Dynamic Analysis of Carrier Structure of a Marine Underwater Mechanical Arm

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Abstract. In this paper, the support structure of a certain type of marine underwater manipulator is taken as the object to carry out solid modeling and mechanical properties analysis. At sea level 5, the maximum stress and displacement of the carrier structure are obtained through static analysis, and the first six frequency modes, peak response frequency and amplitude of the carrier structure are obtained through modal analysis and harmonious response analysis. The results show that the safety can be guaranteed under 5-level sea conditions, and the influence of cyclic loads on the structure is significant. The influence of cyclic loads on the structure should be taken into account when analyzing the structure. The research results have engineering application value and guiding significance for optimum design and safety strength checking of underwater manipulator carrier structure.

1. Introduction

With the rapid development of underwater inspection and maintenance technology of ships in our country, underwater vehicle, as an intelligent device, can replace manual underwater special operation. Its application prospect is very broad. The underwater manipulator provides a feasible way to detect the working conditions of underwater parts of ships, implement underwater emergency repair and replace underwater parts. At present, the technology of underwater working robots in the United States, Japan, Britain, France and other countries is the most developed, most of which are used in underwater maintenance, manned deep submersible and deep-sea working underwater workstations. Therefore, how to realize the transportation, positioning, operation and recovery of the manipulator in the ocean is an urgent problem for all countries under the condition of ensuring the ship's sailing rate and reducing the maintenance cost as far as possible.

In this paper, a carrier structure of underwater manipulator with triangular truss structure as the main body is designed, which can carry and transport the underwater manipulator. SOLIDWORKS is used to build the three-dimensional model of the underwater manipulator carrier structure, and ANSYS is used to carry out static and modal analysis of the structure to evaluate the safety of the underwater manipulator carrier structure. Studying the steady-state response of the structure can help designers overcome resonance, fatigue and other adverse effects caused by forced vibration, and provide technical support for the safe operation of the structure [1].

2. Structure and working principle of marine underwater mechanical arm carrier

The carrier of ship's underwater mechanical arm is mainly composed of triangular truss, working platform, lifting device, suction cup and swinging device, etc., which is mainly used for carrying and
transporting underwater mechanical arm, and the end mechanical arm is used to carry many corresponding auxiliary equipment. To realize underwater observation, inspection and simple maintenance of the hull and appendages below the waterline when the ship stays on the water. The overall structure is shown in figure 1.

![Figure 1. Overall structure.](image)

The structure adopts locking working platform, which consists of main platform and expansion platform. The truss structure is composed of standard section, which adopts triangle structure. Some degrees of freedom of truss structure can be restricted by vacuum suction cup adsorbed on the outside side of ship. The swing device consists of a rotating mechanism and an electric push rod, which can rotate around the bottom end of the truss structure and is used to connect the carrier structure with the mechanical arm. The triangular truss structure is made of 5052 aluminum alloy with yield strength of 195MPa and vertical height of 9m.

3. Environmental load

Under the interaction of random loads such as gravity, wave, sea breeze and ocean current, and drag force and inertia force, the carrier structure of underwater mechanical arm generates dynamic response. In this paper, stokes fifth-order wave theory and Morison wave force are adopted to simulate wave load.

3.1. Stokes wave theory

The waveform of Stokes wave theory is an irrotational wave with periodic fluctuations on its surface. The ratio of effective wave height to wavelength (i.e. wave steepness) H/L is the main factor determining the wave properties [2]. The expression of Stokes fifth-order wave velocity potential is as follows.

\[
\varphi = \frac{c}{k} \sum_{n=1}^{c} \lambda_n c h(nk)(z + h) \sin(n\theta)
\]  

(1)

In the formula, "c" is velocity, m/s; "k" is wave number; "\lambda_n" is known composite function; "z" is height of wave in depth direction, m; "h" is depth, m; "\theta" is phase angle, \(\theta = kx - \omega t\), where "t" is time (s) and "\omega" is wave frequency (rad/s).
3.2. *Drag force around flow*

The drag force on a unit length can be calculated by the following formula.

\[ f_D = \frac{1}{2} C_D \rho A v^2 \]  \hspace{1cm} (2)

In the formula, \( \rho \) "is the density of the fluid, \( \text{g/cm}^3 \); "A" is the projection area of the cylinder perpendicular to the flow direction of the fluid, \( \text{m}^2 \); "D" is the diameter of the cylinder, \( \text{m} \); "\( C_D \)" is the drag coefficient, which reflects the viscous effect of the fluid, which is related to Reynolds number and the roughness of the cylinder; "\( v \)" is the velocity of the fluid, \( \text{m/s} \).

3.3. *Inertia force around flow*

The additional mass around the cylinder which changes its original motion will also produce an additional inertial force along the direction of fluid flow. Therefore, the inertial force acting on the cylinder by the accelerated fluid along the direction of flow is as follows.

\[ f_i = (M_0 + M_w) \frac{d\nu}{dt} = C_M M_0 \frac{d\nu}{dt} \]  \hspace{1cm} (3)

In the formula, "\( C_M \)" is the inertia force coefficient, which reflects the additional mass effect caused by the change of velocity of flow field around the cylinder due to the inertia of fluid and the existence of cylinder [3]. "\( C_m \)" is the additional mass coefficient, \( C_M = 1 + C_m \).

3.4. *Wave force*

In calculating wave forces acting on slender cylinders (\( D/L \leq 0.2 \)), the semi-theoretical and semi-empirical formula Morison equation [4], which is based on flow theory, is still widely used in engineering design, including two components of horizontal drag force and horizontal inertia force.

\[ f = \frac{1}{2} C_D \rho_w D(u - \frac{\partial y}{\partial t})(u - \frac{\partial y}{\partial t}) + C_M \rho_w \frac{\pi D^2}{4} (u - \frac{\partial y}{\partial t} - \frac{\partial^2 y}{\partial t^2}) \]  \hspace{1cm} (4)

In the formula, "\( f \)" is wave force per unit length, \( \text{kN/m} \); "\( u \)" is horizontal velocity of water quality point, \( \text{m/s} \); "\( C_D \)" is resistance factor; "\( C_M \)" is inertia force factor; "\( \rho_w \)" is sea water density, \( \text{kg/m}^3 \); "\( D \)" is pipe diameter, \( \text{m} \); "\( y \)" is displacement, \( \text{m} \); "\( t \)" is time, \( \text{s} \).

4. Static analysis of carrier structure

4.1. *Establishment of finite element model*

From the above formulas, wave loads and circumfluent loads can be calculated. Assuming that they are in the same direction as the working loads, the results are applied to the truss structure, and the finite element model of the structure is established by using ANSYS. In this paper, only the truss structure is analyzed, without considering the force of suction cup and locking device. The upper end of the truss structure is fixed on the working platform, and all degrees of freedom of the upper end are restrained. The displacement degrees of freedom in X, Y and Z directions and rotational degrees of freedom in Y and Z directions are restrained by the sucker.

4.2. *Nonlinear static analysis of structures*

There are many different working conditions of underwater manipulator in actual working conditions, mainly including positioning, detection, grasping and cutting. This paper mainly considers the self-weight of the structure, the environmental load and the working load of the manipulator when cutting. At this time, the working water depth is 5 meters, and the meaningful wave height is 2.5-4 m under the 5-level sea condition. Take 4 m, the effective period of the wave is 9.09s, and the wave velocity, \( U = 14.18 \text{ m/s} \), which is the velocity of the water quality point.

The static analysis of the truss structure is carried out under the 5-level sea condition, and the equivalent stress nephogram (Fig 2) and the deformation nephogram (Fig 3) of the whole structure are
obtained. From Figs 2 and 3, we can see the Mises stress of the truss structure and the deformation of the truss structure under the 5-level sea conditions.

**Figure 2.** Contour nephogram of equivalent stress.

**Figure 3.** Contour nephogram of deformation.

From Fig 2 and 3, we can see that the maximum stress of the truss structure is 169.41 MPa $< [\sigma ] = 195$ MPa, which is less than the allowable stress. That is to say, the truss structure is safe under the static state under the 5-level sea condition. When the loading direction is perpendicular to the side of the ship, the maximum stress and displacement occur at the bottom of the truss structure connected with the swing device. Therefore, the bottom of the truss structure is the dangerous part of the whole carrier structure. Some improvement measures should be taken to improve the safety and stability of the structure in dangerous places, such as increasing the wall thickness of the dangerous part of the truss structure or replacing the existing materials with higher strength materials.

5. Dynamic analysis of carrier structure

5.1. Structural modal analysis

In this paper, modal analysis is used to solve the natural frequencies and periods of the carrier structure. Compared with the natural frequencies of wave loads, the possibility of resonance of the structure is judged, and the vibration period and natural frequencies of the structure are obtained. The data results are arranged as shown in Table 1 [5].
The natural frequency of the first mode of the structure is 11.059 Hz, and the natural vibration period is 0.090 s, which is less than the effective period of the structure under the 5-level sea condition of 9.09 s. Therefore, the structure can avoid the wave period range under the 5-level sea condition without resonance.

### Table 1. The first six natural frequencies and natural vibration periods of truss structures.

| Mode | 1       | 2       | 3       | 4       | 5       | 6       |
|------|---------|---------|---------|---------|---------|---------|
| Natural frequency [Hz]     | 11.059  | 11.827  | 40.061  | 43.350  | 46.297  | 47.465  |
| Cycle [s]                  | 0.090   | 0.085   | 0.025   | 0.023   | 0.022   | 0.021   |

5.2. Harmonic response analysis of structures

In this paper, the harmonic response analysis is carried out by means of modal superposition method. By multiplying the factor of mode shape (eigenvector) obtained from modal analysis and calculating the response of the structure, the solution can be gathered near the natural frequency of the structure, and a smoother and more accurate response curve can be generated [6]. The analysis results of harmonic response of truss structure is shown in Fig 4 and 5.

From Fig 4 and 5, we can see that the vibration displacement changes with the increase of excitation frequency. The peak value appears at 1000 Hz. The maximum vibration displacement in X direction is $3.926 \times 10^{-6}$ mm (Fig 4) and in Y direction is $6.0752 \times 10^{-4}$ mm (Fig 5). At the peak excitation
frequency, the maximum stress of the structure is $1.423 \times 10^4$ MPa, which is less than the allowable stress of the structure and meets the design requirements.

6. Conclusion
Taking the underwater manipulator carrier structure as the research object and based on ANSYS software, the strength and harmonic response of the structure under the 5-level sea condition are mainly analyzed. The following conclusions are drawn:

- The maximum stress and displacement of the structure under static loads are obtained. The results show that the structure is relatively safe under 5-level sea conditions.
- When the direction of environmental load is perpendicular to the ship's side, the dangerous part of the truss structure appears at the junction between the bottom of the structure and the swing device, in which certain measures can be taken to ensure the safety of the structure.
- By modal analysis, the natural frequency of the structure is compared with the wave load frequency, and the natural vibration period of the structure is less than the effective period of the wave. It is predicted that the possibility of resonance of the truss structure under the 5-level sea condition is less.
- The harmonic response analysis of truss structure under wave load is studied. The maximum vibration displacement and stress of the structure under excitation frequency are obtained. It is helpful for designers to overcome the harmful conditions such as resonance and fatigue caused by forced vibration.

7. References
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