ISSN: 1813-4890

Study on Wave Compensation Systems in Marine Engineering

Mingxiao Wang [1], Qiang Ma [2] and Qianyong Zhang [1]

[1]School of Shipping, Shandong Jiaotong University, Weihai 264200, China;

[2] Division of Crew Education and Training Quality Management, Shandong Jiaotong University, Weihai 264200, China.

Abstract

The technology of wave compensation plays a vital role in marine engineering, particularly in offshore drilling, maritime transportation, and offshore construction, where it effectively mitigates the disruptive impact of waves on equipment, ensuring operational safety and efficiency. This paper systematically reviews the research progress of wave compensation systems, encompassing active wave compensation, passive wave compensation, and hybrid wave compensation systems. Through the analysis of the principles, application scenarios, and development trends of these systems, this paper aims to provide a comprehensive reference and guidance for research in this field, while also pointing out the future directions for the advancement of wave compensation technology.

Keywords

Wave Compensation, Active Compensation, Passive Compensation, Marine Engineering.

1. Introduction

As the exploitation of marine resources continues to deepen, offshore operations have gradually increased in various harsh marine environments, and the impact of waves on the safety of offshore equipment and personnel has become an urgent problem to be solved in engineering. The emergence of wave compensation technology aims to reduce the interference of wave motion on equipment and enhance operational efficiency and safety[1]. Wave compensation systems can be classified into active wave compensation (AWC), passive wave compensation (PWC), and hybrid wave compensation (HWC) based on their control methods. This paper provides a detailed overview of various compensation systems, analyzing the current challenges faced by the technology and the future development directions.

Fig. 1 Wind Power Operation and Maintenance Vessels

ISSN: 1813-4890

2. Classification and Principles of Wave Compensation Systems

2.1. Passive Wave Compensation System (PWC)

Passive Wave Compensation Systems (PWC) achieve automatic response to wave motions through mechanical design and hydraulic devices. These systems utilize mechanical springs, cylinders, or hydraulic cylinders, among other components, to absorb the energy of waves, thereby reducing their impact on the operational platform[2]. A typical structure of a PWC system is illustrated in Figure 2.

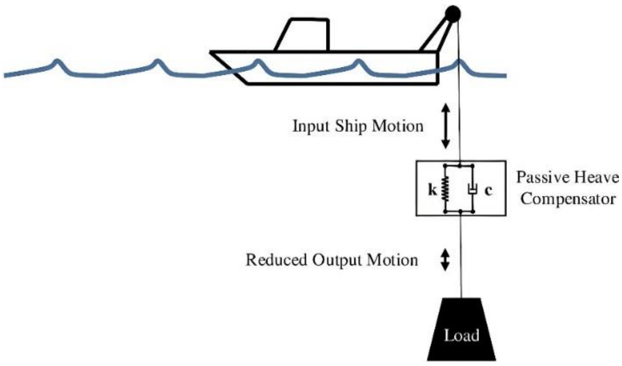

Fig. 2 Passive Wave Compensation System

2.1.1. Basic Principles

The core of a passive wave compensation system lies in adjusting the damping and stiffness of the mechanical system to achieve smooth motion of the equipment amidst waves. Its working principle can be analyzed through a mechanical vibration model:

$$m\ddot{x}(t) + c\dot{x}(t) + kx(t) = F(t)$$

Where m represents the mass of the platform, c is the damping coefficient, k is the system stiffness, and F(t) is the wave force acting on it. By adjusting c and k, the system can reduce the wave-induced motion within a certain range.

Passive compensation systems are simple and cost-effective, but their effectiveness is limited in significant wave conditions.

2.1.2. Application Scenarios

Passive Wave Compensation Systems are typically used in scenarios where the sensitivity to waves is not overly critical, such as maritime transportation and floating platforms. For instance, cranes and lifting equipment often employ this technology to mitigate the effects of sea winds and waves on cargo handling.

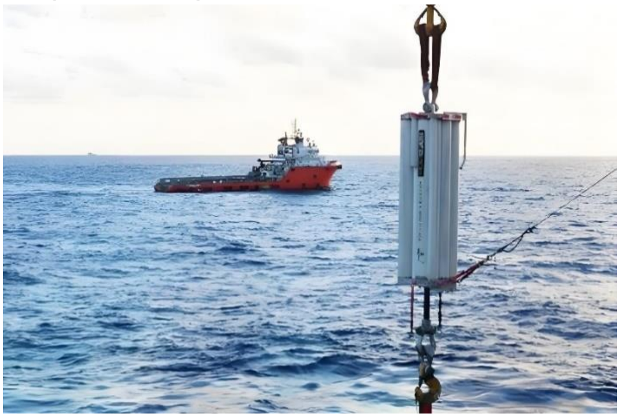

Fig. 3 Passive Wave Compensation System for Offshore Lifting Operations

ISSN: 1813-4890

2.2. Active Wave Compensation System (AWC)

The Active Wave Compensation System (AWC) employs sensors, control systems, and actuators to detect wave movements in real-time and actively control the equipment's attitude to achieve compensation. Compared to passive systems, AWC systems offer greater flexibility and precision, making them particularly suitable for complex sea conditions[3].

2.2.1. Basic Principles

The Active Wave Compensation System relies on sensors to monitor the relative motion between the platform and waves in real-time, and actively adjusts the action of the actuators through a servo system. Its control model typically employs feedback control principles such as PID control, Model Predictive Control (MPC), and others. A typical control framework can be represented as follows:

$$u(t) = K_p e(t) + K_i \int_0^t e(t) d(t) + K_d \frac{de(t)}{dt}$$

Where e(t) represents the system error, and Kp, Ki, Kd are the proportional, integral, and derivative coefficients, respectively. The active compensation system achieves platform stability by adjusting the displacement of servo motors or hydraulic actuators.

2.2.2. Application Scenarios

The Active Wave Compensation System (AWC) is suitable for scenarios requiring high-precision positioning and complex wave environments, such as offshore drilling platforms, deep-sea explorers, and ROV (Remotely Operated Vehicle) operations. In deep-sea operations, the AWC system can significantly reduce the interference caused by waves on equipment through real-time compensation, ensuring the efficiency and safety of the operation.

Fig. 4 Active Wave Compensation System for Offshore Ladders

2.3. Hybrid Wave Compensation System (HWC)

The Hybrid Wave Compensation System (HWC) combines the advantages of both passive and active wave compensation. It leverages the mechanical characteristics of the passive system for basic compensation while enhancing the system's responsiveness and compensation accuracy through active control[4].

2.3.1. Basic Principles

The control strategy of the HWC system is typically divided into two parts: Firstly, the passive system provides preliminary compensation for wave motion through mechanical structures; secondly, the active control system performs fine compensation for residual wave motion based on sensor feedback. Its motion equation can be expressed as:

$$m\ddot{x}(t) + c_p \dot{x}(t) + k_p x(t) = F(t) + u(t)$$

ISSN: 1813-4890

Where cp and kp represent the damping and stiffness of the passive compensation system, respectively, and u(t) is the compensating force generated by the active control.

2.3.2. Application Scenarios

The Hybrid Wave Compensation System (HWC) is widely applied in marine operation equipment, especially in scenarios requiring precise operations under harsh sea conditions. For instance, in deep-sea drilling, the HWC system can significantly improve the stable contact between the drill bit and the seabed, thereby enhancing drilling efficiency and safety.

Fig. 5 Deep-sea Drilling

3. Control Strategies for Wave Compensation Systems

3.1. PID Control (Proportional-Integral-Derivative Control)

PID control is one of the most commonly used control methods in wave compensation systems, enabling precise control of platform position or attitude through adjustment of proportional, integral, and derivative coefficients. The advantages of PID control include its simple structure and ease of implementation. However, in complex wave environments, the system's response speed and stability may be affected[5].

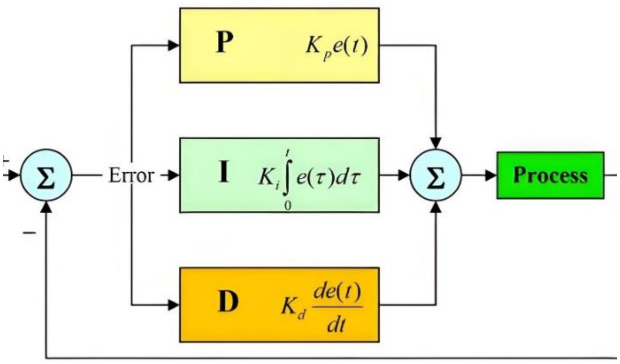

Fig. 6 PID Control

3.2. Model Predictive Control (MPC)

Model Predictive Control (MPC) is a control method based on mathematical models that can predict the future trends of waves and adjust the system's compensation strategy in advance.

The application of MPC in wave compensation enables the system to respond more accurately to complex and variable wave environments. Its control equation is as follows:

$$J = \sum_{i=1}^{N} (y_{ref}(k+i) - y(k+i))^2 + \lambda \sum_{i=0}^{M} u(k+i)^2$$

Where yref represents the reference trajectory, y is the actual output, and λ is the control input weight[6].

3.3. Adaptive Control

Adaptive control strategies can dynamically adjust control parameters based on real-time sea conditions and equipment operating states. This method is particularly suitable for scenarios with drastic changes in marine environments, such as offshore cranes or floating platforms. Through learning and adjustment, an adaptive control system can maintain good control performance under different wave conditions.

4. Applications and Challenges of Wave Compensation Systems

4.1. Offshore Oil Drilling

In offshore oil drilling, wave compensation technology is used to maintain the stability of drilling platforms and reduce the interference of waves on the drill string. Through active or hybrid compensation systems, precision and safety of drilling operations can be ensured [7].

Fig. 7 Offshore Drilling Platform

4.2. Offshore Cranes and Lifting Operations

Wave compensation systems are widely used in offshore cranes and cargo lifting operations, especially in environments with significant waves and winds, effectively reducing crane sway and improving lifting efficiency and safety[8].

Fig. 8 Offshore Crane Operations

4.3. Challenges Faced

Despite significant advancements in wave compensation technology, several challenges remain in its practical application:

• System Response Speed: Wave compensation systems need to respond in real-time to changing sea conditions, and the response speed directly affects the compensation effectiveness.

• Energy Consumption: Active wave compensation systems, in particular, consume a relatively high amount of energy. Finding ways to reduce the system's power consumption is an important research direction for the future.

• Complexity of Marine Environments: In severe sea conditions, such as high waves or hurricanes, existing wave compensation technologies may not fully meet operational requirements. Further enhancements to the system's robustness and adaptability are needed.

5. Future Development Directions

Intelligent Control: Combining artificial intelligence and machine learning technologies, the development of more adaptive intelligent wave compensation systems will become a future trend.

Efficient Energy Management: By optimizing energy management systems, further reductions in the energy consumption of active wave compensation systems can be achieved.

Multi-Sensor Fusion Technology: Utilizing multi-sensor fusion technology can enhance the wave compensation system's ability to perceive complex sea conditions, thereby improving compensation accuracy and response speed.

6. Conclusion

The role of wave compensation technology in marine engineering is paramount. With continuous advancements in technology, the precision and adaptability of compensation systems have been significantly enhanced. This paper provides an overview of the classification, principles, and applications of wave compensation systems, analyzes the challenges currently faced by the technology, and offers insights into future development trends. In the future, through intelligent control and multi-sensor fusion technologies, wave compensation systems will play an even more crucial role in marine engineering.

References

[1] Li Yuming, Liu Wenbin. A comprehensive review of wave compensation technology for offshore operations [J]. Journal of Ocean Engineering and Science, 2018, 7(3): 123-135.

[2] Wang X, Zhang J. Passive wave compensation systems and their application in offshore cranes [J]. International Journal of Offshore and Polar Engineering, 2019, 29(4): 345-350.

[3] Zhao Y, Zhang Y, et al. Active wave compensation technology for offshore platforms [J]. Ocean Engineering Journal, 2020, 57(2): 201-210.

[4] Lu H, Wang Q, et al. Hybrid compensation systems for dynamic positioning in marine environments [J]. Marine Systems and Control Journal, 2017, 2(1): 45-60.

[5] Zhang T, Li M, et al. PID control in wave compensation systems for offshore oil platforms [J]. IEEE Transactions on Control Systems, 2021, 39(6): 789-800.

[6] Li J, Xu Q. Model predictive control applications in wave compensation [J]. Control Engineering Practice, 2020, 92: 104200.

[7] Sun Y, Chen Z, et al. Application of wave compensation in deep-sea drilling platforms [J]. Journal of Petroleum Technology, 2019, 71(3): 301-310.

[8] Dai W, Liu J, et al. Wave compensation in offshore crane operations: Challenges and solutions [J]. International Journal of Automation and Control, 2021, 15(4): 401-415.