Simulation research of the Pulsating Excitation and Vibration Response of Propeller in Wake Field

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Abstract. The pulsating excitation and vibration response of a highly skewed propeller, running in wake field, was studied by the Fluid-Solid Interaction (FSI) simulation. Coupling calculation of elastic propeller was realized on ANSYS-CFX modules based on the CFD/FEM FSI method, and the rigid results were compared. The results show that, the pulsating thrust of the elastic propeller considering FSI effect has the same low frequency peak as the rigid except the low frequency elastic peak (the first-order natural frequency of propeller), and the low-frequency broadband force amplitude of the elastic propeller is an order of magnitude higher than the rigid. In addition to the correlation between blade frequency and shaft frequency, the propeller also has obvious vibration response at the lower natural frequency. The results are significant to the prediction and control of propeller vibration response.

1. Introduction
In the complex incoming flow, the non-uniform wake field of the stern interacts with the rotating propeller and generates the pulsating excitation on blade, causing strong propeller vibration and noise, which seriously affects the ship performance.

In the past propeller noise prediction, the blade is often seen as rigid structure, ignoring low frequency elastic line-spectrum noise caused by the FSI vibration. But actual testing found that low-frequency elastic vibration noise cannot be ignored, which became a hot topic for researchers in recent years.

Lin et al.[1] firstly considered FSI effect and used the VLM/FEM FSI method to analyze the propeller hydrodynamic performance. Then Young[2] and HE et al.[3] analyzed the composite propeller based on BEM/FEM and CFD/FEM FSI method respectively. With the wide use of CFD/FEM FSI method, it becomes feasible to analyze the propeller vibration response based on FSI simulation. Wei et al.[4] analyzed the vibration response of the blade considering the influence of unsteady flow based on FSI method. Zhang et al.[5] analyzed influence of blade rake angle on structural vibration characteristics based on one-way FSI method. Yang et al. [6] took into account the influence of non-uniform incoming flow to forecast the low-frequency vibration of the propeller based on FSI method.

Considering elasticity effect, the CFD/FEM FSI method is adopted to study pulsating excitation and vibration response characteristics of the highly skewed propeller. And the two-way FSI simulation is calculated based on ANSYS-CFX modules in Workbench platform. The pulsating excitation of elastic propeller has been analyzed compared with the rigid under different turbulence models. And the vibration response characteristics of propeller has been further analyzed.
2. Simulation Model

The FSI simulation model is composed of highly skewed propeller model, flow field model and coupling process module, as follows.

2.1. Highly skewed propeller model

The INSEAN E1619 seven-blade highly skewed submarine propeller is adopted in the study, which was designed by INSEAN[7] and widely studied in the International Symposium on Marine Propulsors. The 3-D model of the propeller is shown in Figure 1. And the design parameters are given in Table 1.

In order to ensure that the low-order mode frequencies of the propeller are all within the analysis frequency range (0~100Hz), the material density of propeller is set to 8300kg/m³, the elastic modulus is 11GPa and poisson's ratio is 0.34.

| Table 1. Design parameters of the INSEAN E1619 propeller. |
|----------------------------------------------------------|
| Propeller Type  | INSEAN E1619 |
| Diameter        | 0.485m       |
| Number of Blades| 7            |
| Advanced Speed  | 1.68 m/s     |
| rotate speed    | 280 RPM      |
| Pitch/Diameter Ratio | 1.15 |
| Ae/A0           | 0.608        |
| Hub/Diameter Ratio | 0.226       |
| Direction of Rotation | Right      |

2.2. Flow field model

Flow field model is composed of an inner cylindrical rotating domain wrapping the propeller and an outer cylindrical static domain surrounding the rotating domain. The diameter of the static domain is 5d (d is the propeller diameter) and the length is 7.5d, in which the upstream is 2.5d and the downstream is 5d. The rotating domain diameter is 1.2d and the width is 0.3d. The interface between the flow field and propeller is set as the FSI interface, and mesh generation is based on ICEM. The grid thickness of the first boundary layer on FSI interface is 5×10⁻⁴m. The grid mesh of rotating domain and static domain are shown in Figure 2(a) and Figure 2(b). Where the -X axis is the flow direction.

In the flow field, the General Connection Interface model is used to connect the rotating domain and static domain. And the rotate speed of inner rotating domain is set to 280r/min to simulate propeller rotation. The flow field inlet is set as speed entrance and the outlet is pressure exit in static domain.
For the turbulence model, the computer performance cannot meet the requirements of Scale Solving Simulation such as LES or DES turbulence model [8] [9] for two-way FSI calculation, and the RANS turbulence model is more appropriate. Considering calculation efficiency and accuracy, the turbulence model adopts SST $k-\omega$ turbulence model, which has good performance on wall bounded boundary layer flows [10].

2.3. **FSI model**
The coupling simulation is solved based on the CFX-ANSYS coupling module. Which transmits the data on FSI Interface to achieve the two-way unsteady FSI calculation.

The propeller constraint is fixed support of one-end-surface of the shaft. In the flow field, the Transient Rotor Stator is adopted for the interface between the rotating domain and the outer domain, FSI interface is set as No Slip Wall and outer domain wall as Free Slip Wall. The Second Order Implicit Euler method is used to solve the transient problem. And the time step is set to 0.001s.

3. **Modal Calculation and Hydrodynamic Verification**
Before the analysis of propeller’s FSI vibration response, the modal calculation of propeller and the hydrodynamic validation of flow field model are needed.

3.1. **Propeller wet-mode calculation**
The propeller natural wet-mode is calculated based on ACT_Acoustic module. The fluid calculation domain is a cylinder with diameter of 5d and thickness of 2d, shown in Figure 3. The boundary condition of propeller is fixed support of one-end-surface of the shaft. The interface between propeller and fluid domain is set as FSI surface. The fluid domain is set as Acoustic Body, with density of 1000kg/m³ and sound velocity of 1500m/s. The absorbing boundary condition is applied at the outer of the fluid domain to simulate the infinite domain.
The natural wet frequencies of the first 21 orders of propeller are obtained as shown in Table 2, where each seven order modes have the same blade mode and similar frequency. The first order natural wet frequency of the propeller is about 61.4Hz.

| Propeller mode order | Wet frequency (Hz) |
|----------------------|--------------------|
| 1~7                  | 61.4               |
| 8~14                 | 153.8              |
| 15~21                | 322.4              |

3.2. Hydrodynamic validation of flow field model
Based on the flow field model, the design speed of E1619 seven-blade highly skewed propeller is 280 r/min for hydrodynamic verification. The advance coefficient ($J$) is set to 0.2~1.0 respectively to calculate unsteady hydrodynamic performance of propeller, including the thrust coefficient of $K_t$, torque coefficient of $K_q$ and efficiency of $\eta$. The hydrodynamic simulation results are compared with the hydrodynamic experimental data of E1619 propeller provided by INSEAN [7], and the comparison curve of hydrodynamic results is shown in Figure 4. As the figure shows, the model simulation results are in good agreement with the experimental values, where the thrust error is within 7% and the torque error within 10%. The model meets the requirements of simulation and can be used for the propeller hydrodynamic simulation.

4. Pulsating Excitation and Vibration Response Analysis
Based on simulation model, the two-way FSI simulation was calculated and the pulsating excitation and structural response of propeller were analysed.

4.1. Flow pulsating excitation analysis on propeller
In this study, an "ox horn" type wake field is used for coupling simulation. The velocity distribution of the wake model and the cloud diagram of input velocity distribution of the simulation are shown in Figure 5. The transient hydrodynamic simulation of the rigid propeller was carried out first, then the rigid hydrodynamic results were used as the initial value of the FSI simulation. The propeller pulsating thrust was monitored during the transient calculation.
After 0.1s calculation, the coupling calculation reaches stability. The stabilized FSI pulsating thrust is extracted, and the rigid results with the SST $k$-$\omega$ turbulence model and DES turbulence model respectively are used to compared. The comparison curve of the pulsating thrust amplitude is shown in Figure 6. Considering the FSI effect, the low-frequency line excitation prediction is consistent on axial frequency 4.67Hz (APF), blade frequency 32.67Hz (BPF) and their double frequency compared with the rigid, except the elastic line spectrum appears on propeller’s first order natural frequency. In addition, the amplitude of the low frequency broadband force of the FSI results is higher than that of the rigid by an order of magnitude.

![Comparison curve of propeller’s pulsating thrust](image)

4.2. Vibration response of propeller

The deformation distribution of the propeller is shown in Figure 7. The maximum displacement of the propeller is 2.823mm at the tip of the blade, which is 0.49% of the propeller diameter. The amplitude-frequency curve of tip displacement is shown in Figure 8. It can be seen that the maximum peak of displacement response is at the axial frequency 4.67Hz (APF), and there is also an obvious peak at high axial frequencies. In addition, there is also a peak at about 62Hz (near the natural wet mode
frequency of the propeller) between 13APF and 14APF, which indicates the blade also has obvious vibration at the first natural frequency, besides the axial and high axial frequencies.

![Figure 7. The deformation distribution of the propeller.](image)

![Figure 8. The amplitude-frequency curve of tip displacement.](image)

5. Conclusion
In this paper, based on CFD/FEM FSI method, the E1619 seven-blade highly skewed propeller was used to the coupling simulation under non-uniform wake field. And the characteristics of pulsating excitation and structural response were analysed by comparing the rigid results. The main conclusions are as follows:

1) On the pulse excitation of elastic propeller, the low-frequency line excitation prediction of the FSI simulation is consistent on axial frequency, blade frequency and their double frequency compared with the rigid. And there is elastic line spectrum (propeller’s first order natural frequency) in the FSI prediction but not in the rigid.

2) Considering the FSI effect, the amplitude prediction of the low frequency broadband force of pulsating excitation is higher than that of the rigid by an order of magnitude.

3) The blade has obvious vibration response at the first natural frequency, besides the axial and high axial frequencies.
The study also provides a research approach for the prediction of the flow pulsating excitation and propeller vibration response.

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