Numerical Calculation of the Radiated Noise of Contra-rotating Propellers

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Abstract. Based on the hybrid methods of cavitation transient simulation of multiphase flow and the boundary element numerical acoustic calculation, the noise of contra-rotating propellers in states of cavitation and non-cavitation is calculated, the increase quantity of the noise spectrum level in cavitation relative to in non-cavitation condition is analyzed; the calculated noise value and the tested value are compared. The multiphase flow transient simulation includes three simulations: unsteady Reynolds-averaged Navier-Stokes method (URANS), scale adaptive simulation (SAS) and detached eddy simulation (DES). The testing result shows that the open water performance curve of propellers coincides well with the experimental result in the range of large range of feed coefficient. SAS presents a comparable ability with DES in capturing the pulsating pressure of cavitation and can respond well to the unsteady load noise. RANS (Reynolds-averaged Navier-Stokes) is appropriate for the low frequency noise. The calculating error of line spectrum cavitation volume pulsation 1 kHz is less than 4.23 dB, and the average error of spectrum level 1/3 Octave band is less than 1.83 dB in the frequency band of 1 kHz-3 kHz, and the predicted error of the total sound pressure level is less than 2.74 dB, And the attenuation coefficient of sound pressure level with is calculated by simulation, which can provide certain help for the design and the noise prediction of propellers.

1. Introduction
Propellers are the most important propulsion devices for ships and underwater weapons. Propellers running underwater will change the distribution of underwater velocity field and pressure field, which will produce strong radiated noise, and become the key target of underwater detection. Therefore, the cavitation performance and noise performance of propellers are always as attractive research topics [1]. It is found that if the noise level of propellers is reduced by 10 decibels, the detection range of sonar will be greatly reduced compared with the previous range. According to statistics, the detection range will be reduced by about 30%-50%. In the range of 5 kHz to 10 kHz, the detection range of sonar will decrease by 60%-70% [2, 3].

Propellers produce a kind of mixed noise, which has the characteristics of both mechanical noise and hydrodynamic noise. Ross D [3], Van Oossanan P [4], Tao Duchun [5] [6], Jiang Guojian [7], Etter P C [8], Kummert A [9], Lourens J G [10], Nielsen Ro [11], Parry A B [12] et al. have carried out many researches on the characteristics of noise signal, the modeling method and signal feature extraction.
method of propellers. Arveson P T [13], Wu Guoqing [14, 15] et al. made researches on noise recognition of ships, general framework, line spectrum analysis and extraction, line spectrum stability and uniqueness. Luo Jian [16, 17] et al. made researches on time domain of noise of ships and characteristic refactoring. Du Xuanmin [18] et al. studied the simulation technology of radiated noise of ships. Once cavitation of propellers occurs, cavitation noise becomes the most important radiated noise [19]. Uhlman [20], Yamasaki [21], Achkinadze [22, 23], Kim [24, 26], Xiong Ying [27], Hu Jian [2], Ye Jinming [28], Yang Qiongfang [29], Zeng Sai [30] and others conducted cavitation tests of propellers and predicted the performance of cavitation.

For the underwater vehicles, the front and rear blades of the contra-rotating propellers have opposite rotating directions with characteristics of high efficiency, which can recover rotating energy, and easy to reach torque balance. Therefore, based on the existing research and Navier-Stokes equation, the control model coupled by RANS/LES hybrid model and SST-SAS turbulence model is introduced in this paper, besides, Zwart-Gerber-Belamri cavitation model is selected, the acoustic module K-FWH equation in CFD software of noise performance of propellers is predicted and analyzed numerically, and the noise with and without cavitation for contra-rotating propellers is calculated, the characteristics of the sound pressure spectrum and sound power spectrum in different positions as well as the attenuation characteristic of noise affected by the distance are obtained.

2. Models

2.1. Control Model
Use a hybrid model, a simplified multiphase flow model, to calculate the cavitation flow of propellers, it gets local equilibrium between assumed phases in a short time scale [1], through introduction of the cavitation model to simulate the liquid evaporation, and the vapour condensation, this model is adopted in the mixed area. Ignore the slip of vapour-liquid interface and assume it as an isothermal process and the fluid micelle is a mixture of liquid, vapour and non-condensable gas [29], the control equation is:

\[
\frac{\partial \rho_m}{\partial \tau} + \frac{\partial \rho_m u_j}{\partial x_j} = S_j
\]

\[
\frac{\partial \rho_v}{\partial \tau} + \frac{\partial \rho_v u_j}{\partial x_j} = S_v
\]

\[
\frac{\partial \rho_g}{\partial \tau} + \frac{\partial \rho_g u_j}{\partial x_j} = 0
\]

\[
\frac{\partial P}{\partial \tau} + \frac{\partial \tau_{ij}}{\partial x_j} + \rho_n g_i
\]

The source term is the time conversion rate.

\[S_j = (\bar{m}_l + \bar{m}_v), \quad S_v = -(\bar{m}_l + \bar{m}_v)\]

The density of the mixture is defined by formula (5).

\[\rho_m = a_l \rho_l + a_v \rho_v + a_g \rho_g\]

\[a_l, a_v, a_g\] is the volume fraction of liquid phase, vapour phase and non-condensable gas, respectively and \[\rho_l, \rho_v, \rho_g\] is the density of liquid phase, vapour phase and non-condensable gas respectively.

Mass fraction: \[y_i = a_i \rho_i / \rho_m\]

2.2. Cavitation Model
Selecte Zwart-Gerber-Belamri cavitation model in case of ignoring the bubble’s surface tension and second derivative, the formula shown below can be derived by Rayleigh-Plesset equation [31, 32 and 33].

\[ R_v = F_{\text{vap}} \frac{3a_n (1 - a_v) \rho_v}{R_b} \sqrt{\frac{2P - P}{\rho_j}}, (P \leq P_v) \]  
\[ R_c = F_{\text{cond}} \frac{3a_n}{R_b} \sqrt{\frac{2P - P}{\rho_j}}, (P \geq P_t) \] 

In this formula, \( R_v \) represents the bubble growth process, \( R_c \) is the bubble collapse process, mass fraction \( a_n = 7.8 \times 10^{-4} \), volume fraction \( a_v = 1 \times 10^{-6} \), \( R_b \) is the initial value of radius of bubbles, \( R_b = 1.0 \times 10^{-6} \text{m} \), evaporation coefficient \( F_{\text{vap}} = 50 \), condensation coefficient \( F_{\text{cond}} = 0.01 \), \( P_v = P_{\text{sat}} + 0.5P_{\text{nmb}} \), \( P_{\text{nmb}} = 2pk/3 \).

### 2.3. Prediction Model of Noise

Ffowcs-Williams and Hawkings applied generalized function theory to derive the Lightill equation and sort out the famous FW-H equation [34]. Frances Antonio combined Kirchhoff formula and FW-H equation to derive the K-FWH (Kirchchho-Ffowcs Williams and Hawkings) equation:

The right end of the formula represents two area source term (monopole, dipole) and one volume source term (quadrupole). The monopole source is mainly the sound source generated by squeezing water periodically during the rotation of blades, the dipole source is mainly the sound source generated by the unsteady fluctuation on the surface of blades, and the quadrupole source is mainly the sound source by the turbulence pulsation in the fluid. Since the propeller operates at low Mach, the contribution of the source term of quadrupole is minimal, that is, the first item at the right end of the formula can be ignored.

According to Green's formula and coordinate transformation, the thickness noise component and the attached noise component can be obtained, which is corresponded to the monopole term and the dipole term.

\[ p'(x,t) = p_T'(x,t) + p_L'(x,t) \] 

In this formula:

\[ 4\pi p_T'(x,t) = \int_{r=\infty} \left[ \frac{\rho_v \dot{r}}{r(1 - M_T^2)} \right] dS + \int_{r=\infty} \left[ \frac{\rho_v \left( rM_T \dot{r} + M_T \left( M_T - M^2 \right) \right)}{r^2(1 - M_T^2)} \right] dS \] 

\[ 4\pi p_L'(x,t) = \frac{1}{c_0} \int_{i=\infty} \left[ \frac{l \dot{r}}{r(1 - M_T^2)} \right] dS + \int_{i=\infty} \left[ \frac{l - M_T M_i}{r^2(1 - M_T^2)} \right] dS \]

\[ + \frac{1}{c_0} \int_{i=\infty} \left[ \frac{l \left( rM_T \dot{r} + M_T \left( M_T - M^2 \right) \right)}{r^2(1 - M_T^2)} \right] dS \] 

\( M \) is the Mach number, \( M_T \) is the radial Mach number, \( l_i \) is the local force per unit area of \( i \). It can also be written as the following formula, which can be seen in [29, 35].

\[ p_T'(x,t) = \int_T \int_{A(r)} \rho v \frac{DG}{D\tau} dA(y) d\tau \] 
\[ p_L'(x,t) = \int_T \int_{A(r)} F_i \frac{DG}{D\tau} dA(y) d\tau \]
2.3.1. Law of Radiated Noise of Cavitation Volume. Assume the sheet cavitation is equivalent to a spherical cavitation, and the radiated sound pressure of the spherical cavitation is equivalent to the slowly varying component of the cavitation noise. The calculation of the area of the sheet cavitation is processed by summation, and then the cavitation test theory referred in [29, 31] is used to calculate the sound pressure of the slowly varying part of cavitation, the formula is as follows.

\[
p'(r) = \frac{\rho_c}{4\pi r} \frac{d^2 V_c}{dt^2}
\]  

\(V_c\) : the volume of cavitation;
\(r\) : the distance from the measurement point to the sound source centre;
\(S_i = \sum a_i S_i, i = 1, 2 \cdots, N\)  

\(N\) : the grid number to calculate the surface of propellers;
\(a_i\) : the gas volume fraction of the corresponding grid;
\(S_i\) : the area of grid, namely, the unsteady cavitation area of propellers.

\[
\frac{d^2 V_c}{dt^2} = 6l_c \left( \frac{dl_c}{dt} \right) + 2l_c^2 \frac{d^2 l_c}{dt^2}
\]  

\(l_c\) : the characteristic length of cavitation.

Take the equation (14-16) into equation (13) to obtain the sound pressure of the slowly varying component of radiated noise of cavitation of propellers [36, 37].

\[
p'(r) = \frac{\rho_c}{4\pi r} \left[ 6l_c \left( \frac{dl_c}{dt} \right) + 2l_c^2 \frac{d^2 l_c}{dt^2} \right]
\]  

2.3.2. Law of the Noise Radiation Frequency of Contra-rotating Propellers. There are four characteristic frequencies contained in the radiation noise spectrum of contra-rotating propellers: shaft frequency \(\Omega_{APF}\), front blade frequency \(\Omega_{BPF}\) and its harmonics, rear blade frequency \(\Omega_{BPF}\) and its harmonic wave and the interference frequency \(\Omega_{pBPF} + q\Omega_{BPF}\). These four characteristic frequencies are expressed in a unified relation [30]:

Or in another form: interference frequency \((n_i B_i \Omega_{BPF} + n_i B_i \Omega_{BPF})\); the harmonic wave frequency of the flow field \(m_i B_i \Omega_{BPF}\); \(m_i B_i \Omega_{BPF}\); The fundamental frequency \(\Omega_{BPF}\), \(\Omega_{BPF}\).  

\[
f_{i,j} = m_i B_i \Omega_{BPF} + n_i B_i \Omega_{BPF} \left(1 + \frac{\Omega_{BPF}}{\Omega_{j}}\right) + p\Omega_{i} + s\Omega_{j}
\]  

In the formula, take the order as an integer. \(i, j = 1, 2\) The number of the front and rear blades is \(B_1\), \(B_2\) and their rotation speed is \(\Omega_1\) and \(\Omega_2\) respectively.

3. Turbulence Model
Select the hybrid model RANS/LES coupled by SST-SAS [38] and turbulence model [39], DES [40] is a modification of RANS model; when it is small enough being capable to calculate in LES region, switch it by the subgrid point scale. The region which is close to the solid boundary area or the area where the eddy length scale is less than the maximum lattice scale can be solved by RANS. As the eddy length exceeds the lattice scale, LES simulation is adopted to simulate the flow in vast separation zone.
SST-SAS transport model:

\[
\frac{\partial \rho k}{\partial t} + \frac{\partial}{\partial x_i} (\rho u_i k) = G_k - \rho c^k_\mu k \omega + \frac{\partial}{\partial x_j} \left[ \left( \mu + \frac{\mu_k}{\sigma_k} \right) \frac{\partial k}{\partial x_j} \right] \tag{19}
\]

\[
\frac{\partial \rho \omega}{\partial t} + \frac{\partial}{\partial x_i} (\rho u_i \omega) = \alpha \omega k \rho - \rho \beta \omega^2 + Q_{SAS} + \frac{\partial}{\partial x_j} \left[ \left( \mu + \frac{\mu_\omega}{\sigma_\omega} \right) \frac{\partial \omega}{\partial x_j} \right] + (1 - F_i) \frac{2 \rho}{\sigma_{\omega,2}} \frac{1}{\alpha} \frac{\partial k}{\partial x_j} \frac{\partial \omega}{\partial x_j} \tag{20}
\]

\[
F_i = \tanh \left( \min \left[ \max \left( \frac{\sqrt{k}}{0.09 \omega y}, \frac{500 \mu}{\rho y^2 \omega} \right), \frac{4 \rho k}{\sigma_{\omega,2} D_{\omega,1}^\gamma} \right] \right) \tag{21}
\]

\[
D_{\omega} = \max \left[ 2 \rho \frac{1}{\sigma_{\omega,2}} \frac{1}{\alpha} \frac{\partial k}{\partial x_j} \frac{\partial \omega}{\partial x_j}, 10^{-10} \right] \tag{22}
\]

\( \rho \) is the density of the mixture, \( k \) is the kinetic energy of the turbulence, \( \omega \) the frequency of the turbulence eddy, \( G_k \) the turbulence term, \( \mu_k \) is the viscosity of the turbulence, \( c^k_\mu = 0.09 \), \( \sigma_{k,1} = 1.176 \), \( \sigma_{\omega,1} = 2.0 \), \( \sigma_{k,2} = 1.0 \), \( \sigma_{\omega,2} = 1.168 \), \( \alpha_i = 0.31 \), \( \beta_i = 0.075 \), \( \beta_{i,2} = 0.0828 \).

\[
\mu_k = \frac{\rho k}{\omega} \max \left[ \frac{1}{\alpha}, \frac{SF_k}{\alpha_i \omega} \right] \tag{23}
\]

\( \alpha^* \): Low Reynolds number adjustment coefficient

\[
F_2 = \tanh \left( \max \left[ \frac{2 \sqrt{k}}{0.09 \omega y}, \frac{500 \mu}{\rho y^2 \omega} \right] \right) \tag{24}
\]

\( y \): The distance to the next camber

\[
Q_{SAS} = \max \left[ \rho \eta S^2 \left( \frac{L}{L_{EF}} \right)^2 - C \cdot \frac{2 \rho k}{\sigma_{\phi}} \max \left[ \frac{1}{\omega^2} \frac{\partial \omega}{\partial x_j} \frac{\partial k}{\partial x_j}, \frac{1}{k^2} \frac{\partial k}{\partial x_j} \right] \right] \tag{25}
\]

Where, \( \eta_2 = 3.51 \), \( S \) is the strain, \( C = 2 \), \( \sigma_{\phi} = 2/3 \), \( L = \sqrt{k} / \left( c^k_{\mu} \cdot \omega \right) \) the length scale of the turbulence, \( L_{EF} \) is the length scale of Von Karman, \( \Delta = \Omega \cdot \sigma_{c^k_{\mu}} \), \( \kappa = 0.41 \).

\[
L_{EF} = \max \left[ \frac{\kappa' U'}{U}, C_{y_s} \frac{\kappa \eta_2}{(\beta / c^k_{\mu}) \cdot \Delta} \right] \tag{26}
\]

In Meter’s [40] DES/SST turbulence model, \( F_{SST} = 0 \), \( F_1 \), \( F_2 \) are the mixed functions of BSL/SST model [41, 42].

\[
Y_k = \rho \beta^* k \omega F_{DES} \tag{27}
\]

\[
F_{DES} = \max \left[ \frac{L_k}{C_{des} \Delta_{max}} (1 - F_{SST}), 1 \right] \tag{28}
\]
\[ C_{des} = 0.61 \]  
\[ L_f : \text{the turbulence length scale in the dissipative term of k transport equation;} \]

Convert \( L_f \) to the DES length scale \( \tilde{L} = \min(L_f, C_{des} \Lambda_{max}) \).

In order to improve the stability and convergence time of calculation, the Scalable wall function is adopted, which aims to force the use of logarithmic law by combining the standard wall method. Implement \( \max(y^*, 11.06) \) by a limiter.

4. Model Calculation and Parameter Setting

4.1. Verification and Analysis of Hydrodynamic Performance

Feed coefficient \( J = \frac{V}{nD} \):

- \( n \): Rotating speed of propellers;
- \( V \): advance;
- \( D \): diameter of propellers.

Cavitation number:

\[ \sigma_n = \frac{P - P_v}{\frac{1}{2} \rho n^2 D^2} = \frac{P_h + H_{sh} \rho g}{\frac{1}{2} \rho n^2 D^2} - P_v \]

\( P_h \): the atmospheric pressure on the free surface;
\( P_v \): the saturation vapour pressure;
\( H_{sh} \): the submergence depth of the propeller shaft.

Under different feed coefficients, thrust coefficient \( K_T = \frac{T}{\rho n^2 D^3} \) and torque coefficient \( K_Q = \frac{Q}{\rho n^2 D^5} \).

\( T \): axial thrust;
\( Q \): braking torque.

![Computational domain and the boundary setting of contra-rotating propellers](image-url)
The computational domain consists of two parts, rotating domain and stationary domain of the contra-rotating propellers, the rotation domain adopts tetrahedral grid, and stationary domain using hexahedral grid. The radial diameter of the inner rotation domain is 1.2 times of the diameter of the front blades, the radial diameter of the outer domain is 7 times of the diameter of the front blades, and the inlet and outlet of the outer domain are 5 times and 10 times of the diameter of the front blades respectively. Inlet is used as the boundary condition and outlet is set as the pressure outlet. As shown in figure 2 below. The slip interface is set between the rotation part of the front and rear blades. There are about 2.92 million rotating grid nodes in front blades and 2.51 million rotating grid nodes in rear blades. The total number of grid nodes in the stationary domain is about 650,000.

The results of simulation of thrust and torque coefficients are basically consistent with the variation trend of the test results. Except for some cases far away from the operating point, the error of thrust coefficient is within 3.6% and the error of torque coefficient is within 4.5%, which meets the
requirements of the calculation expectation. The main reasons and influencing factors for this situation are the difference between the roughness of the surface of blades and the actual situation, and the difference caused by the inconsistencies of the grid nodes of the rotation interface between the front and rear blades.

![Figure 5. Open-water performance curves of contra-rotating propellers](image)

Acoustic simulation model is set up as shown in Figure 6 and Figure 7. P1 to P12 are the set monitoring points, P1, P2, P3, P6, P7 and P8 points is 1 times of the diameter from the centre of the sound source, P4 is in the middle of the front and rear blades, located at the largest diameter of the front blades. The distance is 1 times of diameter between P5, P9, P10, P11 and P12 respectively. The experimental feed coefficient is set as $J=0.5$, 0.7 and 0.9 under situation of no cavitation. In the case of cavitation, the feed coefficient $J=0.7$ and the number of cavitations $\sigma_n = 1.92$.

The calculation is set as RANS model firstly, when the calculation is stable, the calculation is transferred to SAS and DES turbulence model, and the acoustic module is added after the calculation process is stable so as to ensure the accuracy of the calculation results.

![Figure 6. Locations of the calculation points in the circumferential direction of the sound field](image)
4.2. Results and Analysis of Numerical Calculation

According to the analysis of sound pressure spectrum characteristics, it can be seen that the changing laws of the sound pressure levels of the monitoring points in the circumference of propellers are similar and the values of sound pressure level are basically the same; the changing laws of the sound pressure levels of the monitoring points in the rear part of propellers are similar and the sound pressure level values decrease continuously according to the distance.

4.3. Attenuation Characteristics of Noise

According to the set monitoring points, the mean values of sound pressure levels on each frequency were taken and the sound pressure levels generated by the propellers were monitored with the reference sound pressure of 10^-6Pa. The axial and radial attenuation characteristics were shown in Figure 10 and
Figure 11. It can be seen from the Figure 10, with the increase of feed coefficient, the average sound pressure level also increases, and the growth amplitude becomes bigger and bigger; with the increase of axial distance deviation from the centre of the propeller, the sound pressure level decreases. At the same time, it can be seen that the sound pressure level decreases with the increase of the velocity of flow. Figure 11 also shows that in the radial direction, with the increase of distance deviation from the centre of the propeller, the sound pressure level gradually decreases, which is similar to the trend of the change amplitude in the axial direction. In addition, it is obvious that the sound pressure level in the axial direction is larger than that in the radial direction at the same position from the centre of the sound source.

4.4. Velocity Influence on the Frequency Spectrum

Figure 12 is the sound pressure level diagram of P1 monitoring point under three different feed coefficients (the reference sound pressure is 10⁻⁶Pa). It can be clearly seen in the figure that with the increase of the feed coefficient, the corresponding total sound pressure value also increases gradually, and the amplitude of the change also increases. This is because at higher speed, the area around the fast-spinning propeller has stronger turbulence pulsation, therefore greater pressure fluctuation occurs.
5. Conclusion

Three methods RANS, SAS and DES are introduced.

1. In the uniform wake field, the hydrodynamic performance and the maximum error of thrust coefficient can be controlled within 5%, the maximum error of torque coefficient within 7.2%. In the non-uniform wake field, the average error of the above two coefficients is about 7% and 7.5% respectively compared with the actual test.

2. The pressure distribution on the surface of blades coincides well with the test, and the general trend of the predicted result is consistent with the test trend. Within the frequency band of 1 kHz-3 kHz, the average spectral level at 1/3Octave centre frequency was predicted to be less than 1.83dB, and the prediction error of the total sound pressure level was less than 2.74dB.

3. Compared with RANS method, DES method captures more fine flow field structure, and DES method makes up for the deficiency of RANS method. The accuracy of DES (detached eddy simulation) and SAS (scale adaptive simulation) for cavitation noise of contra-rotating propellers is basically the same, both can meet the prediction requirements of noise.

References

[1] Wang Chao, Numerical Prediction of Hydrodynamic Performance, Cavitation and Noise Performance of Propellers, Doctoral dissertation, Harbin Engineering University, 2010.

[2] Hu Jian. Research on Cavitation Performance of Propellers and Design of Low-Noise Propellers, D. Harbin: Harbin Engineering University, 2006.

[3] Ross D. Mechanics of Underwater Noise. third ed., Los Altos: Peninsula Publishing, 1983.253-285.
[4] Van Oossanen P. Theoretical Prediction of Cavitation of Propellers J. Marine Technology Society Journal, 1997, 14 (4): 391-409.
[5] Tao Duchun, Cavitation Noise Spectrum of Propellers. J. Acta Acoustica, 1982, 7 (6): 344-350.
[6] Tao D C, A Study on Ship-Radiated Noise Rhythms (I) -- Mathematical Model and Power Spectrum Density. Chinese J Acoust, 1985, 4: 244-256.
[7] Jiang Guojian, Lin Jianheng, Ma Jie et al. Mathematical Model of Cavitation Noise of ship propellers. J. Acta acoustica sinica, 1998, 23 (5): 401-408.
[8] Etter P C, Underwater Acoustic Modeling and Simulation, third ed., New York: Spon Press, 2003. 225-229.
[9] Kummert A, Fuzzy Technology Implemented in Sonar System, IEEE J Oceanic Eng, 1993, 18: 483-490.
[10] Lourens J G, du Preez J A, Passive sonar ML Estimator for Ship Propeller Speed, IEEE J Ocean Eng, 1998, 23: 448-453.
[11] Nielsen R O, Sonar Signal Analysis. Boston: Artech House, 1991. 95-140.
[12] Parry A B, Prediction of Counter-rotation Propeller Noise, Strathclyde University, UK, 1989.
[13] Arveson P T, Vendittis D J. Radiated Noise Characteristic of a Modern Cargo Ship, J. Journal of the Acoustical Society of America, 2000, 107 (1): 118-129.
[14] Wu Guoqing, et al. Ship Noise Identification (I) -- General Framework, Line Spectrum Analysis and Feature Extraction, J. Acta Acoustics, 1998, 23 (5): 394-400.
[15] Wu Guoqing et al. Ship noise identification (II) -- Stability and Uniqueness of Line Spectrum, J. Acta Acoustics, 1999, 24 (1): 6-11.
[16] Luo Jian, Xiang Jinglin, Simulation of Continuous Noise Process, J. Acta Acoustics, Vol 22, No. 6, 1997.
[17] Luo Jian, Time-frequency Reconstruction of Ship Radiated Noise (master's thesis), Northwestern Polytechnical University, 1996.
[18] Du Xuanmin, Ji Zhanghao. Research on the Simulation Technology of Ship Radiated Noise, Acoustic Technology, 1999, 18 (1): 10-14.
[19] Knapp, R.T., et c. Cavitation and Damage[M]. China Water Press, 1981.
[20] Uhlman J S, The Surface singularity Method Applied to Partially Cavitating Hydrofoils, [J], J. S. R, 1987, 31 (2).
[21] Yamazaki, H., Ikehata, M. A Surface Vortex Lattice Method for Calculating Performances of Non-or Super-Cavitating propellers[A]. 20th Symposium on Naval Hydrodynamics[C]. August, 1994.
[22] Achkinadze A S, Fridman G M, Artificial Variation Problems Method for Three-dimensional Lifting Cavity Flow [C], 20th Symposium on Naval Hydrodynamics, Santa Barbara, U.S.A, Aug 1994: 2121-222P.
[23] Achkinadze A S, Fridman GM, A New Algorithm for Numerical Investigation of Unsteady Cavitating Screw Propeller with Use of Variational Approach [C], Third International Symposium on Cavitation, Grenoble, France, April 1998: 279-284P.
[24] Kim Y G, Lee C S, Surface Panel Method for Prediction of Flow around a 3-D steady or Unsteady Cavitating Hydrofoil [A], The Second International Symposium on Cavitation [C], 1994.
[25] Kim Y G, Lee C S, Super-Cavitating Flow Problems about 2-D Symmetric Strut [J], Journal of the Society of Naval Architects of Korea, 1990, 27 (4).
[26] Kim Y G, Lee C S, Lee J T, A Potential-Based Panel Method for the Analysis of A 2-D Super-Cavitating Hydrofoil[J], Transactions of the Society of Naval Architects of Korea, 1991, 28 (2).
[27] Xiong Ying, Numerical and Experimental Study on the Cavitation and Pulsating Pressure of Propellers in Non-uniform Flow Field, D. Doctoral dissertation in Wuhan University of Technology, 2002.
[28] Ye Jinming, Numerical Method and Model Test for Hydrodynamic Performance and Cavitation Prediction of Propeller, D. Doctoral Dissertation in Engineering, Naval University of Engineering, 2008.
[29] Yang Qiongfang, Wang Yongsheng, Zhang Zhihong, et al., J. Determination of Primary Cavitation of Rotating Propeller in Wake Field and Prediction and Verification of Radiated Noise. Acta Acoustica, 2014, 39 (5) 589-604.

[30] Zeng Sai, Du Xuanmin, Fan Wei, Analysis and Numerical Study of Line Spectrum Noise of Underwater Non-Cavitation Noise of Contra-Rotating Propellers, Journal of ordnance J. 2015,36 (6) 1052-1060.

[31] Sheng Lijun et al. Comparative Study on Cavitation Model in Cavitation Flow Simulation of Francis Turbine, J. Water Conservancy and Hydropower Technology, 2016.47 (1). 90-93.

[32] Xiang Min, Simulation Study on Cavitation Flow of Hypercavitation Vehicle Ventilation, D. National University of Defense Science and Technology, 2011.

[33] Wang Baiqiu, Numerical Calculation of Unsteady Cavitation Flow Field of Underwater High-Speed Vehicle, D. Harbin Institute of Technology, 2013.

[34] Ffcowcs J E, Hawkings D L, Sound generated by turbulence and surface in arbitrary motion, J. Philosophical Transaction of the Poyal Society of London, 1969, A264.

[35] Su Yumin, Dou Fengxiang, Liu Yebao, Cui Tong. Study on Cavitation Noise of Propeller, Journal of Wuhan University of Technology [Traffic Science and Engineering] [J]. 2013, 37 (5); 895-899.

[36] Pereiar F, Avellan F, Dupont P. Prediction of Cavitation Erosion: An Energy Approach, Journal of Engineering, 1998; 120 (4):719-727.

[37] Pereiar F, Salvatore F, Felice F det al. Experimental and Numerical Investigation of the Cavitation Pattern on a Marine Propeller. 24th Symposium on Naval Hydrodynamics, office of Naval Research, Fukuoka, Japan,2002.

[38] F.Menter and Y. Egorov, The Scale-Adaptive Simulation Method for Unsteady Turbulent Flow Predictions. Part1: Theory and Model Description, Journal Flow Turbulence and Combustion, 8.113-138.2010.

[39] Egorov Y, Menter FR, Development and Application of SST-SAS Turbulence model in the DESIBER Project, Second Symposium on Hybrid RANS-LES Methods, Corfu, Greece, 2007.

[40] F. R. Menter, M. Kuntz, and R. Langtry, Ten Years of Experience with the SST Turbulence Model, In K. Hanjalic, Y. Nagano, and M. Tummers, editors Turbulence, Heat and Mass Transfer.4. Begell House Inc., 625–632.2003.

[41] M.S.Gritskevich, A.V.Garbaruk, J.Schutze, F.R. Menter, Development of DDES and IDDES Formulations for the k-ω Shear Stress Transport Model, Flow, Turbulence and Combustion, 88(3).431–449.2012.

[42] P.R.Spalart, S. Deck, M.L.Shur, K.D.Squires, M.K.Strelets, and A. Travin. A New Version of Detached-Eddy Simulation, Resistant to Ambiguous Grid Densities,Theoretical and Computational Fluid Dynamics. 20.181–195.2006.