Journal of Applied Mathematics and Physics, 2023, 11, 2503-2514
https://www.scirp.org/journal/jamp
ISSN Online: 2327-4379
ISSN Print: 2327-4352

Numerical Study on the Duct Noise Control of Single-Stage Axial Flow Fan with Wave Leading Edge Stator Blade Configurations

Jianxin Lian, Hang Tong, Liangji Zhang, Weiyang Qiao, Weijie Chen

School of Power and Energy, Northwestern Polytechnical University, Xi'an, China
Email: lianjianxin@mail.nwpu.edu.cn, tonghang@mail.nwpu.edu.cn, zhangliangji@mail.nwpu.edu.cn, qiaowy@nwpu.edu.cn, cwj@mail.nwpu.edu.cn

How to cite this paper: Lian, J.X., Tong, H., Zhang, L.J., Qiao, W.Y. and Chen, W.J. (2023) Numerical Study on the Duct Noise Control of Single-Stage Axial Flow Fan with Wave Leading Edge Stator Blade Configurations. *Journal of Applied Mathematics and Physics*, **11**, 2503-2514.
https://doi.org/10.4236/jamp.2023.118161

Received: June 2, 2023
Accepted: August 28, 2023
Published: August 31, 2023

Abstract

This study focuses on a single-stage axial flow fan, investigating the effect of three kinds of wave leading edge stator blades on its noise reduction. The DDES method and the duct acoustic analogy theory based on the penetrable data surface were used for noise prediction. The results showed that the three kinds of wave leading edge blades were effective in reducing the rotor-stator interaction tonal noise and also have a certain inhibitory effect on broadband noise. The A10W15 stator blade can effectively reduce broadband noise in the frequency range of 2200 - 4200 Hz. When the amplitude is increased to 20, the noise reduction effect is further enhanced. However, when the amplitude is increased to 30, the broadband noise reduction effect is no longer significant. Further research shows that the wave leading edge stator blades can significantly change the pressure fluctuation distribution on the leading edge and suction surface, which control the modal energy distribution. Finally, this paper analyzed multiple factors affecting the broadband noise reduction, such as the noise source cut-off and cut-on effect and correlation. The purpose of this paper is to explore the laws of the influence of wave leading edge blades on the duct noise of real fan, and to reveal its noise control mechanism.

Keywords

Fan, Wave Leading Edge Blade, Duct Noise, Broadband Noise, Noise Source Analysis

1. Introduction

With the rapid advancement of the global economy and international commercial aviation transportation market, the issue of commercial aircraft noise pollution has gained significant attention from society as a whole [1]. The engine noise remains the primary contributor to aircraft noise [2]. The use of high bypass ratio aircraft engines over the past few decades has efficiently controlled engine jet noise by significantly reducing the exhaust velocity of the nozzle. However, an increase in engine bypass ratio leads to larger fan size and fan tip speed, making fan noise a critical source of noise pollution. Therefore, reducing fan noise has become an urgent task [3].

Fan noise can be classified into two types: tonal noise caused by fan rotor-stator interaction [4] [5] [6], and broadband noise generated by fan turbulence [7] [8]. With the help of computer technology, prediction and control technologies for rotor-stator interaction tonal noise have significantly matured. However, prediction and control technologies for broadband noise due to fan turbulence have been developing at a slower pace due to the complexity of the mechanism. The effective control of tonal noise has made the engineering problem of broadband noise of the fan more prominent [9]. This problem has become a considerable challenge that modern civil aviation must address [10].

Numerous scholars have implemented wave leading edge blade configurations in isolated airfoils and found that it can reduce airfoil stall, broadband noise and additional benefits [11] [12] [13]. Extensive research on noise control technology has indicated that bionic blades possess the capability to regulate the spatial and temporal scales of turbulent random variations. Studies have also discovered that biologically inspired configurations transform the structure of turbulent eddies and the correlation between them [14] [15] [16], which eventually governs the spectral structure and sound source mode structure of turbulent broadband noise. Wave leading edge blades have been demonstrated as a promising technique in broadband noise reduction.

In recent years, a few researchers have begun to integrate wave leading edge blade configurations in turbomachinery [17] [18] [19]. However, due to the intricate nature of internal flows and the unique sound mode structure in the duct, these configurations' application is still not mature enough in turbomachinery. Several problems and theories still require thorough research and explanations. Further research on the influence of wave leading edge blades on genuine turbomachinery aerodynamic noise is necessary, specifically in exploring the control effect of wave leading edge blade configurations on sound modes and fan noise source loads.

This article numerically simulates the noise of a single-stage axial flow fan, exploring the influence of wave leading edge amplitude on noise reduction. Section 2 briefly introduces the computational methods used for flow field calculation and sound field calculation, Section 3 briefly introduces the a single-stage axial flow fan and calculation settings, Section 4 presents the results, and delves into the noise reduction mechanism.

2. Methodology

2.1. Numerical Method for Flow Field

The unsteady flow field is calculated using the CFX 2019 R2 code. The DDES (Delayed-Detached Eddy Simulation) based on SST (Shear-Stress Transport) model is used for its reasonable accuracy. The second order backward Euler scheme is used for the transient scheme, and the high resolution scheme is used for the advection scheme.

2.2. Numerical Method for Duct Noise Prediction

Tong [19] introduced the theory of sound propagation in a flowing duct and further derived a method for calculating sound power by using the sound modal amplitudes within the duct. Here, the penetrable data surface (PDS) method is used to integrate the sound source over the source surface, which can simultaneously include both dipole and quadruple sound sources. The expression for the sound modal amplitudes is as follows:

$$A_{mn}(\omega)=\frac{\mathrm{i}}{2\pi(R_D^2-R_H^2)\kappa_{mn}}\cdot\int_{S_F}\left[\Psi_m\left(\kappa_{mn}r\right)\cdot\vec{n}\cdot\nabla\mathrm{e}^{-\mathrm{i}m\theta+\mathrm{i}k_{mn}x}\cdot L_{ij}\right]ds \tag{1}$$

$$L_{ij}=[\rho u_i(u_j+U_{0j}-v_j)+P_{ij}] \tag{2}$$

$$P_{ij}=(p-p_0)\delta_{ij}-\sigma_{ij} \tag{3}$$

$$\sigma_{ij}=\mu(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}-\frac{2}{3}\frac{\partial u_k}{\partial x_k}\delta_{ij}) \tag{4}$$

where: R_D and R_H are radius of duct shroud and hub, respectively; Ψ_m and κ_{mn} are duct mode eigenfunction and eigenvalue, respectively; $\vec{n}$ is normal vector; (x,r,θ) is cylindrical coordinates; L_{ij} is stress tensor; u is fluid velocity; v is surface velocity; p is fluctuating pressure; ρ is fluctuating density; δ_{ij} is delta function; μ is viscosity coefficient; subscript i is outward normal vector of the surface; subscript j is direction of force on the surface; subscript 0 is time-average value.

3. Model and Numerical Set Up

3.1. Fan Model

A single-stage axial flow fan (NPU-Fan) at the Turbomachinery Aerodynamics and Aeroacoustics Laboratory (TAAL) of Northwestern Polytechnical University was studied [19]. **Figure 1** shows the schematic diagram of the NPU-Fan. The design parameters of the NPU-Fan are shown in **Table 1**.

3.2. Wave Leading Edge Blade Parameter

As shown in **Figure 2**, the gray color represents the baseline blade configuration, while the blue color represents the wave leading edge blade configuration. From the figure, it can be seen that the wave leading edge blade achieves the modification of the different blade shapes through two parameters, amplitude (A) and wavelength (W).

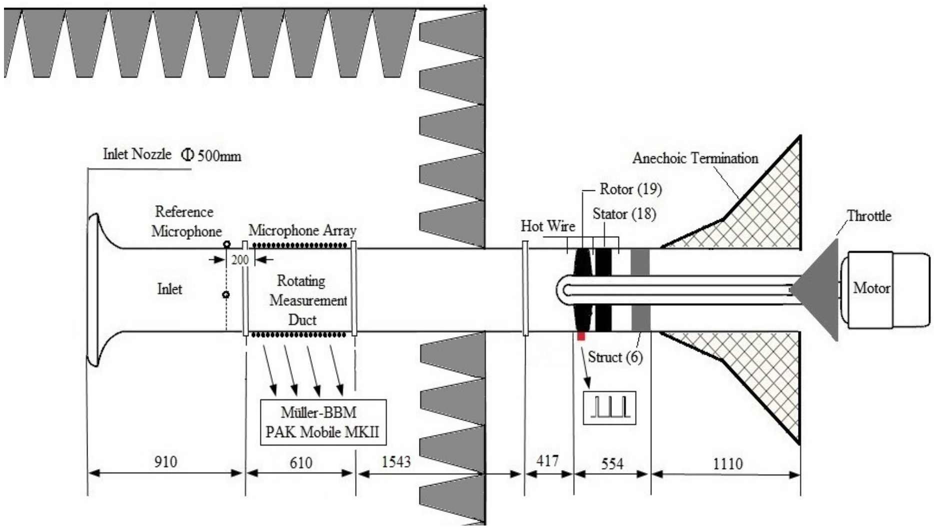


Figure 1. The schematic diagram of NPU-Fan.

Table 1. NPU-Fan design parameter.

Parameter	Value
Rotor blade number	19
Stator blade number	18
Shroud diameter (mm)	500
Hub diameter (mm)	285
Mass flow rate (kg/s)	6.38
Design speed (r/min)	3000
Total pressure ratio	1.02
Airfoil shape	NACA-65

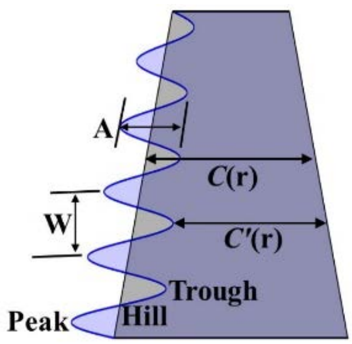


Figure 2. Wave leading edge blade configuration.

$$C'(r) = C(r) + \frac{A(r)}{2}\sin(\frac{2\pi}{W}\cdot r) \tag{5}$$

$$A(r) = \varepsilon \cdot C(r) \tag{6}$$

where: ε is the scaling factor is used to control the magnitude of the amplitude.

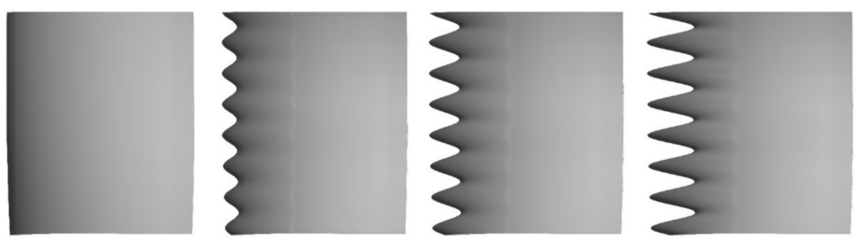
The baseline blade configuration in this study is the optimized fan configuration (CASE V) in which the original rotor and stator blades were bending. The wave leading edge stator blade was developed based on the CASE V configuration, as shown in **Figure 3**.

It should be noted that the nomenclature for the wave leading edge blade in this paper is A_W_. The number after A represents the ratio of the actual amplitude of the wave leading edge blade to the local chord length of the baseline blade, which is calculated using Equation (6), with a unit of "%". The number after W represents the actual length of the wavelength of the wave leading edge blade, with a unit of "mm". This naming convention is advantageous for blades with large changes in chord length and is more concise.

3.3. Numerical Set Up and Boundary Conditions

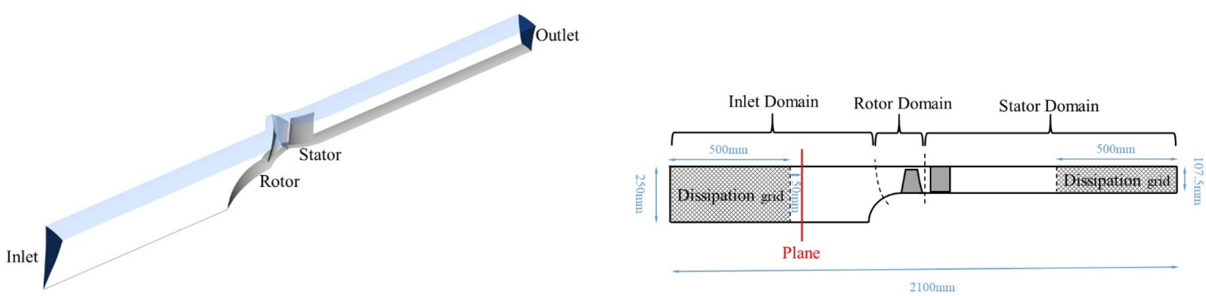
Before conducting the broadband noise calculation, the number of rotor blades of the NPU-Fan was reduced from 19 to 18. Two requirements needed to be ensured during the rotor blade reduction process: 1) the reduced rotor blade solidity was consistent with the original rotor blade solidity; 2) the spacing between the rotor and stator blades was consistent with that of the original rotor and stator blades.

Figure 4(a) shows the unsteady computational domain diagram of the NPU-Fan. The inlet boundary condition of the computational domain is set as total pressure conditions, with values of 97,700 Pa. The outlet boundary condition is set as the average static pressure boundary condition, and keep the mass flow rate close to 6.38 kg/s. The turbulence model selected is the DDES (Delayed-Detached



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

Figure 3. Sketch of the wavy leading edge stator blade. (a) CASE V; (b) A10W15; (c) A20W15; (d) A30W15.



(a) (b)

Figure 4. The configuration of NPU-Fan. (a) Computing domain diagram; (b) schematic size of computational domain.

Eddy Simulation) based on SST (Shear-Stress Transport) model.

Figure 4(b) shows the schematic size of the unsteady computational domain of NPU-Fan. A dissipation grid of length 500 mm is set at the inlet and outlet of the computational domain. The mesh number of inlet domain and rotor domain are approximately 19.51 million, and the number of meshes in the stator domain is approximately 15.15 million. The wall grid thickness of the rotor blade and stator blade surfaces is 0.003 mm, which satisfies the non-dimensional scale condition $y^+ < 1$.

The unsteady calculation uses the steady state calculation result as the initial condition and is advanced for 150 steps ($\Delta t = 7.4074 \times 10^{-6}$) for each rotor blade channel until convergence is achieved at all monitoring points. The flow field information is collected every 3 steps, and a total of 4500 groups of flow field data are obtained for 5 rotor revolutions. The data used to calculate the forward noise was extracted from Plane in **Figure 4(b)**. The FFT settings are as follows: the NFFT number is 900, the FFT data is averaged 10 times, and $\mathrm{d}f = 50\mathrm{Hz}$.

4. Results and Analysis

4.1. Numerical Results of Noise Reduction

DDES can simulate the interaction between rotor wake and stator blades and the interaction between turbulence and blades. Therefore both rotor-stator interaction tonal noise and broadband noise can be obtained with DDES.

4.1.1. Effect on Rotor-Stator Tonal Noise

Figure 5 shows the effects of three kinds of wave leading edge stator blades on rotor-stator tonal noise. It can be seen from the figure that all three kinds of wave leading edge stator blades have a significant noise reduction effect on rotor-stator tonal noise, which generally follows the rule that the larger the amplitude, the more effective the rotor-stator interaction tonal noise reduction effect.

4.1.2. Effect on Broadband Noise

Figure 6 shows the effects of three kinds of wave leading edge stator blades on

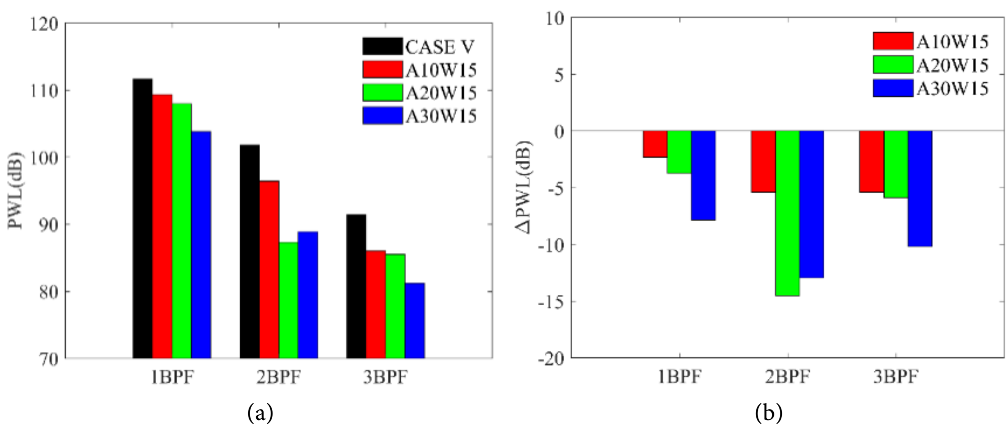
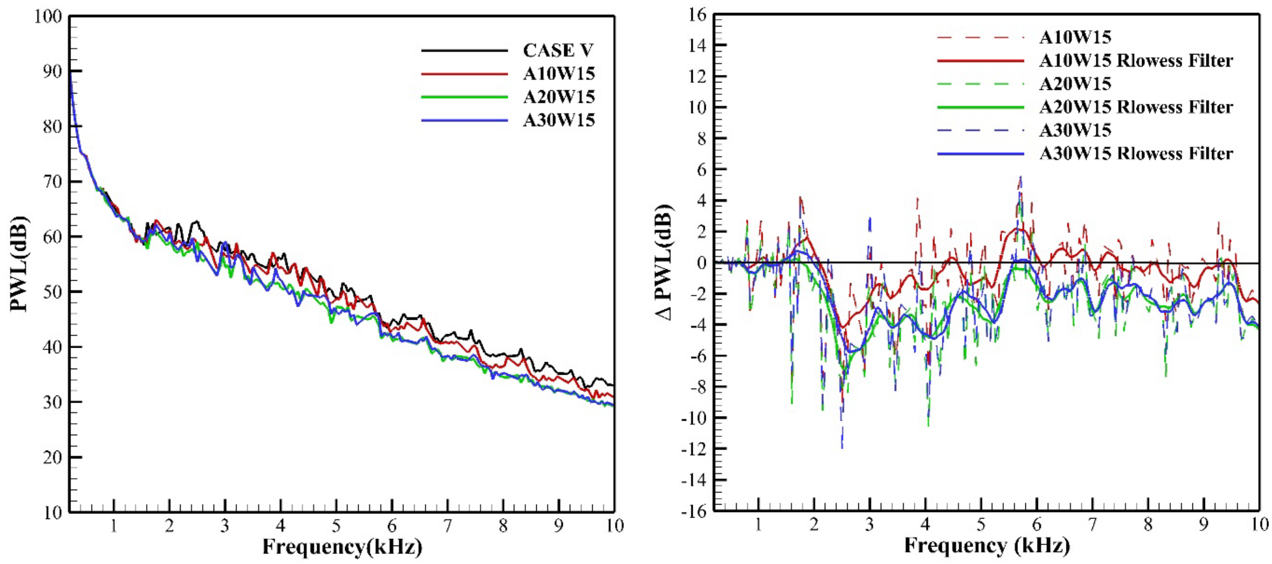


Figure 5. Tonal noise reduction with three kinds of wave leading edge blades. (a) PWL; (b) ΔPWL.

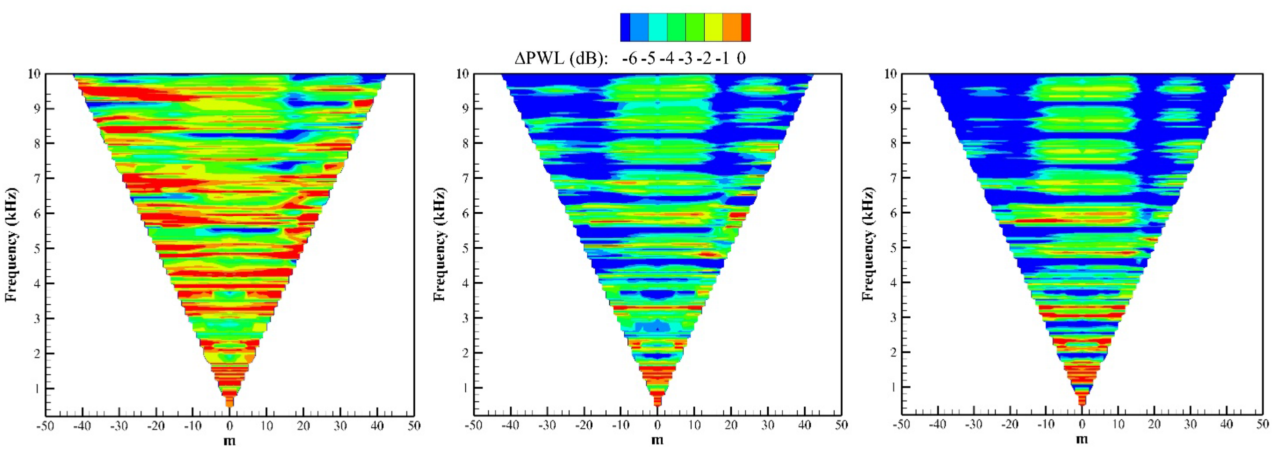
broadband noise. **Figure 6(b)** shows that when the amplitude increases from 10 to 20, the noise reduction effect is further improved by about 2 - 3.5 dB. However, when the amplitude increases from 20 to 30, the noise reduction effect does not significantly improve. The A10W15 stator can effectively reduce the broadband noise in the frequency range of 2200 Hz to 4200 Hz, reaching the maximum noise reduction effect at around 2500 Hz, which is about 4.2 dB. The A20W15 and A30W15 stators have significant noise reduction effects in the frequency range of 2200 - 10,000 Hz, with the maximum noise reduction effect at around 2500 - 2600 Hz, which is about 6 dB.

Figure 7 shows the effects of three kinds of wave leading edge stator blades on circumferential modal energy reduction. It can be seen from the figure that, as the amplitude increases, the circumferential modal energy of high frequency



(a) (b)

Figure 6. Broadband noise reduction with three kinds of wave leading edge blades. (a) PWL; (b) ΔPWL.



(a) (b) (c)

Figure 7. Sound mode control results. (a) A10W15; (b) A20W15; (c) A30W15.

range gradually decreases. The A20W15 stator has the best noise reduction effect, and the wave leading edge stator has a better reduction effect on higher-order circumferential mode.

4.2. Analysis of Physical Mechanism for Noise Reduction

4.2.1. Noise Source Cut-Off and Cut-On Effect

1) Span-wise noise source cut-off effect:

Figure 8 shows the distribution of pressure fluctuation along the leading edge span of the stator blade. It can be seen from the figure that the pressure fluctuation of wave leading edge stator blade exhibits a periodic distribution along the span, which corresponds to the wavelength. The pressure fluctuation of wave leading edge stator blades is smaller than that of the CASE V stator blade along the span.

2) Chord-wise noise source cut-on effect:

Figure 9 shows a schematic of the stator blade and auxiliary lines. The red lines in the figure are numbered from hub to shroud as "Span Line 1-9".

Figure 10 shows the distribution of pressure fluctuation on Span Line 1, 3 and 5. It can be seen from the figure that, a "hump" shaped noise source appears, and its intensity and width increase with amplitude increasing. The intensity of the "hump" shaped noise source is not the strongest on the trough section. The strongest noise sources are on the hill and near-trough sections.

4.2.1. Analysis of Correlation

1) Span-wise correlation

Figure 11 shows the distribution of chord-wise correlation of pressure fluctuation

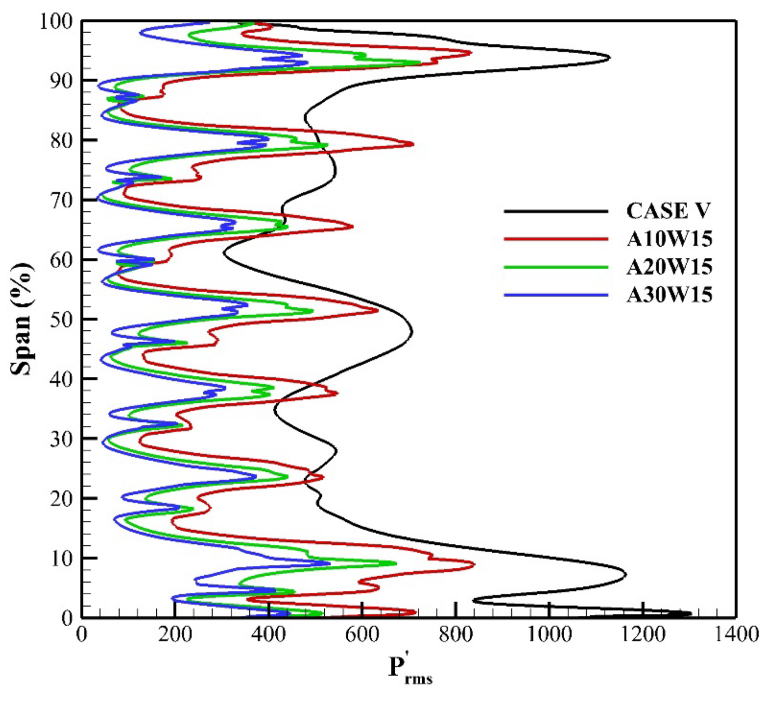


Figure 8. Distribution of pressure fluctuation along the leading edge span.

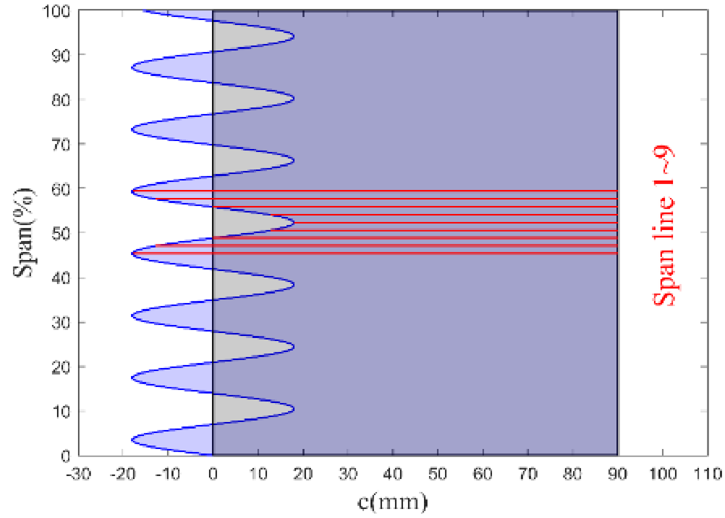


Figure 9. Distribution of pressure fluctuation along the leading edge span.

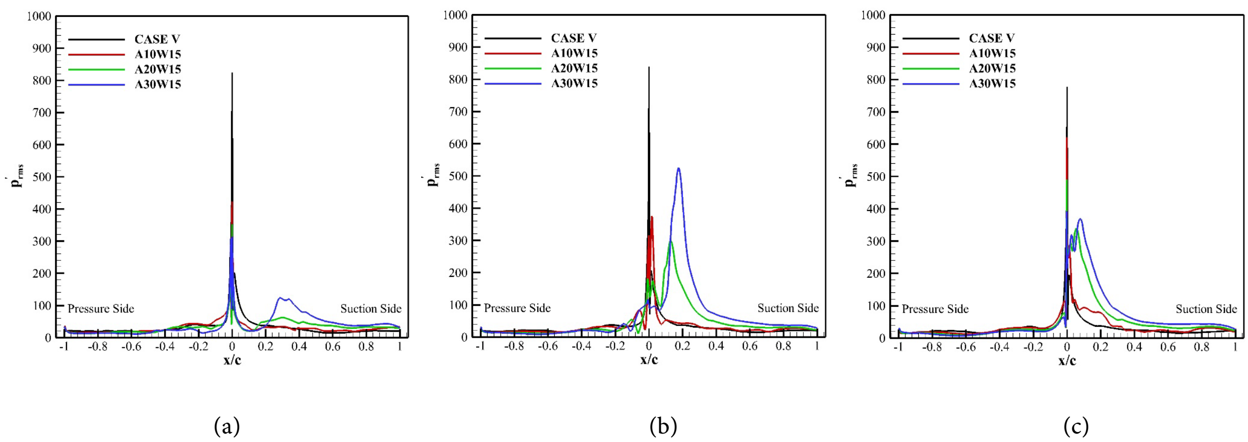


Figure 10. Distribution of power spectral density along the leading edge span. (a) Span line 1; (b) Span line 2; (c) Span line 3.

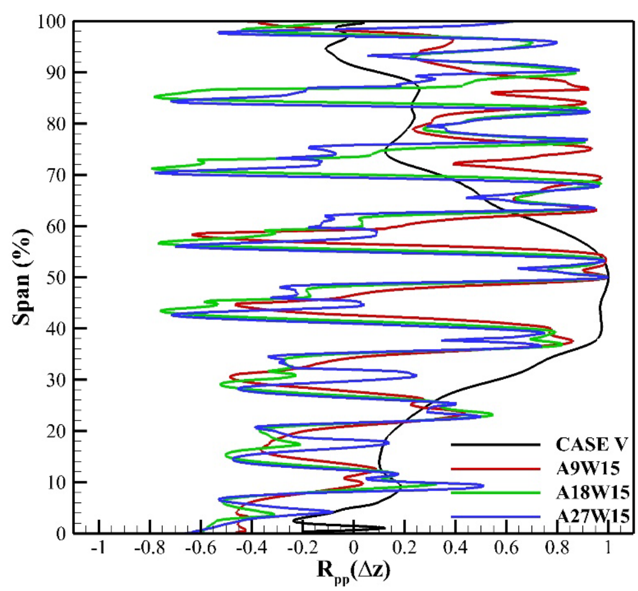


Figure 11. Leading edge span-wise correlation coefficient.

on the leading edge. It can be seen that the chord-wise correlation of the CASE V blade basically decreases with the distance increasing. After adopting the wave-shaped leading edge blade configuration, the chord-wise correlation of the leading edge shows a certain wave-shaped distribution. When the amplitude increases from 0 to 20, the change in chord-wise correlation is significant.

2) Chord-wise correlation

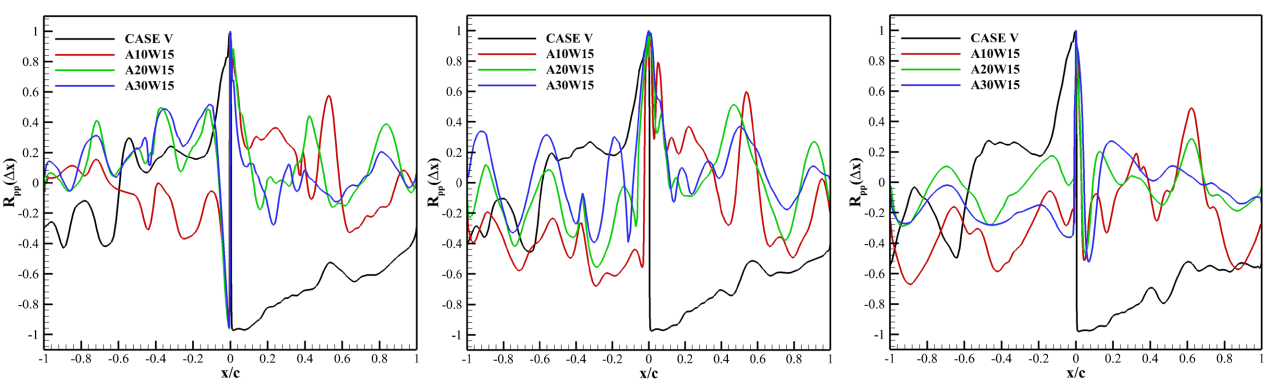
Figure 12 shows the chord-wise correlation distribution of pressure fluctuation of Span Line 1, 3, and 5. It can be seen that the chord-wise correlation of the CASE V blade basically decreases with the increasing distance. After adopting the wave leading edge blade configuration, the chord-wise correlation of the leading edge shows a certain wave-shaped distribution, but the change in chord-wise correlation is not as significant as that in the span-wise correlation.

5. Conclusions

This paper focuses on a single-stage axial flow fan and uses the DDES numerical simulation method combined with acoustic analogy theory to study the influence of wavy leading edge stator blades on noise in the duct and to analyze the related noise reduction physics mechanism. The main research conclusions are as follows:

1) Wave leading edge stator blades have a significant noise reduction effect on rotor-stator interaction tonal noise, which generally follows the rule that the larger the amplitude, the more effective the rotor-stator interaction tonal noise reduction effect. Besides, wave leading edge stator blades also show effect on broadband noise reduction. When the amplitude is less than 30, the broadband noise reduction effect increases with amplitude increasing. However, further amplitude increasing does not have a significant effect on broadband noise reduction. This indicates that there is an amplitude threshold for threshold.

2) It can be seen that the wave leading edge stator blades can effectively reduce the pressure fluctuation of the blade leading edge and the energy distribution in the frequency range of 200 to 10000 Hz. However, it will increase the pressure fluctuation and energy distribution in other regions, especially for the suction



(a) (b) (c)

Figure 12. Leading edge span-wise correlation coefficient. (a) Span line 1; (b) Span line 2; (c) Span line 3.

side, and the pressure fluctuation enhancement effect is more significant with amplitude increasing.

3) Wavy leading edge blades can effectively change the correlation of various points on the leading edge line in space and significantly reduce the spatial correlation of each point on the leading edge line. Wavy leading edge blades can also change the correlation of various points on the chord-wise line in space, but the change in chord-wise correlation is not as significant as that in the span-wise correlation.

4) The sound source cut-off effect and the reduce the spatial correlation on the leading edge line is conducive to broadband noise reduction, while the sound source cut-off effect on chord-wise line is not conducive to broadband noise reduction. The combined effect results in a certain threshold for broadband noise reduction, that is, increasing the amplitude does not further improve the broadband noise reduction.

Acknowledgements

Project grant by National Science and Technology Major Project of China (No. 2017-II-0008-0022), National Natural Science Foundation of China (No. 51776174, No. 52106056, No. 52276038 and No. 51936010), and Supported by Aviation Engine and Gas Turbine Basic Science Center Project (No. P2022-A-II-003-001 and No. P2022-B-II-011-001).

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

[1] Enghardt, L. (2019) Aeroacoustics Research in Europe: The CEAS-ASC Report on 2017 HighLights. *Journal of Sound and Vibration*, **450**, 175-198. https://doi.org/10.1016/j.jsv.2019.03.006

[2] Owen, R. (1979) Energy Efficient Engine: Propulsion System—Aircraft Integration Evaluation. NASA/CR 159488.

[3] Hughes, C. (2013) NASA Collaborative Research on the Ultra High Bypass Engine Cycle and Potential Benefits for Noise, Performance, and Emissions. NASA Technical Memorandum TM-2013-216345.

[4] Wang, L.F. (2017) Experiment and Numerical Study on Duct Mode Identification of Fan Noise (Xi'an). Ph.D. Thesis, Northwestern Polytechnical University, Xi'an.

[5] Tong, H., Li, L., Mao, L.Q., *et al.* (2020) Tonal Noise Reduction of a High-Speed Single Axial Fan with Wavy Leading-Edge Stator. *Acta Aeronautica et Astronautica Sinica*, **41**, 123565. 10.7527/S1000-6893.2019.23565

[6] Tong, H., Ding, S., Xiang, X.S., *et al.* (2021) Numerical Study on Tonal Noise Reduction of Single Axial Fan with Distributed Wavy Leading-Edge Stator. *Journal of Propulsion Technology*, **42**, 2237-2248.

[7] Polacsek, C., Clair, V., Le, G., *et al.* (2015) Numerical Predictions of Turbulence/Cascade-Interaction Noise Using CAA with a Stochastic Model. *AIAA Jour-*

nal, **53**, 3551-3566. https://arc.aiaa.org/doi/10.2514/6.2014-2453 http://dx.doi.org/10.1080/028418501127346846

[8] Tong, H., Li, L., Wang, L.F., *et al.* (2021) Investigation of Rotor-Stator Interaction Broadband Noise Using a RANS-Informed Analytical Method. *Chinese Journal of Aeronautics*, **34**, 53-66. https://doi.org/10.1016/j.cja.2021.02.003http://dx.doi.org/10.1080/028418501127346846

[9] Edmane, E. (2002) Fan Noise Reduction: An Verview. *Aeroacoustics*, **1**, 43-64. https://doi.org/10.1260/1475472021502668 http://dx.doi.org/10.1080/028418501127346846

[10] Yan, Q., Xue, D.W., Gao, X., *et al.* (2022) Acoustic Performance Experimental Technology of Aircraft Nacelle Acoustic Liner. *Acta Aeronautica et Astronautica Sinica*, **43**, 526810. 10.7527/S1000-6893.2022.26810http://dx.doi.org/10.1080/028418501127346846

[11] Polacsek, C., Reboul, G., Clair, V., *et al.* (2011) Turbulence-Airfoil Interaction Noise Reduction Using Wavy Leading Edge: An Experimental and Numerical Study. *Inter-Noise*, Osaka, 4-7 September 2011.

[12] Narayanan, S., Joseph, P., Haeri, S., *et al.* (2014) Noise Reduction Studies from the Leading Edge of Serrated Flat Plates. 20*th AIAA/CEAS Aeroacoustics Conference*, Atlanta, 16-20 June 2010.

[13] Chaitanya, P., Joseph, P., Narayanan, S.C., *et al.* (2017) Performance and Mechanism of Sinusoidal Leading Edge Serrations for the Reduction of Turbulence-Aerofoil Interaction Noise. *Journal of Fluid Mechanics*, **818**, 435-464. https://doi.org/10.1017/jfm.2017.141

[14] Gruber, M., Joseph, P.F. and Chong, T.P. (2010) Experimental Investigation of Airfoil Self Noise and Turbulent Wake Reduction by the Use of Trailing Edge Serrations. 16*th AIAA/CEAS Aeroacoustics Conference*, Stockholm, 7-9 June 2010.

[15] Geyer, T.F., Wasala, S.H., Cater, J.E., *et al.* (2016) Experimental Investigation of Leading Edge Hook Structures for Wind Turbine Noise Reduction. 22*th AIAA/CEAS Aeroacoustics Conference*, Lyon, 30 May - 1 June 2016.

[16] Chen, W.J., Qiao, W.Y. and Wei, Z.J. (2020) Aerodynamic Performance and Wake Development of Airfoils with Wavy Leading Edges. *Aerospace Science and Technology*, **106**, 1-27. https://doi.org/10.1016/j.ast.2020.106216

[17] Zhu, X.Y., Guo, Z.P., Zhang, Y.F., *et al.* (2022) Numerical Study of Aerodynamic Characteristics on a Straight-Bladed Vertical Axis Wind Turbine with Bionic Blades. *Energy*, **239**, 122453. https://doi.org/10.1016/j.energy.2021.122453

[18] Casalino, D., Avallone, F., Martino, I., *et al.* (2019) Aeroacoustic Study of a Wavy Stator Leading Edge in a Realistic Fan/OGV Stage. *Journal of Sound and Vibration*, **442**, 138-154. https://doi.org/10.1016/j.jsv.2018.10.057

[19] Tong, F., Qiao, W.Y., Xu, K.B., *et al.* (2018) On the Study of Wavy Leading-Edge Vanes to Achieve Low Fan Interaction Noise. *Journal of Sound and Vibration*, **419**, 200-226. https://doi.org/10.1016/j.jsv.2018.01.017