The Hydrodynamic Noise Suppression of a Scaled Submarine Model by Trailing-Edge Serrations

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Abstract—Hydrodynamic noise seriously reduces the survival of underwater vehicles. The optimization of line type has been used to reduce hydrodynamic noise for a long history. However, the investigation on reducing hydrodynamic noise by flow control needs intensive study and further development. In order to reduce the hydrodynamic noise of the SUBOFF model, the hush characteristic of owls feather was applied to design the trailing-edge serrations of the sail hull. Numerical simulation is performed to investigate the effects of different serrations amplitude and serrations wavelength on the underwater noise from the model of SUBOFF. The results show that the hydrodynamic noise caused by the separation of the boundary layer and the shedding of the wake vortex has been reduced. The serrations with an amplitude of 0.1c and a chord length of 0.1h reduces hydrodynamic noise by more than 10dB in the frequency from 10 to 2000 Hz. The results provide method for the reduction of underwater noise by flow control.

Keywords—trailing-edge serration, noise suppression, numerical simulation

I. INTRODUCTION

Hydrodynamic noise greatly increases the sonar detection range, thereby reducing the combat effectiveness of underwater vehicles. The normal methods of controlling hydrodynamic noise are linear optimization, little study has been focused on the flow control method to reduce hydrodynamic noise. Inspired by owls, scientists have designed serrations to improve aerodynamic performance on airplanes.

Howe (1-2) analyzed the serrations of owl wings and published the analysis of the reasons for noise reduction of the airfoil with the serrations. Jones (3) performed numerical simulation of NACA0012 airfoil with the trailing-edge serrations. Studies have shown that the serrations limits the maximum scale of the turbulent structure, promotes the growing of the horseshoe vortices, and effectively reduces the aerodynamic noise. Chong (4) measurement experiments in the wind tunnel revealed that when the serrations tip angle and height are large enough, the noise is significantly reduced. Avallone (5) used the PIV technique to observe and confirm that an appropriate serrations can effectively suppress the flow separation on the suction surface and improve the aerodynamic performance of the airfoil.

In this research, the flow and noise control mechanism of the trailing-edge serrations were analyzed by numerical simulation. We also analyzed the parameters of the serrations structure with the best noise reduction effect. The results in this paper provide a new method for the control of hydrodynamic noise.

II. THE THEORY OF NUMERICAL SIMULATION

A. LES Method

The large eddy simulation (LES) method is used to complete the numerical calculation of the flow field and obtain the turbulent fluctuating pressure. The method divides turbulent eddies into large-scale eddies and small-scale eddies. The large eddies are calculated by the N-S equation, and the small eddies is calculated by the pressure model. The N-S equation of the LES is as follows:

\[
\frac{\partial}{\partial t} \overline{\rho u_i} + \frac{\partial}{\partial x_j} \left( \overline{\rho u_i u_j} \right) = -\frac{\partial}{\partial x_j} \overline{\mu \frac{\partial u_i}{\partial x_j}} - \frac{\partial \tau_{ij}}{\partial x_j} \tag{1}
\]

\[
\frac{\partial p}{\partial t} + \frac{\partial}{\partial x_j} \left( \overline{\rho u_j u_i} \right) = 0 \tag{2}
\]

where, \( \tau_{ij} = \rho \overline{u_i u_j} - \rho \overline{u_i u_j} \), is sub-grid stress term. In order to make the equation enclosed, a sub-grid model is needed. The dynamic sub-grid model is proposed by Germano (6). The model can be adapted suitably into local turbulent structure near the wall.

\[
\tau_{ij} = -\frac{1}{3} \tau_{kk} \delta_{ij} = -2 \mu_s \overline{S_{ij}} \tag{3}
\]

where, \( \mu_s \) is the coefficient of sub-grid eddy viscosity.

\[
\mu_s = \left( \rho_{s} \Delta \right) \left| \overline{S} \right| \tag{4}
\]

\[
\overline{S}_{ij} = \sqrt{2 \overline{S_{ij} S_{ij}}} \end{equation},  \quad \overline{S}_{ij} = \frac{1}{2} \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right), \quad \Delta = \left( \Delta, \Delta \right)^{1/3} \tag{5}
\]

where, \( \Delta \) is the scale of the filter, \( C_{l} \Delta \) is the mix length. It can be seen that the dynamic sub-grid model needs to be adjusted to adapt to different calculation processes. The flow field needs to be filtered multiple times, and the results are as
follows:

\[
\begin{align*}
\gamma^2 &= \frac{1}{2\Delta^2} \left( \frac{L_i M_{ij}}{M_{ij} M_{ij}} \right) \\
L_{ij} &= \bar{u}_i u_j - \bar{u}_j u_i \\
M_{ij} &= 2\Delta^2 (\bar{c}_i^2 - 1) \bar{S}_i \bar{S}_j
\end{align*}
\]

(6) (7) (8)

**B. The Calculation of Hydrodynamic Noise**

It is assumed that sound field can be divided into two parts. The inner part is modeled by finite element. The outer part is modeled by infinite element, which simulates the zone of sound extinction. Figure 1 shows the sound field division.

![Fig. 1. The sound field calculation domain division](image1)

**III. THE CALCULATION MODEL AND CALCULATION METHOD**

SUBOFF is a submarine specification model, which is jointly proposed by DARPA and DTRC. The model is the SUBOFF sail hull with body so as to reveal the unstable flow phenomenon caused by the interaction between the sail hull and the body. The model with a scale of 1:48 and a length \( L \) of 1.59m. The sail hull is an approximate airfoil with a chord length of 0.184m. The model is shown in Figure 2.

![Fig. 2. The calculation model](image2)

For the full development of turbulence, a rectangular flow field calculation domain is created. The regions of outer boundary are set as velocity inlet\( (v=8.68\text{m/s}) \), pressure outlet, symmetrical boundary and wall boundary, respectively.

**IV. THE APPLICATION OF TRAILING-EDGE SERRATIONS**

Figure 3 shows the serrations in owls. We designed the trailing-edge serrations on the SUBOFF model based on the owl.

![Fig. 3. The trailing-edge serrations in owls and the sail hull](image3)

As shown in Figure 4, the amplitude \( A \) and wavelength \( \lambda \) of the serrations are the two most important geometric parameters. In this section, we have chosen an amplitude of 0.1c and a wavelength of 0.1h as a typical case to analyze the serrations noise reduction mechanism.

![Fig. 4. The geometric parameters of trailing-edge serrations](image4)

Figure 5 shows the surface pressure at trailing-edge of the model with trailing-edge serrations and the SUBOFF model. The serrations is similar to a flat plate with an angle of attack. The water flows from the high-pressure side to the low-pressure side, and generates a pair of vortices that rotate in opposite directions and move downstream.

![Fig. 5. The pressure at trailing-edge](image5)

Figure 6 shows a pair of vortices with opposite rotation directions between the trailing-edge serrations. The vortices will destroy the boundary layer and inject energy into the boundary layer of the trailing-edge. The momentum exchange of the boundary layer is promoted, thereby delaying the separation of the turbulent boundary layer on the trailing-edge of the sail hull. The hydrodynamic noise generated by turbulent fluctuation pressure, which is caused by the boundary separation, can be reduced.
The vortices between the trailing-edge serrations

Figure 7 shows the vortices diagram of the SUBOFF model and the model with the trailing-edge serrations. The trailing-edge serrations delay the generation of vortices caused by boundary layer separation. At the trailing-edge, the vortices fall off more quickly, and the vortices are smaller and more broken. The trailing-edge serrations will reduce the low-frequency turbulent pressure generated by the large vortices and reduce the low-frequency hydrodynamic noise. At the same time, these vortices are small in size and will produce stronger high-frequency noise.

The SUBOFF model

The model with the trailing-edge serrations

Fig. 7. The vortices surface diagrams

Figure 8 shows the noise level curves of the two models. It can be found that at low frequency ($f<1150Hz$), the noise level of the model with trailing-edge serrations is reduced, because the boundary separation was effectively controlled. The noise level of the model with trailing-edge serrations is greater than the SUBOFF model when the frequency exceeds 1150Hz due to the contributions of the small-scale vortices. Therefore, the trailing-edge serrations improves the hydrodynamic performance, reduces noise at low frequency, and increases noise at high frequency. Due to the long transmission distance of low-frequency noise and short transmission distance of high-frequency noise. Therefore, it can effectively reduce the sonar detection range.

V. THE BEST PARAMETERS OF TRAILING-EDGE SERRATIONS

A. The Choice of Amplitudes

We have calculated the noise of the trailing-edge serrations model with amplitudes of 0.1c, 0.05c, and 0.025c. Figure 9 shows the hydrodynamic noise level curve of different amplitude models. Table 1 shows the total level of noise of different amplitude models. The noise reduction amount becomes greater with the increase of the amplitudes.

Fig. 8. The noise level curves

Fig. 9. The curves of noise level of trailing-edges serrations with different amplitudes

| model  | total noise levels(dB) | noise reduction(dB) |
|--------|------------------------|---------------------|
| SUBOFF | 113.51                 | 0                   |
| 0.025c | 104.60                 | 8.91                |
| 0.05c  | 104.23                 | 9.28                |
| 0.1c   | 103.14                 | 10.37               |

B. The Choice of Wavelength

We fixed the amplitude of the trailing-edge serrations to be 0.1c. Then, we have calculated the noise of the trailing-edge serrations model with wavelengths of 0.2h, 0.1h, 1/15h, 0.05h. Figure 10 shows the hydrodynamic noise level curve of different wavelength models. Table 2 shows the total level of noise of different wavelength models. The amount of noise reduction firstly becomes smaller with the decrease of the wavelengths, and then becomes larger.

Fig. 10. The curves of noise level of trailing-edges serrations with different wavelengths

TABLE I. THE TOTAL NOISE LEVELS OF TRAILING-EDGE SERRATIONS WITH DIFFERENT AMPLITUDES
In conclusion, the model with trailing-edge serrations, of which the amplitude is 0.1c and the wavelength is 0.1h, has the optimum effect of noise reduction at 10-2000Hz. The experimental validation will be carried out in the future.

VI. CONCLUSIONS

The trailing-edge serrations are reconstructed at the the SUBOFF model. The trailing-edge serrations delay the separation of boundary layer and the generation of the vortices caused by the boundary layer separation. However, more small vortices increase high frequency noise. The effects of trailing-edge serrations with different amplitudes and wavelengths on the level of noise are investigated. It is found that the trailing-edge serrations, of which the amplitude is 0.1c and the wavelength is 0.1h, has the optimum effect of noise reduction. The optimum level of noise reduction is 10.371 dB.

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