Numerical Study on Tonal Noise Characteristics of Laminar Airfoils with Permeable Walls: Postprint

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Date: 2025-10-28T17:51:08+00:00

Abstract

Based on the LBM-LES method, direct numerical computations of the acoustic field were performed for a permeable-wall NA-CA0012 airfoil capable of generating tonal noise at a Reynolds number of 2 × 10^5 and an angle of attack of 2°. The acoustic characteristics of the laminar airfoil under various permeable wall parameters were analyzed, along with the influence of permeable wall parameters on the spatial evolution of vortices at the airfoil trailing edge. The study demonstrates that: permeable walls can influence the development of boundary layer vortices; as the permeable wall size decreases, the vortex frequency gradually reduces and the vortex development displays periodic variations; the fundamental frequency of the tonal noise continuously decreases with decreasing permeable wall size, and when the permeable wall size is less than 6% of the airfoil chord length, permeability has a minor effect on the primary tonal noise but further increases its amplitude, with negligible influence on sound directivity; a permeable-wall airfoil with permeability K = 1.7894 × 10^-10 m^2 and a permeable wall size of 10% of the airfoil chord length can effectively suppress the primary tonal noise and reduce the far-field overall sound pressure level amplitude to achieve noise reduction.

Full Text

Numerical Study on Pure Tone Noise Characteristics of Laminar Airfoils with Permeable Walls

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Abstract

Note: The abstract in the original manuscript contains severe encoding corruption and cannot be reliably recovered. The translation begins with the main body of the paper.

1. Introduction

Pure tone noise commonly occurs in industrial equipment such as small unmanned aerial vehicles and small wind turbines used for residential power generation. Permeable walls have attracted considerable attention as an effective means of aerodynamic noise control for aircraft. Z4SdG4S+4S et al. employed direct numerical simulation in 1991 to further investigate previous wind tunnel experiments, validating the experimental results and demonstrating that the interaction between the flow field and aerodynamic noise field of laminar airfoils produces pure tone noise under moderate Reynolds number conditions. More recently, TSWJ+Y et al. further demonstrated that the amplification of disturbances in the separation shear layer on the suction and pressure sides of the airfoil leads to shear layer roll-up and shedding of separation bubble vortices, finding that when vortices do not break upstream of the trailing edge, these structures generate pure tone noise as they pass the trailing edge. 2T, et al. studied the effect of weak adverse pressure gradients on the critical bump height for pure tone noise generation, with experimental results showing that weaker adverse pressure gradients can reduce the critical bump height while having minimal impact on pure tone noise frequency variation. JOOJ2ZJ et al. conducted direct numerical simulations of the NACA0012 airfoil to investigate the mechanisms causing trailing edge noise at moderate Reynolds numbers.

In the military aviation field, Y4F4 et al. conducted wind tunnel experiments on airfoils and cylinders with permeable materials at the trailing edge, and the results showed that permeable materials can produce very ideal effects in reducing trailing edge aerodynamic noise, and Y4I,W et al. performed large eddy simulations of airfoils with trailing edge serrations. The simulation results revealed that the amplitude of sound source pressure in the transition region downstream of the serrations was significantly reduced, and destructive interference was produced in the wall pressure fluctuations near the trailing edge, weakening the acoustic feedback loop and thereby reducing pure tone noise. 2JK et al. conducted numerical simulations of airfoils with elastic plates installed at the trailing edge, demonstrating that passive control methods with locally flow-induced panel vibration can effectively suppress the generation of airfoil pure tone noise.

While research has shown that permeable walls can serve as an effective aerodynamic noise control method, current studies have primarily focused on their impact on trailing edge broadband noise. Further analysis of how permeable wall parameters affect the flow and acoustic fields of pure tone noise from laminar airfoils is therefore necessary.

2. Methodology

This study investigates the effects of permeable walls on pure tone noise characteristics. Both solid and permeable NACA0012 airfoils were used in the calculations. To better represent permeable wall dimensions, different percentages of the airfoil chord length were employed to map their relationship. The permeable wall parameters and operating conditions are shown in [TABLE:N].

The computational domain measures $15c \times 15c$, with direct flow field and acoustic field calculations performed using the LBM method. This study involves multi-scale problems requiring non-uniform quadtree grids. A large sponge layer is utilized, leveraging the spatial filtering characteristics of LBM to attenuate strong disturbances propagating from the airfoil vicinity to various boundaries. The angle of attack is 0°, and the time step is 1×10^{-6} s.

[Figure 0: see original paper] presents a comparison of surface pressure coefficients between solid and permeable airfoils with experimental values. The results show good agreement and consistency under the ITD/LBM method, demonstrating that the selected ITD/LBM method and boundary conditions are reasonable for investigating the effects of different permeable wall parameters on airfoil aerodynamic noise at moderate Reynolds numbers.

3. Results and Analysis

3.1 Large-Scale Structures of Permeable Wall Airfoils Since trailing edge vortex shedding originates from wall vortex development, the vortex shedding frequency is consistent with the wall vortex frequency. To investigate the effects of permeable wall parameters on vortex shedding frequency, [FIGURE:B] shows the variation of boundary layer vortex shedding frequency with permeable wall size for different permeability values.

From [FIGURE:B], when the permeable wall size is less than 5% of the airfoil chord length, the vortex shedding frequencies under different permeability values at the same size are nearly identical, suggesting that a permeable wall size of 5% of the chord length may be a critical value affecting vortex shedding frequency variation. The results also indicate that under different permeability values, the vortex shedding frequency generally decreases as the permeable wall size decreases.

In [FIGURE:B], the dashed diagonal lines compare the development of the same vortex at different times. The time interval between dashed lines represents the streamwise wavelength of large-scale structures, while the slope indicates the vortex convection velocity. Analysis of wall large-scale structures at different permeability values for a permeable wall size of 10% of the chord length shows that the interval between lines gradually increases.

[Figure 1: see original paper] presents the distribution of large-scale structures at the trailing edge of permeable wall airfoils under different permeable wall sizes. The combined analysis of [FIGURE:B] and [Figure 1: see original paper] demonstrates that permeable walls can influence vortex shedding frequency by altering the development of trailing edge vortices, with effective permeable wall sizes likely above 5% of the chord length.

3.2 Pressure Fluctuation Analysis To further understand why permeable walls affect vortex shedding frequency, pressure fluctuation analysis was conducted for different permeability values at a permeable wall size of 10% of the chord length, and for different permeable wall sizes at permeability $k = 1.25 \times 10^{-10}$ m^2.

As shown in [FIGURE:C], when the permeable wall size is 10% of the chord length, pressure fluctuations along the chord length are essentially consistent across different permeability values, indicating that permeability changes have minimal effect on boundary layer disturbance variation, with larger pressure fluctuation values occurring closer to the trailing edge.

The analysis reveals that adding appropriately sized permeable wall material at the airfoil trailing edge can effectively reduce trailing edge disturbances and alter vortex shedding frequency, thereby achieving flow field control.

3.3 Acoustic Characteristics The main pure tone noise frequencies for permeable airfoils of different permeability values at 10% of the chord length are marked with dashed lines in the figure. The results show that as permeable wall size increases, the sound pressure level (SPL) values gradually decrease. Only at 10% does the SPL value fall below that of the solid airfoil (78.1 dB), achieving amplitude reduction effects. Comparison reveals that the main pure tone noise frequencies for all permeable airfoils are lower than those of the solid airfoil, with identical main pure tone noise frequencies across different permeability values.

Comparing the main pure tone noise frequencies under various conditions with [FIGURE:B] demonstrates that under certain conditions, trailing edge vortex frequency is one of the primary causes of pure tone noise generation.

[Figure 10: see original paper] shows the variation of total sound pressure level with permeable wall size for permeable airfoils of different permeability values. The total sound pressure level exhibits an initial increase followed by a decrease as permeable wall size increases. At the optimal configuration, the total sound pressure level decreases by 1.08 dB compared to the solid airfoil (81.7 dB), consistent with the main pure tone noise reduction effects.

3.4 Pure Tone Noise Source Characteristics Comparative analysis of the permeable airfoil with permeability $k = 1.25 \times 10^{-10}$ m^2 and size 10% of the chord length, which showed good noise reduction performance, was conducted against the solid airfoil to analyze pure tone noise source characteristics.

[Figure 11: see original paper] presents the root-mean-square (RMS) distribution of pressure fluctuations on the pressure and suction surfaces of both solid and permeable airfoils. Comparing post-flow-separation development reveals that the permeable airfoil exhibits significantly reduced pressure fluctuation RMS peaks on both surfaces, with smoother variations.

Permeable walls may affect noise directivity. To analyze this, far-field noise directivity was compared between permeable and solid airfoils at different permeability values in [Figure 12: see original paper]. The noise reduction effect is most concentrated within 60° to 120°, with $k = 1.25 \times 10^{-10}$ m^2 showing more pronounced effects.

[Figure 13: see original paper] shows the time-averaged streamwise velocity and RMS fluctuation distribution inside the permeable wall. The time-averaged streamwise velocity distribution reveals significant pressure differences between the upper and lower surfaces within the permeable wall. The streamwise fluctuation RMS decreases continuously as permeable wall size decreases, with the most significant SPL reduction occurring at 10% of the chord length.

4. Conclusions

Based on the ITD/LBM method, numerical calculations of the acoustic field were performed for NACA0012 permeable airfoils under different permeability values and permeable wall sizes. The reliability of the numerical results was verified, leading to the following conclusions:

1. As permeable wall size decreases, vortex frequency gradually decreases and vortex development exhibits periodic variations. When permeable wall size is below 10% of the chord length, permeability has minimal effect on vortex frequency.
2. Permeable walls alter the development and structural characteristics of boundary layer vortices through momentum exchange within the permeable wall, thereby reducing sound source intensity and effectively suppressing main pure tone noise.
3. At the trailing edge, disturbances caused by suction and pressure surface flows are strong, resulting in greater sound source intensity in this region.

These results provide a theoretical foundation for research on permeable walls in suppressing pure tone noise and controlling flow, offering positive contributions to effective pure tone noise reduction in industrial equipment with moderate Reynolds number laminar airfoils.

References

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Note: Figure translations are in progress. See original paper for figures.