

# The suppression of hydrodynamic noise from underwater sonar domes by flow control

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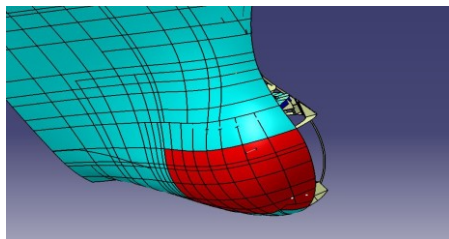
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**Abstract.** Hydrodynamic noise is one of the three major noise sources of underwater vehicles. The sonar dome is a device placed in front of the ship and the submarine to absorb the flow fluctuation and to reduce the hydrodynamic noise, so that the sonar inside the dome is not affected by the external fluid. However, with the increase of the velocity of ships and submarines, cavitation can usually form in the bulge of the sonar domes, which will bring high level of noise to the sonar. The internal self-noise of the sonar dome mainly comes from two areas: the leading-edge stagnation point and the transition zone of boundary layer. In the paper, we designed the leading-edge serrations and dimples in the leading-edge and transition areas of the sonar dome respectively to reduce the movement resistance and prevent the separation of the boundary layer. The research on leading-edge serrations and dimple technology is carried out by using theoretical analysis, numerical calculations. The results show that the leading-edge serrations and dimples can add energy from the outer flow into the boundary layer; the cavitation phenomenon can be delayed. The hydrodynamic noise has been suppressed by about 20dB.

## 1 Introduction

### 1.1 The function of sonar domes

The sonar is a device, which detects the direction, location, and characteristics of the objects in the ocean by the propagation of sound waves in the water. When the ship sails, a dome with good hydrodynamic performance needs to be placed outside the sonar array, to avoid the impact of water flow, reduce the turbulence and suppress the cavitation, and even refrain the direct interference of the arrays by the ‘pseudo-sound’.



**Fig. 1.** The picture of the sonar dome.

The sonar dome is also called as bulbous dome. During the navigation, the pressure and the velocity of the particle in the turbulent boundary layer formed near the sonar dome have intense fluctuations, which radiates the noise directly. So it requires the performance of low noise and high mechanical intensity, even good level of sound transmission and minimum acoustic beam distortion.

Studies show that under the conditions of high speed and high frequency, the main noise is the hydrodynamic noise, especially when the speed of the ships is beyond 10 knots. However, the detection distance of the sonar will increase by 2 to 3 times, if the level of hydrodynamic noise decreases by 10 dB. Therefore, it is of great significance to investigate the suppression of hydrodynamic noise of the sonar dome. At present, the research on the sonar dome is mainly focused on the optimization of the line, structure and material to reduce the drag and hydrodynamic noise.

### 1.2 The level of the research on sonar domes

Dyer[1] established the model of the sonar dome, which is an elastic plate covering on the rectangular cavity, and calculated the noise in the rectangular cavity, which is excited by the turbulent fluctuation pressure of the elastic plate. Dowel[2] used the infinite parallel plate model to calculate the excitation by the mechanical point force and the turbulent fluctuation pressure. He found that the latter is lower. Rao[3] used the model of simply supported rectangular elastic plate to analyze the power spectrum of the vibration from the elastic plate, which is excited by the spectrum of turbulent fluctuation pressure. Lauchle[4] used the theory of sound radiation from the turbulence in the boundary layer and transition area and established the formula for the calculation of the self-noise of the sonar dome. Nautet[5] measured the vibration of the sonar dome and then calculated the

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mechanical noise of the sonar by the method of wave decomposition and the boundary integration.

Zhenbang Sheng [6] made a preliminary summary of the research on the sonar dome. Liming Du[7] proposed four kinds of shape models of the sonar dome and analyzed their hydrodynamic performance. He found that the structure of the streamlined head and the semicircular tail has the optimum performance. Haoguang Sun[8] used a double-layer alloy plate as the sound-transparent window to analyze the plane wave permeability of the double-layer steel plate, and gave the measurement results. He found that the design not only has high mechanical strength, but also has good sound transmission performance at low frequency. Rongbao Wu[9] comprehensively analyzed the structure, strength, sound permeability, corrosion resistance and process welding performance of the double-shell titanium alloy sonar dome. He proposed that the double-shell structure can improve the strength and rigidity of the frame and increase the sound transmission. Shengfeng Fu[10] studied the flow field and sound field of the sonar dome of different materials by numerical simulation method. The properties of flow field and sound field were analyzed. Then, the experimental test was carried out. He found that at the same flow speed, the sonar dome of titanium alloy material has the best inhibition effect of hydrodynamic noise. The sonar dome of glass fibre reinforced plastic material is the second. The sonar dome of rubber material has the worst effect of hydrodynamic noise suppression. It is recommended that the sonar dome should be designed with titanium as if the conditions permit.

From the list, we may find that most researches are focused on the mechanism of noise generation, line type optimization and the materials optimization. There are few researches on hydrodynamic noise reduction of the sonar dome, which is suppressed by the flow control.

### 1.3 The theory of flow control

The inside self-noise of the sonar dome mainly comes from two areas: the leading-edge stagnation point and the transition area of the boundary layer. The leading-edge stagnation point is the area, where the pressure is the largest. The transition area of the boundary layer is the area, where the laminar flow is transformed into the turbulent flow, the velocity is the largest and the pressure is the smallest. When the subsequent development of the turbulence is reattached, the high-pressure fluctuation and radiation noise are generated, which affects the detection performance of the sonar in the dome. In the paper, we designed the serrations and dimples in the leading-edge and the transition areas of the sonar dome, respectively, to reduce the pressure of the stagnation point and suppress the separation of the boundary layer, so that the self-noise of the sonar dome can be decreased.

The advantage of the leading-edge serrations is that the front has the point structure, which can greatly reduce the fluctuation pressure of the sonar dome. At the same time, the sawtooth structure is similar to the vortex generator. The energy can be injected into the fluid of

the boundary layer, to inhibit the separation of the boundary layer. In the study of aeroacoustics, it is shown that the serrations structure can significantly improve the stability of the development of the boundary layer and inhibit the separation of the boundary layer. The dimple is a spherical crown-shaped pit in which an aqueous medium can be stored. When the sonar dome moves, the external fluid rubs against the aqueous medium, of which the frictional resistance is far less than the frictional resistance between the surface of the sonar dome and the aqueous medium, so that the motion resistance can be reduced. In addition, when the external fluid passes through the dimples, small eddies are formed inside the dimples and these small eddies will move away from the dimples. This acts like the vortex generator, which injects energy into the boundary layer and suppresses the separation of the boundary layer. It is meaningful for the suppression of the flow separation phenomenon of the sonar dome at high-speed.

## 2 The method of numerical simulation

### 2.1 The basic equation of fluid dynamics

The continuity equation, velocity potential function, wave equation and Navier-Stokes equation (N-S equation) are derived from the law of mass conservation, the law of momentum conservation and the law of energy conservation, which are suitable for solving various fluid motion problems. These basic equations are as follows.

The continuity equation

$$-div(\rho_0 u) = \frac{\partial \rho}{\partial t} \quad (1)$$

The velocity potential function

$$\nabla^2 \Phi = \frac{1}{c_0^2} \frac{\partial^2 \Phi}{\partial t^2} \quad (2)$$

The acoustic wave equation

$$\nabla^2 p = \frac{1}{c_0^2} \frac{\partial^2 p}{\partial t^2} \quad (3)$$

The Navier-Stokes equation

$$\frac{\partial \mu_i}{\partial t} + \frac{\partial(\mu_i \mu_j)}{\partial x_j} = f_i - \frac{1}{\rho} \frac{\partial p}{\partial x_i} + \nu \frac{\partial^2 \mu_i}{\partial x_i \partial x_j} \quad (4)$$

$$\frac{\partial \mu_i}{\partial x_i} = 0 \quad (5)$$

where,  $\mu_i$ 、 $\mu_j$  is the fluid velocity,  $f_i$  is the mass force intensity,  $\rho$  is the fluid density,  $P$  is the fluid pressure,  $\nu$  is the kinematic viscosity coefficient,  $div$  is the divergence operator,  $\nabla^2$  is the Laplace operator.

### 2.2 The LES method

In the theory of large eddy simulation (LES), the small eddies less than a certain size are filter out. Then, the

large eddies are brought into the N-S equation for the solution. To reflect the influence of small eddies on the flow field, the sub-grid model is processed on the filtered small-scale eddies. The N-S equation filtered by the filter function is as follows

$$M^2 \left\{ \frac{\partial \bar{p}}{\partial t} + \bar{u}_j \frac{\partial \bar{p}}{\partial x_j} \right\} + \frac{\partial \bar{u}_j}{\partial x_j} = 0 \quad (6)$$

$$\frac{\partial \bar{u}_i}{\partial t} + \bar{u}_j \frac{\partial \bar{u}_i}{\partial x_j} = - \frac{\partial \bar{p}}{\partial x_i} + \frac{1}{\text{Re}} \frac{\partial}{\partial x_j} \left( \frac{\partial \bar{u}_i}{\partial x_j} + \frac{\partial \bar{u}_j}{\partial x_i} \right) - \frac{\partial t_{ij}}{\partial x_j} \quad (7)$$

The Smagorinsky-Lilly sub-grid scale stress model is chosen to close the governing equation.

### 2.3 The theory of Lighthill's acoustic analogy

The theory of Lighthill's acoustic analogy deforms the fluid mechanics N-S equation, then, the data of flow field is considered as the sound source, and introduced into the numerical calculation of the sound field. The sound field is divided into near field and far field, where the near field acts as the area of sound source and the far field acts as the area of sound radiation. The assumption is that the sound field is not affected by the flow of far field. On the basis, the two equations--the continuity equation of flow field and the momentum conservation equation--can be simplified. Then, a new equation can be obtained, which is the Lighthill's acoustic analogy equation.

$$\frac{1}{c_0^2} \frac{\partial^2 P_a}{\partial t^2} - \frac{\partial^2 P_a}{\partial x_i \partial x_j} = \frac{\partial^2 T_{ij}}{\partial x_i \partial x_j} \quad (8)$$

$$T_{ij} = \rho_0 u_i u_j$$

Eq.(8) is to calculate the flow noise from the turbulence. The flow-induced noise is calculated by the FW-H equation.

The far-field solution can be obtained by the combination of the free space Green's function and the Kirchhoff surface integral method. Then, the flow-induced noise can be gotten.

$$\begin{aligned} \frac{1}{c_0^2} \frac{\partial^2 p'}{\partial t^2} - \nabla^2 p' &= \frac{\partial^2}{\partial x_i \partial x_j} [T_{ij} H(f)] \\ - \frac{\partial}{\partial x_i} \left\{ [P_{ij} n_j + \rho u_i (u_n - v_n)] \delta(f) \right\} \\ + \frac{\partial}{\partial t} \left\{ [\rho_0 v_n + \rho (u_n - v_n)] \delta(f) \right\} \end{aligned} \quad (9)$$

## 3 The numerical simulation

The process of hydrodynamic noise numerical simulation is mainly divided into the model establishment, the mesh division, the flow field

calculation, the sound field calculation and post-process of the results.

### 3.1 The model establishment

The front part of the sonar dome is the area of the stagnation point of the flow and faces the current, where the fluctuation pressure is the largest. After the flow develops backward along the flow stagnation area, the transition area of the boundary layer of the sonar dome is formed, where the fluid turns from laminar flow into turbulent flow. The model of the sonar dome was established with the height of 0.13 m, the feature length of 0.2 m, and the widest part of 0.12 m.

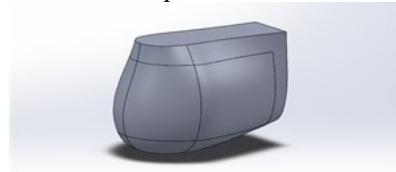


Fig. 2. The model of the sonar dome.

Based on the model of the sonar dome, the calculation model with the leading-edge serrations and the dimples is shown in Fig.3. The wavelength is 0.008 m and the periods are 0.0065 m. The dimples have a radius of 0.004 m and the pitch of 0.012 m.

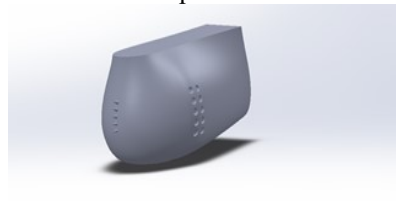


Fig. 3. The model of the sonar dome with the leading edge serrations and the dimples.

### 3.2 The flow field calculation

The model is imported into the software, FLUENT, meshed and calculated. The flow field is a rectangular parallel pipe with the length of 1 m, the width of 0.36 m and the height of 0.36 m. The mesh is fulfilled by the ICEM, and the total number of computational grids is 2.3 million.

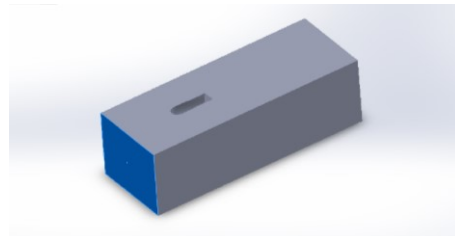
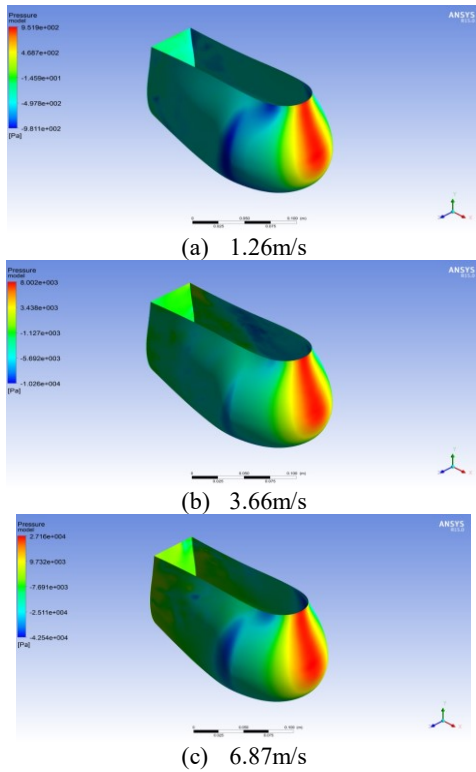


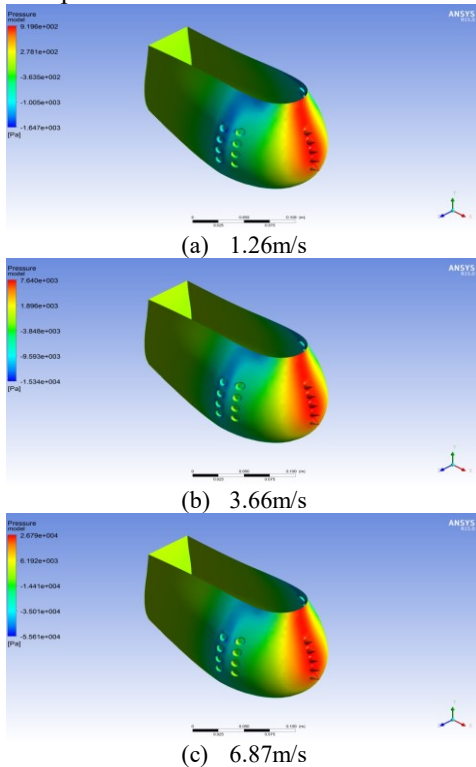
Fig. 4. The mesh grid of the flow field.

After the flow field calculation of two kinds of the sonar dome at three different flow velocities was completed, which are 1.26 m/s, 3.66 m/s, and 6.87 m/s, the pressure contour diagram of the original sonar dome and that with the leading-edge serrations and the dimples is shown in Fig.5 and Fig.6.



**Fig. 5.** The pressure contour of the sonar dome at different velocities.

As can be seen from Fig.5, the fluctuation pressure at the stagnation point is large. With the increase of the velocity, the fluctuation pressure increases. However, the fluctuation pressure in the transition area is lower.



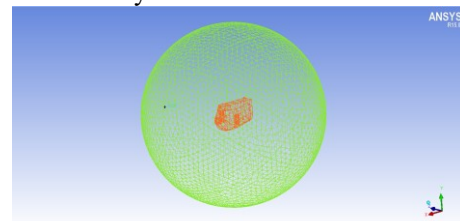
**Fig. 6.** The pressure contour of the sonar dome with the leading-edge serrations and the dimples.

Compared to the original model, we may find that after the leading-edge serrations and the dimples are added, the level of fluctuation pressure at the stagnation point is reduced, however, the level of the fluctuation

pressure in the transition area is enhanced. The fluctuation pressure becomes more even, not converged as before. The effect of the leading-edge serrations and the dimples on the fluctuation pressure is as we expected.

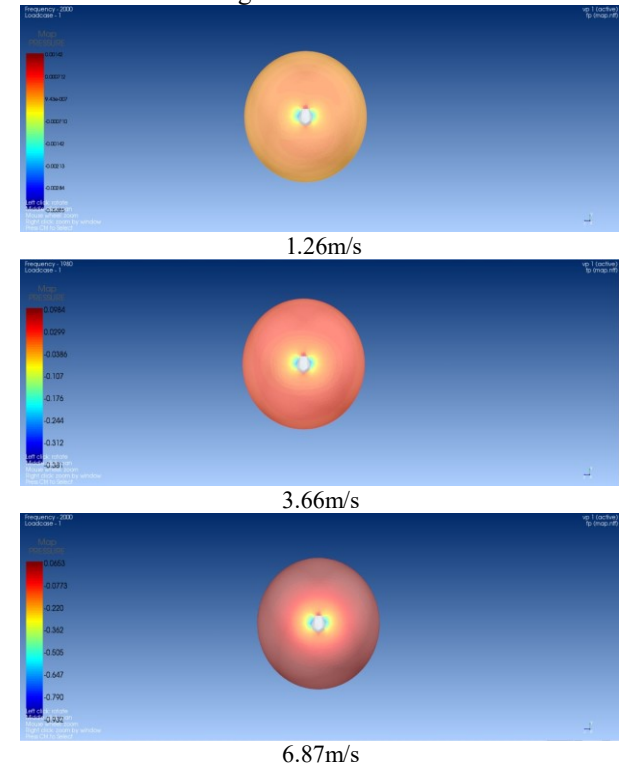
### 3.3 The sound field calculation

As seen in Fig.7, this is the model of the sound field calculation. The spherical sound field is centred at the plane of the sonar dome, and the diameter of the sphere is 1.5m. The grid is divided by the ICEM, and the number of sound field grid is about 1 million. As we know, the plane part of the sonar dome is actually connected to the ship and the sonar is installed inside, if the outside noise is decreased, the self-noise will be decreased. Therefore, only the outside sound field of the sonar dome is analyzed.



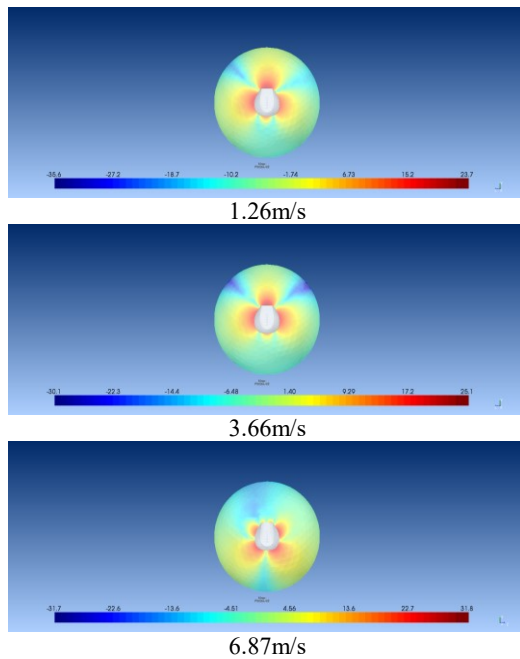
**Fig. 7.** The mesh model of sound field of the sonar dome.

The sound field is calculated by the software, ACTRAN, and the distribution of sound pressure of the model is shown in Fig.8.



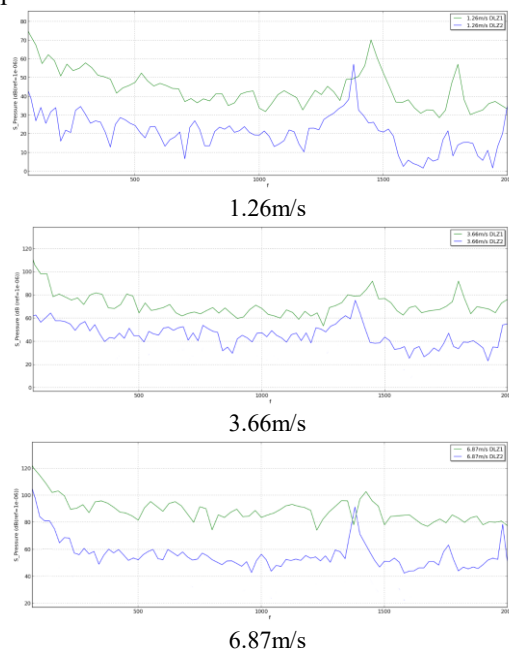
**Fig. 8.** The distribution of sound pressure of the sonar dome at different velocities at the frequency of 2000Hz of the original mode.

When the frequency is 2000 Hz, with the increase of flow velocities, the level of sound pressure of the sonar dome is increasing. The sound field has a good bilateral symmetry, which meets the practical situation.



**Fig. 9.** The distribution of sound pressure of the sonar dome at different velocities at the frequency of 2000Hz of the model with the leading-edge serrations and the dimples.

As seen in Fig.9, the distribution of sound pressure around the sonar dome with the leading-edge serrations and the dimples is similar with the original model, and the pressure distributes more even.



**Fig. 10.** The comparison curve of sound pressure level between the original model and that with the leading-edge serrations and the dimples. The green line is the curve of sound pressure level of the original model, while the blue line is the curve of sound pressure level of the model with the leading-edge serrations and the dimples

Fig.10 shows the comparison curve of sound pressure level between the original model and the model with the leading-edge serrations and the dimples at three different velocities. It can be seen that after the leading-edge serrations and the dimples are added into the original model of the sonar dome, the sound pressure level of the hydrodynamic noise can be reduced by about 20dB.

Furthermore, the effect of the leading-edge serrations and the dimples on the suppression of hydrodynamic noise is better in the low frequency range than that in the high frequency range.

## 4 Conclusions

The sonar dome requires the performance of lower hydrodynamic noise, higher sound transmission and better mechanical intensity. In the paper, we designed the leading-edge serrations and the dimples of the sonar dome, to reduce the fluctuation pressure at the stagnation point and suppress the separation of the boundary layer. Therefore, the self-noise of the sonar dome has been reduced. Since the area of the leading-edge serrations and the dimples is much less, compared to the surface area of the sonar dome, the mechanical properties of the sonar dome can not be disturbed and the sound field performance of the sonar dome can not be changed, either. The calculation of flow field and sound field of the model has been numerically done by the combination of the software, FLUENT and ACTRAN.

Compared to the original model, the fluctuation pressure at the stagnation point of the sonar dome is reduced, the separation of the boundary layer is inhibited and the stability of the boundary layer is improved. Therefore, the turbulent fluctuation pressure has been decreased and the hydrodynamic noise has been suppressed. The results show that the level of the hydrodynamic noise can be reduced up to 20 dB with the placement of the leading-edge serrations and the dimples.

It is believed that the results in the paper can provide a new way to suppress the hydrodynamic noise of the sonar dome of the ships at high speed. The results can also provide technical support for the control of the hydrodynamic noise of the sonar dome in the future.

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