Research on a Wave Power Generation and Anti-rolling Device for Ships

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Abstract. Inertial wave energy converter is a new technology to extract wave energy. The existing research mainly applies it to autonomous underwater vehicle or special wave power generation equipment. This paper explores the application of inertial wave energy conversion technology in ships to convert wave energy into electrical energy while reducing ship sway. Taking a work boat as an example, this paper first establishes the ship model in ANSYS and uses the panel method based on potential flow theory to obtain the hydrodynamic parameters of roll motion. The rolling random wave moment is simulated by equal frequency method. The mathematical model of the wave-ship-gyro system is described, and the system is simulated in the Simulink environment. Some physical limitations of the device and the classic passive PD controller of this system are introduced. The focus is on how to select the gyro angular momentum at the beginning of the design to match the ship to achieve the best power generation effect. Finally, the simulation results are analysed and the new power generation technology is evaluated.

1. Introduction
The average wave energy density perpendicular to the wave propagation direction is about 2-3 kw/m². Wind energy density on the ocean surface in the windward direction is about 0.5kw/m² on average. Solar energy density on the horizontal surface of the ocean surface is about 0.1-0.3kw/m²[1]. Designing a device that can absorb the wave energy into the power required for its operation during driving will be of great significance for improving economy. In recent years, it has been proposed to use inertial wave energy conversion technology for charging on autonomous underwater vehicles. Compared to other wave energy generation methods, the entire unit operates in a sealed float to protect it from seawater corrosion to provide a more reliable and durable power generation system[2].

This paper designs a device which utilizes the rolling motion of the ship in the wave to drive the gyro precession of the large moment of inertia, and uses its considerable precession torque to generate electricity while reducing the ship's roll motion. Starting from the establishment of the ship model, it aims to explore a ship gyro power generation technology with certain anti-rolling effect. The matching relationship between gyro angular momentum and ship parameters under passive PD control is emphatically studied.

2. Generation of Random Wave Torque
According to the superposition principle of irregular waves, it is assumed that irregular waves are superposed by many regular waves with different frequencies, different wave heights and random phases. The mathematical expression of irregular wave height with time is as follows:
\[ \zeta = \sum_{n=1}^{\infty} \zeta_n \cos(k_n x - \omega_n t + \varepsilon_n) \]  

(1)

\( k_n \) is the wave number of the nth wave, and the random phase \( \varepsilon_n \) can take any value between 0 and 2\( \pi \). To simplify the problem, it is assumed that all single regular waves have the same propagation direction, which is called long peak wave. The wave data used are obtained from the coast of Pantellaria, Italy \(^{[3]}\). \( \zeta_{\omega/3} = 3.25 \text{m} \), characteristic period \( T_1 = 8 \text{s} \). Then the spectral density formula of ITCC two-parameter spectrum is obtained in Fig 1.

\[ S_\zeta(\omega) = 173 \frac{\zeta_{\omega/3}^2}{\omega^5 T_1^4} \exp\left\{-691 \frac{(\omega T_1^4)^{-1}}{1}\right\} \]  

(2)

The energy on both sides of the curve is neglected, which is less than 1/50 of the peak value of spectral density. In theory, the more regular waves \( n \) are used to simulate random waves, the more accurate the simulation is. Here we take into account the rapidity of the simulation so that \( n = 50 \). In the obtained frequency range, the frequencies are divided into 50 parts according to the interval \( \Delta \omega \). Their wave height of each regular wave is:

\[ \zeta_n = (2S_\zeta(\omega_n)\Delta \omega)^{1/2} \]  

(3)

The transfer function \( F_{(\omega)} \) of the first order wave excitation moment (the sum of Froude-Krylov force and diffraction force) obtained by ANSYS finite element analysis software is shown in Fig 2. It represents the magnitude and phase delay of wave moments generated by a frequency wave acting on the hull at a unit wave height. We only consider the change of wave with time at a certain location, so \( k_n x \) in equation (1) is a fixed value. The phase difference of wave \( A(\omega_n) \) at each frequency is also constant, so \( k_n x + \delta_n + \varepsilon_n \) in each regular wave can be combined into a random term \( \varepsilon_n \). Therefore, random wave forces superimposed by regular waves can be expressed as equation (4). The resulting wave moment curve is shown in Fig 3.

\[ M_{x0}(t) = \sum_{n=1}^{50} F(\omega_n) \zeta_{\omega_n}(t) = \sum_{n=1}^{50} |F(\omega_n)| (2S_\zeta(\omega_n)\Delta \omega)^{1/2} \cos(\omega_n t + \varepsilon_n) \]  

(4)
3. Establishment of Mathematical Model of Hull-Gyroscope

3.1. Mathematical Model

As shown in Fig. 4, o – xyz is a coordinate system fixed to the hull. The wave moment M acts on the hull in the x direction to cause a roll motion. o1 – x1y1z1 is a coordinate system fixed to the gyro. The gyro effect generated by the combination of the gyro rotation speed γ and the ship rolling speed φ generates torque along the y1 axis. By connecting the PTO device to the precession shaft, energy can be extracted from the system. The use of two gyro with opposite speeds can counteract the moment of the gyro acting on the ship in other directions. If we use passive PD control, that is, PTO applies angle-dependent damping torque and angular velocity-related damping torque $M_{PTO} = k\dot{\beta} + c\dot{\beta}$ to the precession axis, where the angular velocity correlation term is used to convert into electric energy:

$$P_{output} = k\dot{\beta}^2$$  \hspace{1cm} (5)

The angle dependent term is similar to the pendulum effect and its total power is zero. There is equation (6) on the precession axis of the gyro:

$$I_{y1}\ddot{\beta} + (I_{x1} - J)\dot{\beta}\dot{y}\cos\beta = -k\dot{\beta} - c\dot{\beta}$$  \hspace{1cm} (6)

γ is the gyro rotation angular velocity, and J is the rotational inertia of the gyro rotation axis. The second term on the left side of equation (6) is at least two orders of magnitude smaller than the other terms. We can design the gyro's moment of inertia relationship to satisfy $I_{y1} = I_{x1} = 0.5J$ \cite{4}. If we consider the moment of inertia of the PTO equipment attached to the precession shaft y1, it is feasible to design a power generator with $I_{y1} = J$\cite{5}. So the formula is simplified to:

$$I_{y1}\ddot{\beta} + k\dot{\beta} + c\dot{\beta} = J\dot{y}\dot{\phi}\cos\beta$$  \hspace{1cm} (7)

According to the theory of Cummins \cite{6}, only the hull roll motion is considered, and the time domain motion equation of the hull in the wave is:

$$[I_{xx} + I_{xx}'(\infty)]\dot{\phi}(t) + \int_0^t K(t - t')\dot{\phi}(t')dt' + V\dot{\phi}(t) + D\dot{\phi}(t) = M_{wave}(t) - nJ\dot{\phi}\dot{\cos}\beta$$ \hspace{1cm} (8)

n is the number of gyro, $I_{xx}$ is the roll moment of inertia and $I_{xx}'(\infty)$ is the additional mass when the frequency is infinite. The convolution term is radiation damping and $V\dot{\phi}(t)$ is the roll viscous damping correction. The main damping contribution of the ship in the roll is viscous damping. The calculation of the panel method of ANSYS cannot consider the viscous damping, so it needs to be corrected \cite{7}. The viscous damping correction amount is 8% of the critical damping $D_{critical}$. Specifically to the roll motion, the critical damping of a rigid body is:

$$D_{critical} = 2[(I_{xx} + \Delta I_{xx})K_{roll}]^{1/2}$$ \hspace{1cm} (9)

$K_{roll}$ is the stiffness in the roll direction, and $\Delta I_{xx}$ is the additional mass at the ship’s resonant roll frequency.

Figure 4. Hull-Gyro Device
3.2. Substitution of convolution term

The convolution term in the time domain equation of motion represents the memory effect of the ocean free surface, that is, the change in fluid momentum at a certain time affects the motion of the fluid afterwards. The calculation of convolution terms in time domain simulations is very time consuming. A state space equation with the same linear properties can be used instead. The additional mass $I(\omega)$ and potential flow damping $R(\omega)$ obtained by ANSYS AQWA can be used for frequency domain identification [8]. The process of identification is shown in Fig 5. The identification result is shown in Fig 6.

We don't have to care too much about convolution substitution accuracy, because a rough approximation of the fluid memory term can still lead to a good approximation of the wave force-ship motion response model. This is due to the feedback structure of the force-motion model, which filters out most of the dynamics of the convolution term [9]. So we should not only evaluate the convolution model, but also the force-motion model to avoid excessive effort in improving the convolution model. Using the above theory, a mathematical model of ship roll is established. As shown in Fig. 6, the rolling RAO curve of the obtained mathematical model fits well with the RAO curve of AQWA finite element analysis, which proves the validity of the above theory.

![Figure 5. Frequency domain identification process](image)

![Figure 6. Fitting Results of Frequency Domain Characteristics of Radiation Damping](image)

![Figure 7. Model Response and AQWA Data](image)

3.3. Physical constraints

The gyro precession angle should be limited to a certain range in consideration of the physical limitations of the actual device. It can be known from equation (7) that when the gyro precession angle reaches 90 degrees, the gyro precession torque is zero, which is very dangerous. Therefore, we should always pay attention to the change of the precession angle when designing the control law of the device. The $c\beta$ term torque on the right side of equation (7) (similar to the pendulum effect) can help the gyroscope get rid of this critical situation. Therefore, the $c$ term cannot be zero. We specify $c \geq 5$ in this simulation, and only the simulation result with the maximum precession angle less than 75 degrees is regarded as a valid result.
4. Gyro moment of inertia matching

Based on the ship parameters given at the beginning of the design, the best matching gyro moment of inertia should be found first. Gyro speed changes very slowly under actual working conditions, and the gyro has the highest speed limit due to physical structure. In order to make the gyro's moment of inertia change over a wide range, the total angular momentum can be changed by changing the number of gyros. In this way, the influence of gyro angular momentum on power generation and anti-rolling effects is studied. The gyro used in this simulation has moment of inertia is 47kg.m² and rated rotation speed is 3800r/min.

Fig 8 shows the variation of maximum power generation and corresponding anti-rolling angle with gyro angular momentum. The decreasing roll angle change is similar to the change trend of the maximum power generation amount. Therefore, appropriately increasing the gyro moment of inertia can not only increase the power generation but also improve the anti-rolling effect. Increasing the angular momentum when the angular momentum is small can significantly increase the maximum power generation. However, after the angular momentum increases to a certain extent, the maximum power generation is a constant value, which has reached the power generation limit of the device. This limit may be related to the hull parameters in addition to the level of wave encountered.

![Figure 8. The Change Rule of maximum power generation and corresponding anti-rolling](image)

Therefore, when seeking the best gyro angular momentum matching the hull, the following factors should be taken into account: increasing the volume of gyroscope caused by increasing angular momentum, increasing the cost of gyroscope in order to increase the maximum gyroscope speed, and maintaining the energy required for higher rotation speed. For example, increasing the number of gyros from 210 to 270 increases the moment of inertia by 28.6%. At the same time, the power generation is only increased by 0.5%, which is obviously uneconomical. However, if the ship is to be able to generate maximum power in rare high-grade sea conditions, a greater maximum angular momentum is required. In most small sea conditions, the maximum angular momentum is superfluous. It is possible to reduce the gyro rotation speed (the number of working gyros can be reduced when multiple gyros are operated) to improve efficiency. We select the case where the number of gyros is 210 for further analysis, and the result is shown in Fig 9.

The precession angle data in Fig 9 has been corrected to zero the case where the maximum precession angle is greater than 75 degrees. The combination of k and c parameters in the zero-value region near the origin in Fig 9 should be avoided in the actual situation. The maximum power generation increases first and then decreases with the increase of k, and decreases with the increase of c. The anti-rolling effect is basically consistent with the maximum power as the changes of k and c. When the power generation is the largest, the anti-rolling is also in a better area, and the device should be in this state as much as possible.

Optimizing control strategies has the potential to increase power generation. However, the decisive factor is that the work boat is designed to ensure better seakeeping without any anti-rolling device. Its hydrostatic restoring force, radiation force and rolling damping are all considerable. Although the existing AUV power generation research is in principle the same as the inertial wave power generation of ships, it has different physical limitations. AUV power generation equipment is a kind of unmanned equipment used for power generation. In order to obtain maximum power, it is not necessary to
consider the bearing capacity of people or cargo to the sway angle and angular velocity of the floating body like a ship. It also allows the shape of the float to be changed to increase the efficiency of absorbing wave energy, but the shape design of the ship requires consideration of various factors.

Figure 9. (a), (b) and (c) are respectively correspondent with roll reduction, precession angle and power generation varying with K and C

5. Summary

This paper designs a ship wave energy absorber that can generate electricity while reducing roll. First, the random wave moment is simulated by the equal frequency method and the equivalent state space representation of the radiative force is obtained by frequency domain identification. Next, the wave-hull-gyro system is simulated under passive PD control. The maximum power generation increases as the gyro angular momentum increases, but eventually becomes saturated. After that, the variation law of device parameters under passive PD control is explored and some suggestions are given. Finally, the difference between this kind of equipment and the traditional inertial wave energy converter equipment is discussed. The application of the inertial wave energy converter to ship power generation has attractive prospects, but it is still in the exploratory stage. Based on this paper, further control strategy research can be carried out to increase power generation.

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