Wing," The Asia-Pacific International Symposium on Aerospace Technology (APISAT), P00234, 2021.
- [3] Kok, M., Smith, J. G., Wohl, C. J., Siochi, E. J. and Young T. M., "Critical Considerations in the Mitigation of Insect Residue Contamination on Aircraft Surfaces," Progress in Aerospace Sciences 75 (2015) 1-14, 2015.
- [4] Krueger, W., "Systematic Wind-Tunnel Measurements on a Laminar Wing with Nose Flap," NACA Technical Memorandum No. 1119, 1947.
- [5] Pott-Pollenske, M., Almoneit, D. and Wild J., "On the Noise Generation of Krueger Leading Edge Devices," AIAA Paper 2015-3142, 2015.
- [6] Akaydin, H. D., Housman, J. A. Kiris, C. C. Bahr, C. J. and Hutcheson, F. V., "Computational Design of a Krueger Flap Targeting Conventional Slat Aerodynamics," AIAA Paper 2016-2958, 2016.
- [7] Bahr, C. J., Hutcheson, F. V., Thomas, R. H. and Housman, J. A., "A Comparison of the Noise Characteristics of a Conventional Slat and Krueger Flap," AIAA Paper 2016-2961, 2016.
- [8] Pott-Pollenske, M. and Delfs, Y., "Krueger Noise Generation and its Comparison to Slat Noise," AIAA Paper 2023-4480, 2023.
- [9] Khorrami, M. R., Berkman, M. E., and Choudhari, M. M., "Unsteady Flow Computations of a Slat with a Blunt Trailing Edge," *AIAA Journal*, Vol. 38, No. 11, November 2000, pp. 2050-2058.
- [10] Choudhari, M. M., Lockard, D. P., Macaraeg, M. G., Singer, B. A., Streett, C. L., Neubert, G. R., Stoker, R. W., Underbrink, J. R., Berkman, M. E., Khorrami, M. R., and Sadowski, S. S., "Aeroacoustic Experiments in the Langley Low-Turbulence Pressure Tunnel," Tech. Rep. NASA TM-2002-211432, NASA, 2002.
- [11] Pascioni, K. A., Cattafesta, L. N., and Choudhari, M. M., "An Experimental Investigation of the 30P30N Multi-Element High-Lift Airfoil," AIAA 2014-3062, 2014.
- [12] Murayama, M., Nakakita, K., Yamamoto, K., Ura, H., Ito, Y., and Choudhari, M. M., "Experimental Study on Slat Noise from 30P30N Three-Element High-Lift Airfoil at JAXA Hard-Wall Low-Speed Wind Tunnel," AIAA Paper 2014-2080, 2014.
- [13] Murayama, M., Yokokawa, Y., Ura, H., Nakakita, K., Yamamoto, K., Ito, Y., Takaishi, T., Sakai, R., Shimoda, K., Kato, T., and Homma, T., "Experimental Study of Slat Noise from 30P30N Three-Element High-Lift Airfoil in JAXA Kevlar-Wall Low-Speed Wind Tunnel," AIAA Paper 2018-3460, 2018.
- [14] Murayama, M., Yokokawa, Y., Ito, Y., Yamamoto, K., Takaishi, T., Ura, H., and Hirai, T., "Study on Noise Generation from Slat Tracks Using a High-Lift Wing Model," AIAA Paper 2015-3141, June 2015.
- [15] Murayama, M., Yokokawa, Y., Ito, Y., Yamamoto, K., Takaishi, T., Ura, H., and Hirai, T., "Study on Change of Noise Generation by Slat Track Shape," AIAA Paper 2016-2959, June 2016.
- [16] Ribeiro, A. F., Murayama, M., Ito, Y., Yamamoto, K., and Hirai, T. "Effect of Slat Tracks and Inboard Slat Tip Geometry on Airframe Noise," AIAA Paper 2022-2952, 2022.
- [17] Yamamoto, K., Murayama, M., Isotani, K., Ueno, Y., Hayashi, K., and Hirai, T., "Slat Noise Reduction Based on Turbulence Attenuation Downstream of Shear-layer Reattachment," AIAA Paper 2022-2954, 2022.
- [18] Murayama, M., Sakai, R., Ito, Y., Masataka, K., Yokokawa, Y., Ura, H., Yamamoto, K., Takaishi, T., Hayashi, K., Ueno, Y., and Isotani, K., "Noise Reduction Design for High Lift Devices of Regional Jet," AIAA Paper 2022-2955, 2022.

- [19] Pott-Pollenske, M. and Delfs, J., “Krueger Noise Generation and its Comparison to Slat Noise,” AIAA Paper 2023-4480, 2023.
- [20] Housman, J. and Kiris, C., “Slat Noise Predictions using High-Order Finite-Difference Methods on Overset Grids,” AIAA Paper 2016-2963, 2016.
- [21] Guo, Y.P., Burley, C., and Thomas, R.H., “Modeling and Prediction of Krueger Device Noise,” AIAA Paper 2016-2957, 2016.
- [22] Soni, M., Ewert, R., Dierke, J., and Delfs, J., “Evaluation of the Noise Reduction Potential of a Krueger Flap High-Lift device via the Lattice Boltzmann Method,” AIAA Paper 2023-4447, 2023.
- [23] Choudhari, M. and Lockard, D. P., “Assessment of Slat Noise Predictions for 30P30N High-Lift Configuration from BANC-III Workshop,” AIAA Paper 2015-2844, 2015.
- [24] Choudhari, M., Bahr, C., et al., “Simulations & Measurements of Airframe Noise: a BANC Workshops Perspective,” Proceedings of NATO STO-MP-AVT- 246 Specialists Meeting on Progress and Challenges in Validation Testing for Computational Fluid Dynamics (NATO STO-MP-AVT-246), NATO Science and Technology Organization (STO), STO-MP-AVT- 246, p.10, 2016. <https://www.sto.nato.int/publications/STO%20Meeting%20Proceedings/STO-MP-AVT-246/MP-AVT-246-16.pdf>
Also available as: NASA Tech. Rep. NF1676L-23007, 2016.
<https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20160012014.pdf>
- [25] Noelting, S., Bres, G. and Dethioux, P., “A Hybrid Lattice-Boltzmann/FW-H Method to Predict Sources and Propagation of Landing Gear Noise,” AIAA Paper 2010-3976, 2010.
- [26] Fares, E. and Noelting, S., “Unsteady Flow Simulation of a High-Lift Configuration Using a Lattice Boltzmann Approach,” AIAA Paper 2011-0869, 2011.