PROCEEDINGS of the
24th International Congress on Acoustics

October 24 to 28, 2022, in Gyeongju, Korea

Extended abstract

ABS-0549

Aeroacoustic-structural interactions of a multi-panel airfoil configuration for tonal noise reduction

Irsalan ARIF[1]; Muhammad Rehan NASEER[2]; Garret Chi Yan LAM[3]; Randolph Chi Kin LEUNG[4]

Department of Mechanical Engineering, The Hong Kong Polytechnic University, Hong Kong

ABSTRACT

In this paper, a multi-panel airfoil configuration (MPC) is designed to achieve airfoil tonal noise reduction over a wide range of angle of attack (*AoA*) at a Reynolds number of 50000 and a Mach number of 0.4. The aeroacoustic-structural interactions of the designed airfoil are explored using reduced order modelling (ROM). The range of operational *AoA* for the present study is chosen from 1° to 7° to analyze the tonal component of airfoil noise. The design methodology of the multi-panel airfoil is based on the preliminary analysis of the rigid airfoil to ascertain the optimum panel locations and their structural properties. Subsequently, an airfoil configuration based on three resonant elastic panels with different structural properties is designed and its noise reduction potential is assessed at varying *AoA*s. ROM analysis shows a non-linear response in the noise reduction characteristics for the airfoil ranging from 6.75 dB to 7.92 dB over the complete range of *AoA*. The structural analysis shows a complex vibration pattern for all the panels which clearly indicates the presence of complex structural interaction among the panels for MPC airfoil at varying *AoA*.

Keywords: Aeroacoustics, Tonal noise, Vibrations

1. INTRODUCTION

Self-noise generation of an airfoil operating at low/moderate freestream Reynolds number (Re) is one of the most undesirable aspects associated with its operations [1-3]. Over the years, researchers have studied and explored the phenomenon of airfoil self-noise generation which involves the interaction among different physical mechanisms involving hydrodynamics, acoustics, and even structural dynamics in some cases [4-7]. Motivated by the flexibility of the bat wings and its adaptability features, flexible wings/airfoils have received significant attention in past few decades due to their favorable characteristics at low Re flow and improved airfoil aerodynamics at certain flow conditions [8-10]. The membrane wings/airfoils are found to have better static stability [11] as well as high lift to drag ratio as compared to rigid wing/airfoil [12]. Furthermore, these flexible airfoils have shown to be effective in delaying stall characteristics at high AoA [9]. However, the existing methods are limited to provide tonal noise reduction at a specific design condition only and may not remain effective for an airfoil operating at variable loading condition such as variable angle of attack (AoA). In this study, a multi-panel airfoil configuration (MPC) is designed with an aim to achieve tonal noise reduction at a wide range of operating AoA.

[1] irsalan.arif@connect.polyu.hk
[2] rehan.naseer@connect.polyu.hk
[3] garret.lam.hk@connect.polyu.hk
[4] randolph.leung@polyu.edu.hk

2. METHODOLOGY

The present study utilizes high-fidelity direct aeroacoustic simulation (DAS) for its capability to resolve the coupling between the unsteady airfoil aerodynamic and acoustic solutions with high accuracy [13]. To solve the unsteady compressible Navier-Stokes (N-S) equations, conservation element and solution element (CE/SE) method is adopted. Since, it is too prohibitive in extensive deployment of resources and time to search for optimal design with DAS, a Reduced Order Model (ROM) is developed and successfully implemented. ROM only requires 10% of the computational time required for its corresponding DAS simulation and can provide a reasonable qualitative assessment of tonal noise reduction by the designed configuration [14].

The adopted methodology for the design of multi-panel configuration for different AoAs ranging from 1° to 7° is divided into three major stages as shown in Figure 1. In Stage 1, the flow characteristics of the rigid airfoil (RS) at selected *AoA*s are determined individually by DAS. The results of DAS analyses also help in determining the steady base flow at respective *AoA*s for subsequent ROM analyses. In the next stage (Stage 2), the airfoil configuration with single elastic panel is designed for each *AoA*. The structural properties and suitable location of the panel on the airfoil surface at each *AoA* are determined based on the rigid airfoil characteristics evaluated in Stage 1. In the final stage (Stage 3), a conceptual design of a multi-panel configuration is presented which is aimed to possibly achieve tonal noise reduction at different *AoA*s. The structural properties and locations of the elastic panels in this configuration are based on the ROM results obtained in Stage 2. Finally, the effectiveness of the designed multi-panel configuration in airfoil tonal noise reduction is evaluated at different AoAs by PEM. The final schematic sketch of the multi-panel airfoil configuration (MPC) designed for the present study is shown in Figure 2.

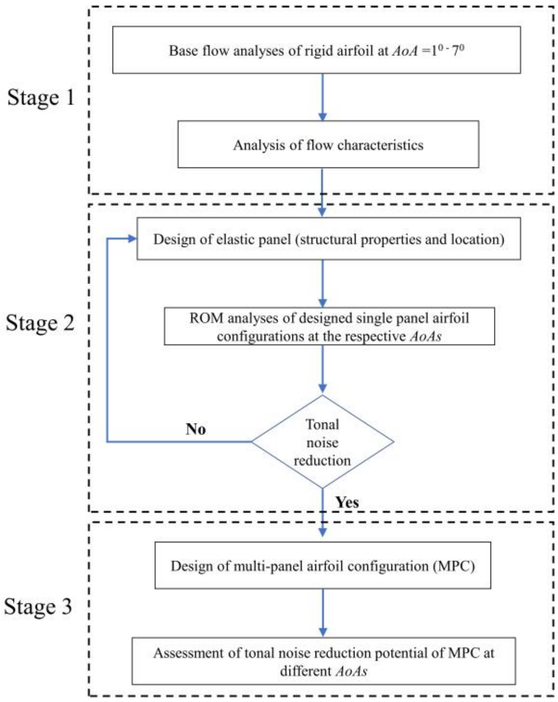

Figure 1 – Designed methodology

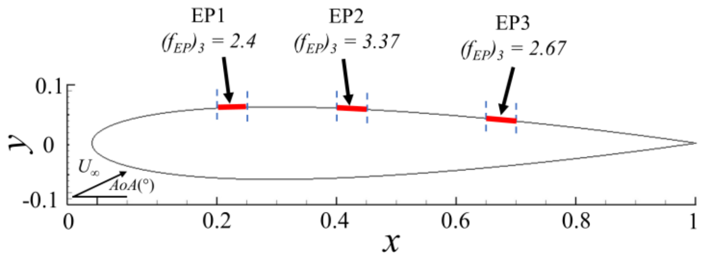

Figure 2 – Schematic sketch of the MPC design concept

3. RESULTS AND DISCUSSION

The effectiveness of MPC in tonal noise reduction at different *AoA*s is evaluated with ROM analysis. Figure 3(a)-(c) show the azimuth plots of p'_{rms} at $r = 3$ for both RS and MPC at each *AoA*. At $AoA = 5°$ (Figure 3(b)), a significant reduction in p'_{rms} is observed at all azimuth locations for MPC as compared to RS. Furthermore, the azimuth plot for MPC appears to be asymmetric around $\theta = 0°$ where the reduction in p'_{rms} appears to be significant in the third quadrant. At $AoA = 3°$ (Figure 3(a)), a reduction in p'_{rms} is observed for most azimuth locations; however, a slight amplification is also observed between $120° \leq \theta \leq 140°$. At $AoA = 7°$, the reduction in p'_{rms} in first quadrant is much higher than $AoA = 3°$ and a greater region of amplification in p'_{rms} is also observed between $120° \leq \theta \leq 170°$.

The extent of noise reduction achieved by MPC is evaluated by analyzing the $\Delta SPL = SPL_{\mathrm{RS}} - SPL_{\mathrm{MPC}}$ at different *AoA*s and shown in Figure 3(d). The noise reduction achieved by MPC at $AoA = 5°$ is much higher than other *AoA*s where an average reduction of 4.41 dB is observed with a maximum reduction of 7.92 dB at $\theta = 185°$. At $AoA = 3°$, an overall average noise reduction of 2.20 dB is observed with a maximum reduction of 7.73 dB at $\theta = 178°$. However, a maximum noise amplification of 1.46 dB is also observed at $\theta = 126°$. At $AoA = 7°$, an overall average noise reduction of 1.41 dB is observed with a maximum reduction of 6.75 dB at $\theta = 60°$ but a maximum noise amplification of 1.70 dB is also observed at $\theta = 164°$. Table 1 shows a comparative analysis of noise reduction at all *AoA*s along with the noise reduction achieved by the corresponding single-panel configurations. It is interesting to observe that an enhancement in the maximum noise reduction is achieved by MPC as compared to single-panel configuration at each *AoA*; however, the average noise reduction is reduced for $AoA = 3°$ and remains almost similar at $AoA = 7°$. The overall noise reduction for MPC is observed to be highest at $AoA = 5°$ whereas the highest noise reduction for single-panel configuration is observed at $AoA = 3°$. The possible cause of higher noise reduction at $AoA = 5°$ for MPC may be attributed to the fact that all the panels are exposed to region of high boundary layer flow instabilities at this *AoA* as compared to that for $AoA = 3°$ and 7°. Furthermore, the panels' inter-dynamical interactions appear to play a critical role in enhancing/degrading the noise reduction of panel-airfoil configuration. However, exploration of these effects would require multiple DAS calculations for better in-depth evaluation which is left to future study.

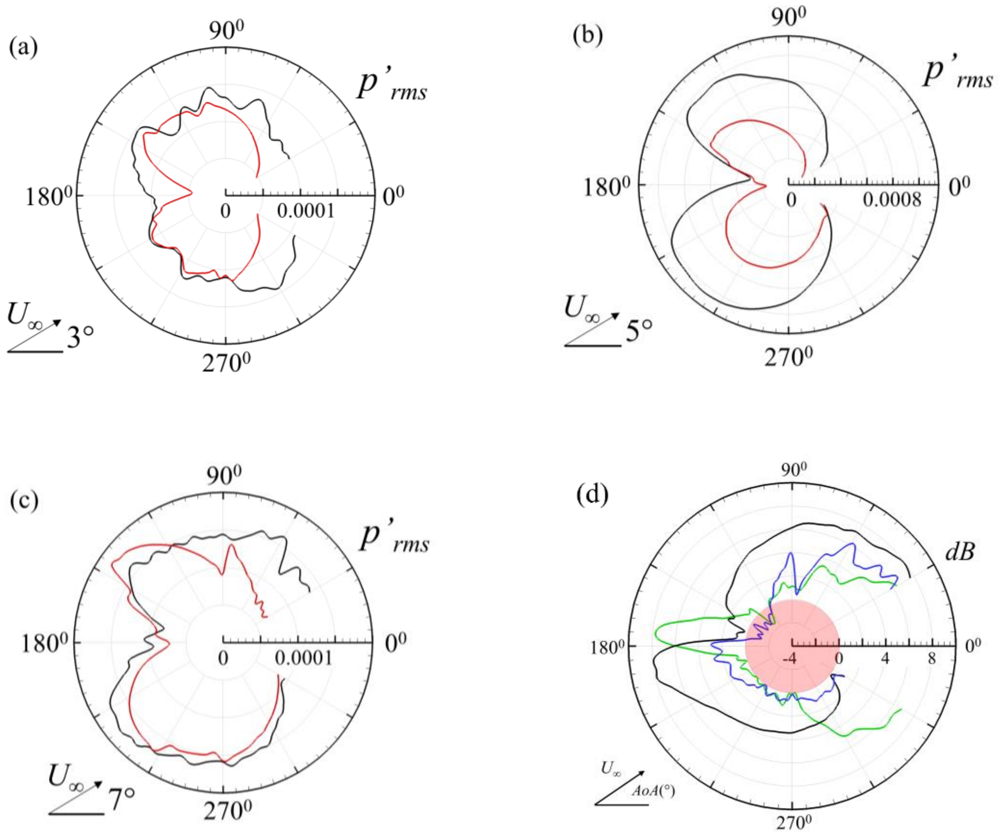

Figure 3 – Comparison of azimuth distributions of p'_{rms} at r = 3 between MPC and RS. (a) AoA = 3°, (b) AoA = 5°, (c) AoA = 7°. ——, RS; ——, MPC; and (d) Comparison of azimuthal distribution of ΔSPL at r = 3 between MPC and respective RS. ——, AoA = 3°; ——, AoA = 5°; ——, AoA = 7°. The area shaded in red indicates SPL amplification.

Table 1 – Effectiveness of multi-panel configuration at different flow conditions

	Multi-panel configuration (MPC) / Single-panel configuration				
AoA (°)	Avg $\Delta SPL_{reduction}$ (dB)	Max $\Delta SPL_{reduction}$ (dB)	θ_{max} (°)	Max ΔSPL_{amp} (dB)	θ_{max} (°)
3	2.20 / 3.53	7.73 / 5.60	178 / 210	1.46 / -	126 / -
5	4.41 / 2.12	7.92 / 2.41	185 / 130	- / -	- / -
7	1.41 / 1.10	6.75 / 2.92	60 / 168	1.70 / -	164 / -

4. CONCLUSIONS

A multi-panel configuration (MPC) based on three elastic panels is designed to provide tonal noise reduction over a range of AoA. ROM analysis shows a non-linear response in the noise reduction characteristics for the airfoil ranging from 6.75 dB to 7.92 dB over the complete range of *AoA*. The study can further help in the design of a noise control method which is effective for a range of airfoil operating conditions.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the support from the Research Grants Council of the Government of Hong Kong Special Administrative Region under grant number 15208520. The first and fourth authors are grateful to a generous research donation from Philip K. H. Wong Foundation under grant number 5-ZH1X (now N-ZH1X). The third author is grateful to stipend support to his study from the Department of Mechanical Engineering, The Hong Kong Polytechnic University.

REFERENCES

1. Arbey, H. and Bataille, J., Noise generated by airfoil profiles placed in a uniform laminar flow. Journal of Fluid Mechanics. 1983(134):33–47.
2. Brooks, T. F., Pope, D. S., and Marcolini, M. A., Airfoil self-noise and prediction. In: NASA Reference Publication. 1989.
3. Fink, M. R., Prediction of airfoil tone frequencies. Journal of Aircraft. 1975(12):118–120.
4. Arcondoulis, E., Doolan, C. J., Zander, A. C., Brooks, L. A., and Liu, Y., An investigation of airfoil dual acoustic feedback mechanisms at low to-moderate Reynolds number. Journal of Sound and Vibration. 2019(460):114887.
5. Desquesnes, G., Terracol, M., and Sagaut, P., Numerical investigation of the tone noise mechanism over laminar airfoils. Journal of Fluid Mechanics. 2007(591):155–182.
6. Jones, L. E. and Sandberg, R. D., Numerical analysis of tonal airfoil self-noise and acoustic feedback-loops. Journal of Sound and Vibration. 2011(330):6137–6152.
7. Arif, I., Lam, G. C. Y., Wu, D., and Leung, R. C. K., Passive Airfoil Tonal Noise Reduction by Localized Flow-Induced Vibration of an Elastic Panel. Aerospace Science and Technology. 2020(106319).
8. Smith, R. and Shyy, W., Computation of unsteady laminar flow over a flexible two-dimensional membrane wing. Physics of Fluids. 1995(7):2175–2184.
9. Lian, Y. and Shyy, W., Laminar-turbulent transition of a low Reynolds number rigid or flexible airfoil. AIAA Journal. 2007(45):1501–1513.
10. Gordnier, R. E., High fidelity computational simulation of a membrane wing airfoil. Journal of Fluids and Structures. 2009(25):897–917.
11. Stanford, B., Sytsma, M., Albertani, R., Viieru, D., Shyy, W., and Ifju, P., Static aeroelastic model validation of membrane micro air vehicle wings. AIAA Journal. 2007(45):2828–2837.
12. Stanford, B., Ifju, P., Albertani, R., and Shyy, W., Fixed membrane wings for micro air vehicles: Experimental characterization, numerical modeling, and tailoring. Progress in Aerospace Sciences. 2008(44):258–294.
13. Lam, G. C. Y., Leung, R. C. K., Seid, K. H., and Tang, S. K., Validation of CE/SE scheme in low Mach number direct aeroacoustic simulation. International Journal of Nonlinear Sciences and Numerical Simulation. 2014(15):157–169.
14. Arif, D. Wu, G. C. Y. Lam, and R. C. K. Leung, “Exploring airfoil tonal noise reduction with elastic panel using perturbation evolution method. AIAA Journal. 2020(58): 4958–4968.