The Study of Prediction Method on Propeller Broadband Noise

Yihong Chen, Denghai Tang, Zhuqing Liu and Hongxing Sun

Abstract In this paper, a prediction method of hydrofoil broadband noise is developed based on large eddy simulation (LES) methods and Ffowcs Williams-Hawkings (FW-H) equations. The broadband noise of an airfoil is calculated and the comparison of computed and measured sound pressure spectra shows good agreement over approximately a decade of frequency. The broadband noise of five different hydrofoils are calculated and presented in this paper. The relationship between the broadband noise of hydrofoils and the hydrofoil thickness and camber distributions are discussed. An optimized hydrofoil is presented in this paper for which the broadband noise is about 4 dB lower than NACA-66mod foil.

1 Introduction

The propeller broadband noise spectrum is contributed by the sound radiation of the trailing edge flow of propeller blade and interaction between tip vortex and blade. Turbulence with various scales eddies in these flows is directly related to generation of the noise. So, how to obtain the detail structures of flow field around the propeller becomes one of the key points in propeller broadband noise prediction by numerical methods. Large eddy simulation (LES) method can get adequate flow details with relatively high accuracy, as well as satisfy the requirement of the sound source simulation calculation for noise prediction.

Wang and Moin (2000) used numerical methods to simulate trailing edge flow, and then the trailing edge noise was predicted by the acoustic disturbance

Y. Chen (✉) · D. Tang · Z. Liu · H. Sun
China Ship Scientific Research Center, Wuxi, China
e-mail: 5784362@qq.com

Y. Chen · D. Tang · Z. Liu · H. Sun
National Key Laboratory on Ship Vibration & Noise, Wuxi, China

Y. Zhou et al. (eds.), *Fluid-Structure-Sound Interactions and Control*, Lecture Notes in Mechanical Engineering, DOI: 10.1007/978-3-642-40371-2_34,

equations. Moreauy used LES methods to calculate foil flow field, then solved the foil trailing edge noise by FW-H equations, and the comparison of computed and experimental results shows good agreement. In conclusion, the numerical prediction method of broadband noise using LES combined with acoustical methods have already been studied and validated in different fields.

In order to predict the hydrofoil broadband noises, the turbulent flow around a two-dimensional hydrofoil is calculated as a time series by LES, and then the broadband noise is predicted using the FW-H equations. The broadband noises of five different two-dimensional hydrofoils are calculated, and the relationships between the broadband noise of hydrofoil and the hydrofoil thickness and camber distributions are discussed.

2 LES Numerical Calculation Method

The basic assumptions of LES are that: (1) transport is largely governed by large—scale unsteady flow and these structures can be computationally resolved; (2) small—scale flow features can be under taken by using appropriate subgrid scale turbulence models. In LES, the motion is separated into small and large eddies, and the large eddies is achieved by means of a low—pass filter. The filter function $G(x, y)$ implied here is following:

$$\int_{v} G(x,y)\mathrm{d}y = 1 \tag{1}$$

Filtering the Navier—Stokes equation, one obtain equations as follows:

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_i}(\rho \overline{u}_i) = 0 \tag{2}$$

$$\frac{\partial}{\partial t}(\rho \overline{u}_i) + \frac{\partial}{\partial x_j}\left(\rho \overline{u}_i \overline{u}_j\right) = \frac{\partial}{\partial x_j}\left(\mu \frac{\partial \sigma_{ij}}{\partial x_j}\right) - \frac{\partial \overline{p}}{\partial x_j} - \frac{\partial \tau_{ij}}{\partial x_j} \tag{3}$$

$\tau_{ij} = -\left(\overline{u_i u_j} - \overline{u}_i \overline{u}_j\right)$ is subgrid scale stress tensor. The subgrid scale stresses resulting from the filtering operation are unknown, and require modeling.

3 Broadband Noise Numerical Calculation Method

Ffowes Williams and Hawkings (1969) utilized the generalized function theory to obtain the classic equation that has become associated with their names. If we take a time derivative of the generalized continuity equation, subtract the divergence of the generalized momentum equation, and then rearrange terms, the FW-H equation can be written as the following inhomogeneous wave equation:

$$\frac{1}{c^2}\frac{\partial p'}{\partial t} - \nabla^2 p' = \frac{\partial}{\partial t}[(\rho_0 v_n + \rho(u_n - v_n)]\delta(f) - \frac{\partial}{\partial x_i}\left[P_{ij}n_j + \rho u_i(u_n - v_n)\right]\delta(f) + \frac{\partial^2}{\partial x_i \partial x_j}[T_{ij}H(f)] \tag{4}$$

where u is the velocity vector in fluids, v is the velocity vector of subject surface, c is the acoustic velocity in stable fluids, T_{ij} is Lighthill stress tensor, $\delta(f)$ is Dirac delta function, $H(f)$ is Heaviside unit function, which is 0 when $f < 0$ and 1 when $f \geq 0$.

The FW-H approach has several advantages. First, the three source terms in the FW-H equation each have clear physical meaning, which is helpful in understanding the noise generation. The thickness noise (monopole source) is determined completely by the geometry and kinematics of the body. The loading noise (dipole source) is generated by the force that acts on the fluid as a result of the presence of the body. The quadrupole source term accounts for nonlinear effects. Second, the separation of the source term also is an advantage numerically because not all terms must be computed at all times if a particular source does not contribute to the sound field.

4 The Broadband Noise Computation and Validation of Foil

In order to validate the prediction method of foil broadband noise, the noise of a three-dimension foil is computed and compared with the measured result. The model foil is a 45° asymmetrically beveled trailing edge attached to a flat strut with an elliptical leading edge. The chord length L, thickness H, and span length D of the foil are 910, 50.8, and 610 mm, respectively, the foil profile schematic diagram is shown in Fig. 1. The noise of foil was measured in anechoic wind tunnel of Notre Dame University, the wind speed is 30 m/s, and the attack angle is 0°.

The Large eddies simulation are performed in the calculated area as $4L$ (streamwise, x) × $2L$ (normal, y). A structured grid is adopted with total grid number of about 600,000. The time step for the calculations is 5×10^{-5} s, so the relating noise analytical frequency can reach 10 kHz.

The compared results between the computed and measured sound pressure spectra are shown in Fig. 2. The comparison result shows good agreement both in the frequency spectrum characteristics and sound pressure spectra.

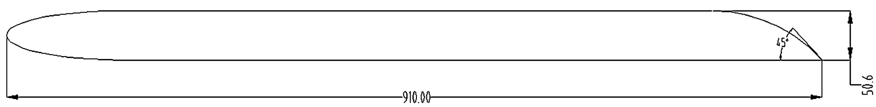


Fig. 1 Schematic of foil profile geometry

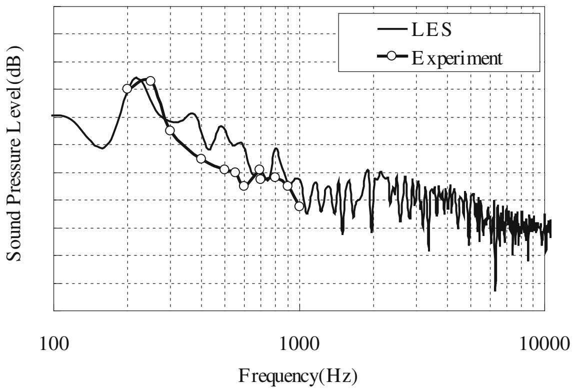


Fig. 2 Comparison of computed and experimental sound pressure spectra

5 The Noise of Five Different Hydrofoils and Discuss

The broadband noise of five hydrofoils with different thickness and camber distribution are computed using the broadband noise prediction method based on LES and FW-H. The chord and maximum thickness of all of five hydrofoils are 45 and 4.5 mm, respectively.

5.1 The Broadband Noise of Hydrofoils with Different Thickness Distribution

NACA-66mod is the basic scheme foil and named NO. 1, NO. 2 and NO. 3 are two new foils with different thickness distributions (Fig. 3), and camber distributions of the two new foils are same a NO. 1 (Fig. 4).

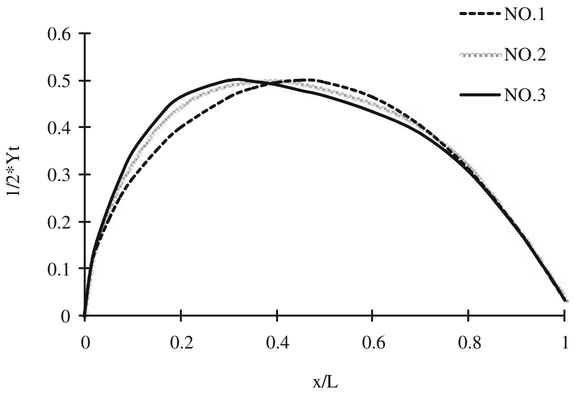


Fig. 3 Thickness distributions of three hydrofoils

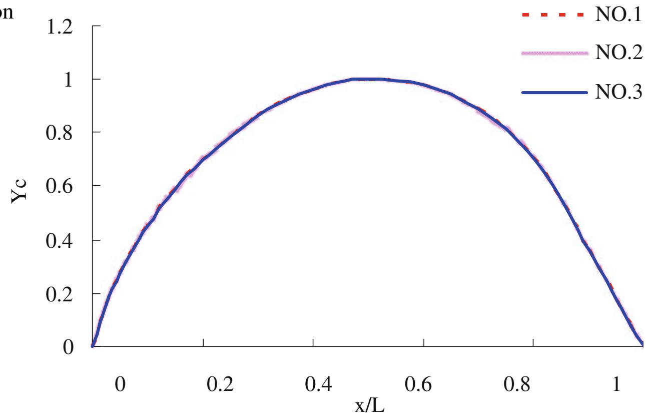


Fig. 4 Camber distribution of three hydrofoils

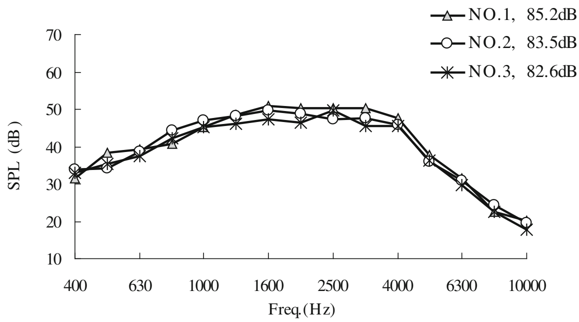


Fig. 5 The broadband noise of three hydrofoils with different thickness distributions

The broadband noise of three hydrofoils are compared and shown in Fig. 5. The prediction results of three hydrofoils broadband noise show that the thickness distribution of hydrofoils induces the broadband noise. The noise of NO. 3 hydrofoil is the lowest of three hydrofoils, and that is 2.6 dB lower than noise of NO. 1 hydrofoil. Forwarding the maximum thickness position of hydrofoils is effective in reducing broadband noise of hydrofoils.

5.2 The Broadband Noise of Hydrofoils with Different Camber Distribution

NO. 4 and NO. 5 are another two new hydrofoils that have different camber distributions from the NACA-66mod (Fig. 6), and the thickness distributions of NO. 4 and NO. 5 hydrofoils are the same as NO. 3 (Fig. 7).

The broadband noise of three hydrofoils are compared and shown in Fig. 8. The prediction results of three hydrofoils broadband noise show that the camber distribution of hydrofoils also induces the broadband noise. The noise of NO. 5 hydrofoil is the lowest of three hydrofoils and, that is, 2 dB lower than noise of

Fig. 6 Camber distributions of three hydrofoils

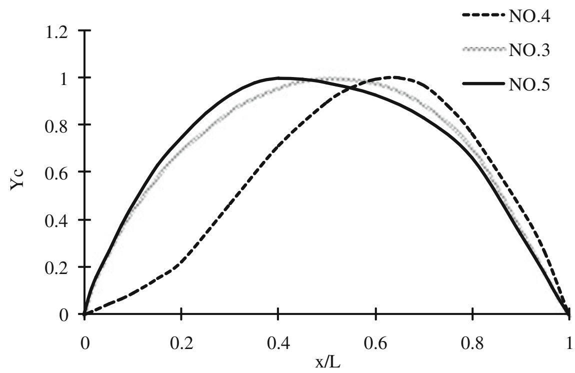


Fig. 7 Thickness distributions of three hydrofoils

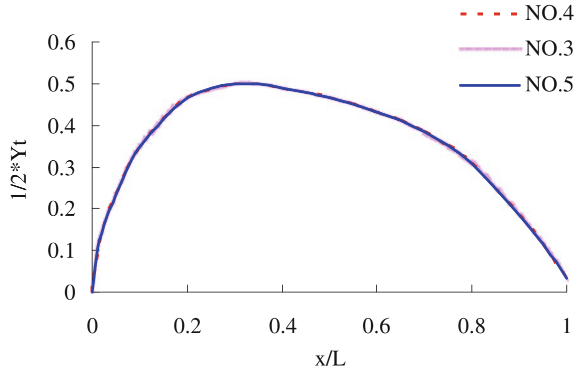
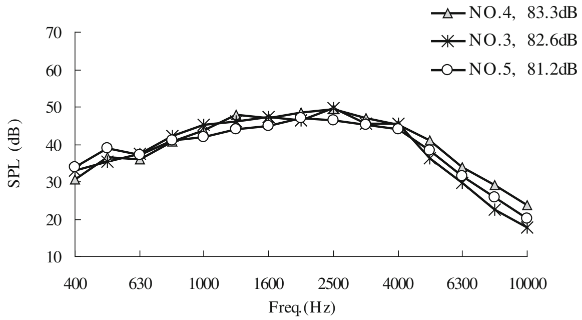


Fig. 8 The broadband noise of three hydrofoils with different camber distributions



NO. 3 hydrofoil. Forwarding the maximum camber position of hydrofoils is also effective in reducing broadband noise of hydrofoils.

Based on the predicted results of all five hydrofoils, both maximum thickness and camber position forwarding are effective in reducing broadband noise of hydrofoil. As the optimized design model, NO. 5 hydrofoil is about 4.0 dB lower than NACA-66mod foil.

6 Conclusions

In this paper, a prediction method of foil broadband noise is developed based on LES methods and FW-H equations. An airfoil broadband noise is calculated using the prediction method, and the comparison of computed and measured sound pressure spectra shows good agreement. The noise of five hydrofoils with different thickness and camber distributions are computed by the prediction method that developed in this paper. The calculation results of five hydrofoils show that both moving the maximum thickness and camber forward are effective in reducing broadband noise. As the optimized design model, NO. 5 hydrofoil is about 4.0 dB lower than NACA-66mod foil.

References

Ffowcs-Williams JE, Hawkings DL (1969) Sound generation by turbulence and surfaces in arbitrary motion. Proc. Roy. Soc. London A264:321–342

Wang M, Moin P (2000) Computation of trailing-edge flow and noise using large-eddy simulation. AIAA J 38(12):2201–2209