Numerical investigation of flow and noise characteristics of the sea suction value

Rongtao Zeng¹,³, Mingkang Sun¹, Jian Liu¹, Zongliang Bai²,.*, Daoyuan Song³,.*, Sha Wen⁴

¹ State Key Laboratory of Hydrosience and Engineering, Department of Energy and Power Engineering, Tsinghua University, Beijing 100084, China;
² China Ship Development and Design Center, Wuhan 430064, China;
³ College of Electrical Engineering, Naval University of Engineering, Wuhan 430033, China;
⁴ Political College, National Defence University, Shanghai 200433, China.
*Corresponding author E-Mail: xiaobai_hust@126.com; zxpbabymail01@163.com.

Abstract. The ship industry has been developed considerably in the engineering applications of deep-sea energy extraction, and the hydrodynamic performance and noise level of ships have become the focus of research for scholars and industries. In order to study the flow characteristics and acoustic characteristics of the sea suction valve, this paper conducts numerical simulation of the internal flow field and acoustic characteristics of the sea suction valve and the noise elimination trunk structure based on the numerical method of computational fluid dynamics. Through the study and analysis of different sea suction valve structures and different depths of noise elimination trunk on the flow characteristics and acoustic characteristics, it is helpful to provide guidance for engineering optimization design.

1. Introduction

Deep-sea energy is becoming more and more important in the future development of human society, and the demand for deep-sea energy extraction is gradually increasing [1-2]. With the improvement of science and technology, the ship industry has also developed significantly in deep-sea energy extraction, among which the hydrodynamic performance and noise level of ships have been widely concerned by experts, scholars and industrial sectors [3]. Scholars and engineers have carried out research in various aspects in order to improve the operational efficiency of ship equipment while reducing resistance and noise. The sea suction valve is important equipment of the ship's seawater discharge system, and like many hydraulic machinery and equipment, seawater passing through the sea suction valve will generate vortex [4], cavitation, dead water zone and other phenomena, which will cause pipeline loss [5], vibration [6-7] and noise [8], and finally affect the hydrodynamic efficiency and comprehensive performance of hydraulic machinery and ships [9].

With the development of computer performance and computational fluid dynamics, numerical simulation of the flow field has gradually become a new method for predicting and optimizing the design of hydraulic machinery flow characteristics [10], reducing the cost investment brought by experimental tests. Some scholars have carried out a detailed numerical study on the internal flow of the sea suction valve [11] to study the effects of different valve openings and flow rates on the flow
field characteristics of the sea suction valve, and the results show that vortices and pressure pulsations are the main causes of the valve flow characteristics and noise generation. In order to explore more accurate numerical calculation methods and turbulence models, Lu et al [12] used four turbulence models to calculate the flow noise of the ship, and found that the RNG $k-\varepsilon$ turbulence model combined with the FW-H acoustic model could obtain more accurate calculation results. Three-dimensional numerical simulation on the internal flow field of the sea suction valve can reveal the distribution of turbulent energy in the flow field and the magnitude of transverse pulsation force on the valve [13], and based on the calculation results, the valve shape optimization measures were proposed to effectively reduce the flow noise. Bai et al [14] proposed three measures to optimize the design of the valve flow path and found that the total pressure loss was reduced by 14.5%-23.46% after the optimization, and the reliability of the numerical calculations was verified by experiments.

In this paper, the method of numerical computation is employed to simulate the internal flow field and acoustic characteristics of the sea suction valve and noise elimination trunk structure, and the effects of the sea suction valve structure and noise elimination trunk structure on the flow characteristics and flow noise is presented. On the basis, some optimization measures for engineering design are recommended.

2. Model construction and mesh arrangement

2.1. Mathematical model

A relevant mathematical model is established to study the flow characteristics and acoustic characteristics of sea suction valve. The flow calculation model is based on the mass conservation of fluid micro clusters to obtain the continuity equation and momentum conservation equation as follows.

$$\frac{\partial \rho}{\partial t} + \frac{\partial (\rho v_x)}{\partial x} + \frac{\partial (\rho v_y)}{\partial y} + \frac{\partial (\rho v_z)}{\partial z} = 0$$

$$\frac{\partial \rho v_x}{\partial t} + \nabla \cdot (\rho v_x V) = \frac{\partial \tau_{xx}}{\partial x} + \frac{\partial \tau_{yx}}{\partial y} + \frac{\partial \tau_{zx}}{\partial z} - \frac{\partial p}{\partial x} + \rho f_x$$

$$\frac{\partial \rho v_y}{\partial t} + \nabla \cdot (\rho v_y V) = \frac{\partial \tau_{xy}}{\partial x} + \frac{\partial \tau_{yy}}{\partial y} + \frac{\partial \tau_{zy}}{\partial z} - \frac{\partial p}{\partial y} + \rho f_y$$

$$\frac{\partial \rho v_z}{\partial t} + \nabla \cdot (\rho v_z V) = \frac{\partial \tau_{xz}}{\partial x} + \frac{\partial \tau_{yz}}{\partial y} + \frac{\partial \tau_{zz}}{\partial z} - \frac{\partial p}{\partial z} + \rho f_z$$

The numerical simulation methods for fluids can be divided into direct and non-direct simulation methods. The direct simulation method is a direct numerical calculation of the three-dimensional unsteady Navier-Stokes equation. Non-direct simulation is the indirect calculation on turbulence pulsation magnitude by means of simplified approximation. The Reynolds-averaged Navier-Stokes equation method, which calculates only the large-scale mean flow, is the numerical method currently available for the engineering [15]. The effect of all turbulent pulsations on the mean flow is closed with the turbulent mode theory, which makes the calculation less complicated. By deriving the continuum and momentum equations, the expressions of Reynolds-averaged Navier-Stokes equation are defined as follows.

$$\frac{\partial}{\partial t} (\rho u_i) + \frac{\partial}{\partial x_j} (\rho u_i u_j) = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j} \left( \mu \frac{\partial u_i}{\partial x_j} - \rho u_i u_j \right) + S_i$$

$$\frac{\partial}{\partial t} (\rho \phi) + \frac{\partial}{\partial x_j} (\rho u_j \phi) = \frac{\partial}{\partial x_j} \left( \Gamma \frac{\partial \phi}{\partial x_j} - \rho u_j \phi \right) + S$$

When introducing the turbulent kinetic energy equation, the updated equation is defined as follows.
\[
\frac{\partial (\rho k)}{\partial t} + \frac{\partial (\rho k u_i)}{\partial x_i} = \frac{\partial}{\partial x_j} \left[ \left( \mu + \frac{\mu_t}{\sigma_k} \right) \frac{\partial k}{\partial x_j} \right] + \mu_t \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \frac{\partial u_i}{\partial x_j} - \frac{\rho C_D}{l} k^{3/2}
\]

The left two terms in the above equation represent the transient and convective term of the fluid, while the right three terms represent the diffusion, generation and consumption term, respectively.

The Ffowcs Williams-Hawkings (FW-H) acoustic integration equation, which is the preferred method for far-field noise prediction, is the main basis for the acoustic calculation model. This model can calculate the acoustic signal radiated to the far field by the near-field flow. The FW-H equation converts the continuum and momentum equations into the exact form of the non-simultaneous fluctuation equation. The pressure radiated into the fluid medium by the flow over a surface in the computational region using the FW-H equation is expressed as follows.

\[
p'(x,t) = p'_T(x,t) + p'_L(x,t) + p'_Q(x,t)
\]

Where the monopole term is

\[
p'_T(x,t) = \frac{1}{4\pi} \left\{ \frac{\partial}{\partial t} \left[ \int_S \frac{Q}{r(1-M_r)} ds \right] \right\}
\]

The dipole term is

\[
p'_L(x,t) = \frac{1}{4\pi} \left\{ \frac{\partial}{\partial x_i} \left[ \int_S \frac{L_i}{r(1-M_r)} ds \right] \right\}
\]

The quadrupole term is

\[
p'_Q(x,t) = \frac{1}{4\pi} \left\{ \frac{\partial^2}{\partial x_i \partial x_j} \left[ \int_V \frac{T_{ij}}{r(1-M_r)} dv \right] \right\}
\]

2.2. Physical model

The geometric models of the research object are established in this paper, and the schematic diagram of structures including the sea suction valve, right angle valve, noise elimination trunk and permeable holes are shown in Figure 1 to Figure 4.
2.3. Mesh generation
The finite volume method is the most effective numerical computational method in computational fluid dynamics, of which basic idea is to divide the computational region into a grid and to surround...
each grid point with a control volume that does not overlap with each other. The partial differential equations are solved for each control volume, resulting in a set of discrete equations in which the unknowns are the characteristic variables of the grid points.

The meshing of the structural components is shown in Figure 5 to Figure 7. A high-quality hexahedral structured mesh is selected because of the high solution accuracy and fast convergence. The area near the sea suction valve and its outlet is a region of dramatic flow changes, which requires appropriate mesh encryption. At the same time, several boundary layer meshes are arranged near the wall of the sea suction valve for better capturing the flow conditions within the boundary layer.

![Figure 5. Mesh generation of sea suction valve.](image)

![Figure 6. Mesh generation of noise elimination trunk.](image)

![Figure 7. Mesh generation of permeable hole.](image)
3. Numerical methods and data monitoring

3.1. Numerical methods
The implicit unsteady time processing format is chosen for the calculation because of the unsteady computational conditions. The time step is set to 0.001s and each time step is iterated 5 times. The medium in the fluid domain is water, the density of the liquid is constant, and the reference pressure is set to 1 atm. Separate flow is chosen for the flow simulation, turbulence is chosen for the flow pattern, the SST $k$-$\omega$ model is chosen as the turbulence model, and the time discretization format is second order, the Reynolds time-averaged Navier-Stokes equation is enabled. Exact wall distance and full Y+ wall treatment are chosen for the near-wall treatment.

In addition, it is necessary to make suitable settings for the acoustic calculations. The acoustic model is employed and the Ffowes Williams-Harkings unsteady model is chosen. It is also needed to select the FW-H surface and the impermeable surface, where the outer surface of sea suction valve, the wall of noise elimination trunk and permeable hole are selected.

3.2. Data monitoring
The velocity-inlet boundary condition is set at the inlet of sea suction valve, with the velocity amplitude is set to 0.4 m/s and the turbulent intensity is set as 0.3. The pressure-outlet boundary condition is set at the external flow field boundary away from the permeable hole, while the rest of the structure wall is set to the no-slip wall.

Furthermore, far-field noise monitoring points are needed for monitoring far-field noise. As shown in Figure 8, 19 monitoring points are set on a semicircle around the permeable hole with the distance of 20m, corresponding to 0-180 degrees. The purpose is to make monitoring preparation for monitoring far-field noise and obtaining noise directivity curves. After the calculation, the broadband noise source model is chosen, and the Curle and Proudman model can be selected, the relevant calculation results can be obtained by further iterating.

![Figure 8. Monitoring points of far-field noise.](image)

During the calculation, monitoring points are set up near the center of the permeable holes, as shown in Figure 9, to monitor the change of pressure in order to observe the convergence of the calculation.
3.3. Calculation cases
To study the effects of different sea suction valve structures and noise elimination trunk depths on flow field characteristics and flow noise, the calculated conditions for sea suction valve and right angle valve, and two depths of noise elimination trunk are shown in Table 1.

| Cases | Sea suction value structure | Depths of noise elimination trunk | Other related structures                              |
|-------|------------------------------|----------------------------------|------------------------------------------------------|
| 1     | sea suction value            | 1-grid                           | Permeable holes, external monitoring area            |
| 2     | sea suction value            | 3-grid                           | Permeable holes, external monitoring area            |
| 3     | right angle valve            | 1-grid                           | Permeable holes, external monitoring area            |
| 4     | right angle valve            | 3-grid                           | Permeable holes, external monitoring area            |

4. Results and discussions
4.1. Flow filed analysis
Regarding the study of the flow field around sea suction value, this paper mainly carries out the flow calculation of the sea suction valve and right angle valve, in which the flow process of the sea suction valve at different moments is shown as follows.
Figure 10 represents that the fluid enters the sea suction valve structure and fills the cavity of the valve from 0s to 0.3s, and at the same time produces a certain velocity impact on the wall of the valve, resulting in a high-velocity region and a large velocity gradient in the area of the sea suction valve.
When it comes to 0.6s to 0.9s, the fluid gradually flows out of the sea suction valve structure and enters the noise elimination trunk. Due to the larger cavity volume of the noise elimination trunk, the fluid flowing out of the sea suction valve starts to diffuse rapidly into the trunk, and a certain flow velocity distribution can be observed at the permeable holes. When it comes to 1.2s to 2.1s, it can be observed that the fluid flowing from the sea suction valve starts to impact the wall of the trunk, and the velocity gradient near the permeable hole also gradually increases. As the calculation is carried out, it can be found that the fluid flow process performs a stable trend, and the area of diffusion in the trunk remains generally consistent, and the flow in the permeable holes also shows a stable process.

When the structure is a right angle valve, the flow process of the right angle valve at different moments is shown below.
Figure 11. Velocity distribution of the right angle valve structure at different moments.

During the process of 0s to 0.3s, the fluid enters the right angle valve structure and fills the cavity of the valve quickly in Figure 11. Due to the characteristics of the right-angle valve structure, an obvious high-speed region can be seen to form near the bend, which is caused by the impact of the fluid. When it comes to 0.6s to 0.9s, the fluid gradually flows out of the right angle valve structure and enters the noise elimination trunk. The jet velocity released from the right angle valve is relatively lower and the jet area is relatively smaller, while the flow velocity near the permeable hole also gradually increases, but the overall velocity amplitude is small. During the process of 1.2s to 2.1s, it can be observed that the fluid flowing out from the right angle valve forms a certain impact on both the bottom and the side wall surface of the trunk, and leads to a certain increase in the velocity gradient near the permeable hole. As the calculation is carried out, it can be found that the fluid flow process also gradually represents a stable trend, and the area of diffusion in the trunk remains consistent.

Through the comparative observation, it can be revealed that the special structure of the right angle valve will lead to a more uniform flow of fluid inside the right angle valve, and a smaller impact on the jet on the valve, which makes the fluid enter the noise elimination trunk with a significantly lower fluid velocity and a relatively smaller impact on the wall of the noise elimination trunk. Due to the large volume of the noise elimination trunk, the kinetic energy has been attenuated to a large extent when the fluid flow passes through the permeable holes, which eventually leads to a slower flow rate into the noise monitoring area through the permeable holes.
In the case of the sea suction valve structure, the flow process represents a steady state when the calculation process reaches 100s, the maximum flow velocity in the 3-grid noise elimination trunk is 1.157m/s and the maximum flow velocity in the 1-grid noise elimination trunk is 1.166m/s, with a difference of 0.78%. In the case of the right angle valve structure, the flow process shows a steady state when the calculation process reaches 100s, the maximum flow velocity in the 3-grid noise elimination trunk is 0.965m/s and the maximum flow velocity in the 1-grid noise elimination trunk is 0.959m/s, with a difference of 0.62%. This indicates that the effect of 3-grid and 1-grid noise elimination trunk is not significant for the flow stability.

4.2. Near-field acoustic characteristics

To observe the pressure fluctuations and noise levels near the sea suction valves, several monitoring points are set up near the permeable holes. By collecting pressure data from the monitoring points and processing the data using the Fast Fourier Transform method, the time domain pressure is converted into the sound pressure level (SPL) in the frequency domain, which is used as a comprehensive evaluation of the noise. On this basis, the frequency spectrum of the sound pressure level at the near-field monitoring points is analysed.

![Figure 12. Comparison of SPL at monitoring points near permeable holes.](image)

As can be seen in Figure 12, the noise is mainly concentrated in the low frequency, while there is relatively small amplitude in the high frequency in the four conditions. In the range of 4.79-19.68Hz, the near field noise levels of the four cases vary in a complex manner. On the whole, the noise decibel values of sea suction valve and 3-grid trunk, the right angle valve and 3-grid trunk are slightly smaller, but the difference is not significant. When the frequency is greater than 19.68Hz, two peaks appear obviously in the sea suction valve with 1-grid and 3-grid trunk, and they are larger than the corresponding noise values of the right angle valve with 1-grid and 3-grid trunk. In general, the noise of the right angle valve structure is smaller than that of the sea suction valve structure in the low frequency range. And the noise impact brought by the 3-grid and 1-grid noise elimination trunk is not obvious.
Figure 13. Comparison of Curle contours in valve and 1-grid trunk.
The distribution of dipole noise sources is shown in Figure 13 and Figure 14. It can be revealed that the Curle surface sound power values are relatively small under both cases, which mainly concentrated near the valve wall. The Curle surface sound power values on the wall of the sea suction valve are larger than that on the wall of the right angle valve. From the Curle surface sound power analysis, the role of the noise elimination trunk is extremely obvious, the dipole noise on the wall of the noise elimination trunk is relatively small, which mainly concentrated on the wall of the valve structure.
Figure 15. Comparison of Proudman contours for sea suction valves with different trunks.

The quadrupole source distribution of the sea suction valve under different trunks is shown in Figure 15, from which it can be seen that the Proudman sound power value is very small and mainly concentrated in the internal flow channel area of the sea suction valve. It is mainly related to the internal flow turbulence energy distribution. As the fluid flows into the structure of the sea suction valve, it flows in the special cavity and causes jet impact on the wall, thus creating a local area with high turbulence energy inside the sea suction valve.

4.3. Far-field acoustic characteristics

In this paper, 19 far-field monitoring points distributed in a semicircle of 20m radius with the centre of the permeable hole as the origin are set up to study the far-field acoustic characteristics. The FW-H integral equation is calculated to obtain the noise at the monitoring points, and the sound pressure data at the far-field monitoring points are collected by turning on the FW-H solver after one passing cycle.

Figure 16. Directivity curve.

As can be seen in Figure 16, the directivity curves of far-field noise represent a semi-butterfly-shaped distribution for each case, and a relatively small value exists in the 120° direction. The total SPL of the right angle valve is smaller than that of the sea suction valve with 1-grid and 3-grid trunks. For the sea suction valve, the difference between the total SPL of 1-grid and 3-grid trunks is very
small, with an average difference of 0.3% and a maximum difference of 0.47%, which is 0.04Db. While the difference between the total SPL of 1-grid and 3-grid trunks for the right angle valve is also small, with an average difference of 1.5%.

5. Conclusion

Based on the numerical method of computational fluid dynamics, this paper conducts numerical simulations about the internal flow field and acoustic characteristics of the sea suction valve and the noise elimination trunk. By comparing and analyzing the effects of different noise elimination trunk and different sea suction valve structures on the flow field characteristics and acoustic features, the main conclusions are drawn as follows.

1. Under the conditions of sea suction valve structure and the right angle valve structure, the flow process represents a steady state when the calculation process reaches 100s, and the fluid velocity in the trunk differs by 0.78% and 0.62%, indicating that the depth of noise elimination trunk has little effect on the flow stability effect.

2. For the four cases of the right angle valve and the sea suction valve with 1-grid and 3-grid noise elimination trunk, the near-field noise is mainly concentrated in the low frequency, and the high frequency amplitude is relatively small. In the range of 4.79-19.68Hz, the noise decibel values of the sea suction valve with 3-grid trunk and the right angle valve with 3-grid trunk are slightly smaller, but the difference is not significant. When the frequency is greater than 19.68Hz, the two peaks of the sea suction valve with 1-grid and 3-grid trunk appear obviously greater than that of the right angle valve with 1-grid and 3-grid trunks. In the low frequency range, the noise of the right angle valve structure is smaller than that of the sea suction valve structure, and the noise effect brought by the 3-grid and 1-grid noise elimination trunk is smaller.

3. By comparing the analysis of broadband noise sources, it is found that the Curle surface sound power values are relatively small, while the values on the wall surface of the sea suction valve are larger than that on the wall surface of the right angle valve. The role of the noise elimination trunk is very obvious, because the dipole noise on the wall of the noise elimination trunk is relatively small, mainly concentrated on the wall of the valve structure.

4. The directivity curves reveal that the far-field noise directivity curves show a semi-butterfly-shaped distribution in each case, and there exists a relatively small value in the 120° direction. The total SPL of the right angle valve is smaller than that of the sea suction valve for both the 1-grid and 3-grid trunks.

Through the study of this paper, the following engineering optimization recommendations are obtained. When the fluid enters the noise elimination trunk, the flow stability is better with the right-angle valve structure, and the difference between the 1-grid and the 3-grid noise elimination trunk is small. The flow noise is the smallest when choosing the right angle valve structure, and the effect of the 1-grid and the 3-grid noise elimination trunk on the flow noise is not significant.

References

[1] Zhang W, Xie X, Zhu B, et al. Analysis of phase interaction and gas holdup in a multistage multiphase rotodynamic pump based on a modified Euler two-fluid model[J]. Renewable Energy, 2021, 164: 1496-1507.

[2] Zhang W, Zhu B, Yu Z. Characteristics of bubble motion and distribution in a multiphase rotodynamic pump[J]. Journal of Petroleum Science and Engineering, 2020, 193: 107435.

[3] Zhang L, Duan J, Da L, et al. Vibroacoustic radiation and propagation properties of slender cylindrical shell in uniform shallow sea[J]. Ocean Engineering, 2020, 195: 106659.

[4] Hu Z, Huang C, Huang Z, et al. A Method of Bending Shrinkage Groove on Vortex Suppression and Energy Improvement for a Hydrofoil with Tip Gap[J]. Processes, 2020, 8(10): 1299.

[5] Duan J, Zhang L, Da L, et al. A hybrid algorithm of underwater structure vibration and acoustic radiation-propagation in ocean acoustic channel[J]. International Journal of Naval Architecture and Ocean Engineering, 2020, 12: 680-690.
[6] Zhang W, Chen Z, Zhu B, et al. Pressure fluctuation and flow instability in S-shaped region of a reversible pump-turbine[J]. Renewable Energy, 2020, 154: 826-840.

[7] Duan J, Zhang L, Sun X, et al. An equivalent source CVIS method and its application in predicting structural vibration and acoustic radiation in ocean acoustic channel[J]. Ocean Engineering, 2021, 222: 108570.

[8] Huang Z, Huang Z, Fan H. Influence of C groove on energy performance and noise source of a NACA0009 hydrofoil with tip clearance[J]. Renewable Energy, 2020, 159: 726-735.

[9] Zhang J, Fan H, Zhang W, et al. Energy performance and flow characteristics of a multiphase pump with different tip clearance sizes[J]. Advances in Mechanical Engineering, 2019, 11(1): 1687814018823356.

[10] Fan H, Zhang J, Zhang W, et al. Multiparameter and multiobjective optimization design based on orthogonal method for mixed flow fan[J]. Energies, 2020, 13(11): 2819.

[11] Jiang S, Zhang J, Wu C, et al. Three dimensional numerical simulation of flow fields inside sea suction valve[J]. Chinese Journal of Ship Research, 2009, 4(2): 37-41.

[12] Lu Y, Zhang H, Pan X. Comparison between the simulations of flow-noise of a submarine-like body with four different turbulent models[J]. Chinese Journal of Hydrodynamics, 2008, 23(3): 348-355.

[13] Cui M, Tang K, Liu H. Optimization of the valve internal flow channel based on CFD approach[J]. Chinese Journal of Hydrodynamics, 2010, 25(4): 438-445.

[14] Bai Z, Duan C, Sun R, et al. Numerical simulation of flow fields inside sea suction valve and optimization of the flow channel [J]. Ship Science and Technology, 2016, 038(003):41-44,49.

[15] Zhang J, Zhang Q, Wang H, et al. Study on heat transfer performance of shaft seal in HTR-PM circulator. In the Proceedings of the International Conference on Nuclear Engineering (ICONE) 2019.27. The Japan Society of Mechanical Engineers, 2019: 1776.