Numerical Prediction of the Hydrofoil Noise

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Abstract. Using the improved Sauer cavitation model and K-FWH acoustic model proposed by Yang Qiongfang to numerically calculate the unsteady cavitation flow field of NACA0015 three-dimensional hydrofoil, the noise of the three-dimensional hydrofoil was calculated, and the cavitation process and cavitation noise of the hydrofoil were numerically predicted. The results demonstrate that the hydrofoil cavitation shows distinctive characteristics of pulsation and periodicity. The main cause of formation and detachment of cavitation bubbles is the reverse jet nearby the hydrofoil wall due to eddies. By analyzing the sound pressure pulsation characteristics of each monitoring point, it can be concluded that the noise transmission in the leading edge of the hydrofoil is consistent with the direction of the mainstream, no reverse transmission. In the development process of cavitation, the noise signals in cavitation area tend to be superimposed downstream. When the signals transmit to the flowing area at the trailing edge of the hydrofoil, they gradually attenuate until being exhausted.

Keywords: Hydrofoil; cavitation; noise; numerical prediction.

1. Introduction

Noise can be divided into cavitation one and non-cavitation one, which depends on the hydrofoil follows with cavitation or not, if cavitation occurs, the noise will have obvious change.

Cavitation is a phenomenon of bubbles produced in liquid. Cavitation noise appears after the formation and collapse of bubbles. It generally occurs at an interface with relative movement between a fluid and a solid \cite{1}. Cavitation flow almost contains all complicated flowing phenomena: turbulence, multiphase flow, phase transition, compressible and unsteady characteristics, etc. \cite{2-3}. In the field of underwater weapons, cavitation noise is a critical technology to be solved in the development of new submarines and torpedoes \cite{4}. Cavitation development takes on several different forms: inception cavitation, sheet cavitation, cavitation cloud and super-cavitation \cite{5}. When cavitation develops into a certain stage, bubbles will collapse or detach, which may cause strong noise, oscillation or cavitation erosion \cite{6}.

Scholars at home and abroad have done a lot of theoretical and experimental research on the hydrofoil and acoustic radiation. Kjedlsen and Arndt et al. \cite{7} conducted experimental research on NACA0015 hydrofoil. Leroux et al. \cite{8} conducted an experimental study on cavitation development of NACA66 a single hydrofoil surface. Zhang Bo \cite{9-10} et al. conducted time-frequency analysis on the unsteady
dynamic characteristics of the cavitation around the hydrofoil. Chao Tsung and Chahine et al. calculated the acoustic signals of the three-dimensional hydrofoil eddy bubbles development under different cavitation numbers. Fuji [11] et al. studied the influence of the hydrofoil geometry on the cavitation dynamic characteristics. Huang Jingquan [12], Qi Dingman [13-14], Pu Zhongqi [15] et al carried out theoretical and numerical studies on the cavitation noise. Lyamshev [16], Morozov [17], Boguslavskii [18] et al. established a cavitation noise model on bubble groups by using statistical method. Chahine [19], D'Agostinol [20], Omta [21] et al. also established a cavitation noise model about bubble groups successively.

In recent years, numerical simulation has become a powerful tool to study computational fluid dynamics (CFD) on the fluid movement. At present, the numerical calculation and solution of cavitation flowing are mostly based on Navier-Stokes equations, which can be divided into two categories: one is an interface tracing method on a single phase flow, and the other is a uniform hybrid flow model. In the second type -- the cavitation flow model, based on transport equation, is applied more extensively and deeply, it assumes the mass or the volume of vapor phase as a transport item to establish a corresponding transport equation, which is more conducive for numerical calculation. In view of the actual working conditions of the hydrofoil, methods as shown below are always used to calculate the turbulence: Direct Simulation (DNS), Reynolds Average Method (RANS), Large Eddy Simulation (LES), and Hybrid Turbulence Model.

In order to illuminate basic characteristics of the cavitation noise of the hydrofoil, the improved Sauer cavitation model with K-FWH acoustic model proposed Yang Qiongfang [23-24] was applied in this paper, meanwhile, the hydrodynamic relationship between the hydrofoil and the mechanism of cavitation and cavitation noise was studied, the hydrofoil noise was calculated, and the process of cavitation and cavitation noise of the hydrofoil were analyzed in detail, which has great practical significance in reduction and inhibition of the cavitation noise.

2. Mathematical model

Continuous equations of fluid movement:

Mass equation:

$$\frac{\partial \rho_m}{\partial t} + \nabla \cdot (\rho_m \mathbf{u}) = 0$$  (1)

Momentum equation:

$$\frac{\partial \rho_m \mathbf{u}}{\partial t} + \nabla \cdot (\rho_m \mathbf{u} \mathbf{u}) = -\nabla p + \nabla \cdot \mathbf{\tau} + S_m$$  (2)

Where: \( \tau = \mu \left( \nabla \mathbf{u} + (\nabla \mathbf{u})^T - \frac{2}{3} \delta \nabla \cdot \mathbf{u} \right) \)

The mixture density is defined by formula:

$$\rho_m = a_l \rho_l + a_v \rho_v + a_g \rho_g$$  (3)

\( a_l \), \( a_v \), \( a_g \) are the volume fractions in liquid phase, vapor phase and non-condensable gas respectively; \( \rho_l \), \( \rho_v \), \( \rho_g \) are the densities in liquid phase, vapor phase and non-condensable gas respectively.

Mass fraction is defined by:
3. Cavitation model
Using the improved Sauer cavitation model proposed by Yang Qiongfang [23-24] as the cavitation model.

\[ \dot{m} = \frac{C_{\text{prod}} 3a_x (1 - a_x) \rho_v}{R_B} \sqrt{\frac{2|P_v - P|}{3 \rho_i}} \text{sign}(P_v - P) \]  

(5)

\[ \dot{m} = \frac{C_{\text{dest}} 3a_x \rho_v}{R_B} \sqrt{\frac{2|P_v - P|}{3 \rho_i}} \text{sign}(P_v - P) \]  

(6)

Where \( \dot{m} \) define the evaporation and condensation processes of vapor respectively, the mass fraction \( a_x = 7.8 \times 10^{-4} \), volume fraction \( a_v = 1 \times 10^{-6} \), \( R_B \) the initial value of bubble radius, \( R_B = 1.0 \times 10^{-6} \) m, evaporation coefficient \( C_{\text{prod}} = 50 \), condensation coefficient, \( C_{\text{dest}} = 0.01 \), \( P_v = P_{\text{sat}} + 0.5P_{\text{turb}}, P_{\text{turb}} = 2\rho k / 3 \).

4. The Large Eddy Simulation Model (LES)
A filtered variable is denoted in the following by an overbar and is defined by:

\[ \overline{\Phi}(x) = \frac{1}{V} \int \Phi(x') G(x; x') dx' \lim_{\delta x \to 0} \]  

(7)

Where \( D \) is the fluid domain, and \( G \) is the filter function that determines the scale of the resolved eddies.

The unresolved part of a quantity \( \Phi \) is defined by: \( \Phi' = \Phi - \overline{\Phi} \) and \( \Phi' \neq 0 \).

The discretization of the spatial domain into finite control volumes implicitly provides the filtering operation:

\[ \overline{\Phi}(x) = \int \Phi(x') dx', x' \in V \]  

(8)

Where \( V \) is the control volume. The filter function \( G(x; x') \) implied here is then

\[ G(x; x') = \begin{cases} 
1 / V, x' \in V \\
0, \text{ otherwise}
\end{cases} \]  

(9)

Filtering the Navier-Stokes equations leads to additional unknown quantities. The filtered momentum equation can be written in the following way:

\[ \frac{\partial}{\partial t} (\overline{\rho U_i}) + \frac{\partial}{\partial x_j} (\overline{\rho U_i U_j}) = - \frac{\partial \overline{\rho}}{\partial x_j} + \frac{\partial}{\partial x_j} \left[ \mu \left( \frac{\partial \overline{U_i}}{\partial x_j} + \frac{\partial \overline{U_j}}{\partial x_i} \right) \right] + \frac{\partial \tau_{ij}}{\partial x_j} \]  

(10)

Where \( \tau_{ij} \) denotes the subgrid-scale stress. It includes the effect of the small scales and it is defined by
\[
\tau_{ij} - \frac{1}{3} \delta_{ij} \tau_{kk} = 2 \mu_{sgs} S_{ij} S_{ij} = \frac{1}{2} \left( \frac{\partial \bar{U}_i}{\partial x_j} + \frac{\partial \bar{U}_j}{\partial x_i} \right)
\]

(11)

Where the eddy viscosity \( \mu_{sgs} \) represents all turbulent scales, the subgrid-scale viscosity only represents the small scales.

It should be noted that the isotropic part of \( \tau_{kk} \) is not modeled, but added to the filtered static pressure.

Three models are available to provide the subgrid-scale (SGS) viscosity \( \mu_{sgs} \).

Subgrid-scale Models WALE Mode The wall-adapted local eddy-viscosity model [25] is formulated local and uses the following equation to compute the eddy-viscosity:

\[
\mu_{sgs} = \rho C_w \Delta^2 \left( \frac{S^d_{ij} S^d_{ij}}{(S_{ij} S_{ij})^{5/2} + (S_{ij} S_{ij})^{5/4}} \right)
\]

(12)

\[
L_s = C_w \Delta = \min(\kappa d, C_w V^{1/3})
\]

(13)

Where \( \kappa \) is the vonKármán constant, \( d \) is the distance to the closest wall. \( C_w = 0.325 \);

Where \( S^d_{ij} \) denotes the trace less symmetric part of the square of the velocity gradient tensor:

\[
S^d_{ij} = \frac{1}{2} \left( g_{ij}^2 + g_{ji}^2 \right) - \frac{1}{3} \delta_{ij} x^2
\]

(14)

And where \( g^2_{ij} = g_{ik} g_{kj} \), \( g_{ij}^2 = \partial \bar{U}_i / \partial x_j \) and \( \delta_{ij} \) are the Kronecker symbol. The tensor \( S^d_{ij} \) can be rewritten in terms of the strain-rate and vorticity tensors in the following way:

\[
S^d_{ij} = S_{ik} S_{kj} + \Omega_{ik} \Omega_{kj} - \frac{1}{3} \delta_{ij} (\bar{S}_{mn} \bar{S}_{mn} - \bar{\Omega}_{mn} \bar{\Omega}_{mn})
\]

(15)

Where the vorticity tensor \( \bar{\Omega}_{ij} \) is given by:

\[
\bar{\Omega}_{ij} = \frac{1}{2} \left( \frac{\partial \bar{U}_i}{\partial x_j} - \frac{\partial \bar{U}_j}{\partial x_i} \right)
\]

(16)

The main advantages of WALE model are the capability to reproduce the laminar to turbulent transition and the design of the model to return the correct wall-asymptotic \( y^+ \)-variation of the SGS viscosity.

Use hybrid length-scale to calculate the eddy-viscosity in Wmles model.

\[
v_i = \min[(kd_w)^2, (C_{Smag} \Delta)^2] \cdot \left[ 1 - \exp \left( -\left( y^+ / 25 \right)^3 \right) \right]
\]

(17)

Where is \( d_w \) the wall distance, \( S \) is the strain rate, \( \kappa=0.41 \) and \( C_{Smag} = 0.2 \) are constants, and \( y^+ \) is the normal to the wall inner scaling. The LES model is based on a modified grid scale to account for the grid anisotropies in wall-modeled flows: \( \Delta = \min \left( \max \left( C_w \cdot d_w, C_w \cdot h_{\text{max}}, h_{wn} \right), h_{wr} \right) \)

Here, \( h_{\text{max}} \) is the maximum edge length for a rectilinear hexahedral cell (for other cell types and/or conditions an extension of this concept is used). \( h_{wn} \) is the wall-normal grid spacing, and \( C_w \) is a constant.
5. Noise prediction model

Ffowcs-Williams and Hawkings applied generalized function theory to derive the Lightill equation and sorted out the well-known FW-H equation [26]. Combining with Kirchhoff formula and FW-H equation, Frances and Antonio derived K-FWH (Kirchhoff - Ffowcs Williams and Hawkings) equation:

\[
\frac{1}{c_0^2} \frac{\partial p'}{\partial t'} - \nabla \cdot \mathbf{v}' = \frac{\partial}{\partial x_j} \left[ (T_0 H(f)) - \frac{\partial}{\partial x_i} \left[ (p_0 n_i + p u_i - v_i) \delta(f) \right] + \frac{\partial}{\partial t} \left[ (p_0 v_i + p(u_i - v_i)) \delta(f) \right] \right]
\]

(18)

The right side of formula denotes two area source terms (monopole, dipole) and one individual volume source term (quadrupole). The formula consists of a volume and a surface integral polynomials. The surface integral polynomial shows contributions to noise because of the monopole source, dipole source and a part of quadrupole source, while the volume integral shows contribution from the quadrupole outside of the control surface.

Corresponding monopole, \( p_T'(x,t) \) denotes the sound pressure caused by thickness. Corresponding dipole, \( p_L'(x,t) \) is the sound pressure caused by load. The formula is as defined by:

\[
4 \pi p_T'(x,t) = \int_{r=0}^r \left[ \frac{\rho_0 v_0}{r(1-M_s)^2} \right] dS + \int_{r=0}^r \left[ \frac{\rho_0 v_0}{r^2 (1-M_s)^3} \left( r^n f_1 + c_0 (M_t - M_s^3) \right) \right] dS
\]

(19)

\[
4 \pi p_L'(x,t) = \int_{r=0}^r \left[ \frac{l_1 f_1}{r(1-M_s)^2} \right] dS + \int_{r=0}^r \left[ \frac{l_1 - l_2 M_s}{r^2 (1-M_s)^3} \right] dS + \int_{r=0}^r \left[ \frac{l_1 f_1 + c_0 (M_t - M_s^3)}{r^2 (1-M_s)^3} \right] dS
\]

(20)

\( M \) denotes the Mach number, \( M_s \) the radial Mach number, \( l_i \) the local force of \( i \) to the unit area.

The following formula can be written as well, see [27][28].

\[
p_T'(x,t) = \int_{\tau=0}^{T} \int_{A(y)} \rho v_0 \frac{DG}{Dr} dA(y) d\tau
\]

(21)

\[
p_L'(x,t) = \int_{\tau=0}^{T} \int_{A(y)} F_i \frac{DG}{Dr} dA(y) d\tau
\]

(22)

Computational domain and boundary conditions

Unsteady calculation was conducted on NACA0015 hydrofoil, being as a research object, which is used to study the incoming flow velocity and the sound radiation law of the foil shape when the attack angle of foil shape changes. According to different cavitation numbers to adjust the outlet static pressure, pressure coefficient of cavitation number hydrofoil surface, Strauha number and Reynolds number are respectively defined as follows:

- Cavitation number: \( \sigma = \frac{P_e - P_t}{\frac{1}{2} \rho v^2} \); pressure coefficient: \( C_p = \frac{P_e - P_t}{\frac{1}{2} \rho v^2} \); Strauha number: \( St = \frac{f c}{V} \).
- Reynolds number \( Re = \frac{Vc}{\nu} \); \( P_e \): environmental pressure; \( V \): incoming flow velocity; \( P_t \): saturation vapor pressure; \( f \): cavity detachment cycle; \( c \): chord length of hydrofoil; \( \nu \): viscosity coefficient.

Hence, several working conditions were set up: the incoming flow velocity 16.91m/s, the attack angle is set in five working conditions: 0°, 3°, 6°, 9° and 12° and the environmental pressure is set up as 51957Pa.

Settings of the computational domain are shown in figure 1.
Figure 1. Computational domain and boundary conditions

Figure 2. Settings of monitoring points

Figure 3. Close-up view of grid near the leading edge and the trailing edge of the hydrofoil

Figure 4. Monitoring curves for lift and drag coefficients at $\alpha=3^\circ$, $v=16.9\text{m/s}$

In view of the changing curves for lift and drag coefficients of the hydrofoil during the unsteady calculation process, both the lift coefficient and drag coefficient of the hydrofoil take on periodical change, which shows the periodical detachment of the eddies.

6. Result analysis

6.1. Noise law for cavity during its unsteady growth process

Figure 5. Sound pressure spectrum curves of point r1 at 0°, 3° and 6°

Figure 6. Sound pressure spectrum curves of point r1 at 9° and 12°
Figure 7. Sound pressure spectrum curves of point r5 at 0°, 3° and 6°

Figure 8. Sound pressure spectrum curves of point r5 at 9° and 12°

Figure 9. Sound pressure spectrum curves of point r6 at 0°, 3° and 6°

Figure 10. Sound pressure spectrum curves of point r6 at 9° and 12°

Figure 11. Sound pressure spectrum curves of point r7 at 0°, 3° and 6°

Figure 12. Sound pressure spectrum curves of point r7 at 9° and 12°

Figure 13. Sound pressure spectrum curves of point r8 at 0°, 3° and 6°

Figure 14. Sound pressure spectrum curves of point r8 at 9° and 12°
Figure 15. Sound pressure spectrum curves of point r9 at 0°, 3° and 6°

Figure 16. Sound pressure spectrum curves of point r9 at 9° and 12°

Figure 17. Sound pressure spectrum curves of point r10 at 0°, 3° and 6°

Figure 18. Sound pressure spectrum curves of point r10 at 9° and 12°

Figure 19. Sound pressure spectrum curves of point r11 at 0°, 3° and 6°

Figure 20. Sound pressure spectrum curves of point r11 at 9° and 12°

Figure 21. Sound pressure spectrum curves of point r12 at 0°, 3° and 6°

Figure 22. Sound pressure spectrum curves of point r12 at 9° and 12°
6.2. Transverse attenuation coefficient of noise.

Figure 23. Sound pressure spectrum curves of point r13 at 0°, 3° and 6°

Figure 24. Sound pressure spectrum curves of point r13 at 9° and 12°

Figure 25. Sound pressure spectrum curves of point r14 at 0°, 3° and 6°

Figure 26. Sound pressure spectrum curves of point r14 at 9° and 12°

Figure 27. Sound pressure spectrum curves of point r16 at 0°, 3° and 6°

Figure 28. Sound pressure spectrum curves of point r16 at 9° and 12°

Figure 29. Transverse attenuation coefficient with angle(point1-9)

Figure 30. Transverse attenuation coefficient with angle(point10-16)
6.3. Density characteristic of the acoustic power spectrum

Take the average sound pressure level on each frequency band according to the monitoring points, monitor the sound pressure level produced by the hydrofoil. The transverse and longitudinal attenuation characteristics with angle and distance, see figure29-32. It can be clearly seen that with the increase of distance, the sound pressure level decreases gradually, but the level increases significantly at 0.1 m - 0.2 m and 0.3 m - 0.5 m. The attenuation accelerates at 0.5 m -- 0.6m, while increases significantly at 0.6m -- 0.8m, meanwhile, with the increase of angle, the sound pressure level (SPL) decreases gradually, but the SPL obviously becomes dictively bigger at 6° than other angles. With the increase of distance in longitudinal direction, the SPL also represents a trend of attenuation. The SPL increases significantly from 0.1m to 0.42m and then decreases to 0.58m. Similarly, with the increase of angle of the hydrofoil, the SPL gradually decreases, but the SPL is obviously greater at 6° than other angles.

7. Conclusion
In this paper, under the incoming flow velocity 16.91m/s, the attack angle is set in five working conditions: 0°, 3°, 6°, 9° and 12° and the environmental pressure is set up as 51957Pa. LES model is adopted to calculate the three-dimensional unsteady cavitation noise of NACA0015 hydrofoil:
1. The unsteady characteristics of the hydrofoil during the cavitation process also make its lift and drag coefficients with the same features – the unsteady characteristics, namely periodic fluctuation, and its changing law is the same. The inception, development, fracture, detachment and collapse of cavitation can affect the pressure distribution of the hydrofoil surface, and the fluctuation of cavitation is the main factor both for the noise formation and the loss of lift.

2. The unsteady process of the hydrofoil cavitation is a relatively complex physical process, including cavitation inception and its development, fracture, detachment and collapse, the process has obvious features of pulsation and periodicity. According to the flow structure at different moments, the reverse jet nearby the hydrofoil wall caused by eddies is the main cause for the formation and detachment of cavitation bubbles, and also is the main cause for the noise changing. The noise transmission in the leading edge of the hydrofoil is consistent with the direction of the mainstream, no reverse transmission. In the development process of cavitation, the signals of noise in cavitation area tend to be superimposed downstream. When signals transmit to the flowing area at the trailing edge of the hydrofoil, they have attenuated till exhausted gradually.

3. According to the sound pressure spectrum characteristics, power spectrum characteristics and noise attenuation characteristics with distance and attack angle at different monitoring points, it can be obtained that with the increase of the distance from the sound source, the sound pressure level and power spectrum density gradually decrease, and in this paper shows they increase to a certain extent at 6° and then decrease. It can be clearly seen from the transverse and longitudinal attenuation figures that the sound pressure level with the angle and distance is significantly greater at 6° than other angles.

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