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ARTICLE

Vibration Isolation Characteristics of Impedance-balanced Ship Equipment Foundation under Unbalanced Excitation

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ABSTRACT

A new type of impedance-balanced ship equipment foundation structure based on the principle of impedance balancing using a "discontinuous panel-vibration isolation liquid layer-foundation structure" is proposed to solve the problem of poor low-frequency vibration isolation of the foundation under unbalanced excitation of shipboard equipment. Based on the finite element method, the influence of characteristic parameters of the foundation panel structure on its vibration reduction characteristics under unbalanced excitation is explored. The results show that the vibration isolation level of the impedance-balanced foundation is 10 dB higher than the traditional foundation in the low-frequency band of 10-500 Hz when subjected to combined excitation of concentrated force and moment. Increasing the thickness of the impedance-balanced foundation panel can enhance the isolation effect. Increasing the number of sub-panels can effectively reduce the vibration response of the foundation panel and enhance the isolation performance of the foundation. The connection stiffness between sub-panels has a small effect on the isolation performance of the foundation.

1. Introduction

As the main structure connecting the equipment to the ship structure, the equipment foundation acts as a main medium for the transmission of vibration energy from the equipment to the outside of the ship. The impedance characteristic of the foundation is a critical parameter that characterizes the ability of the foundation structure to resist mechanical vibration. It is also the main index to reflect the vibration isolation performance of the equipment foundation [1,2]. Thus, the analysis of foundation impedance is important for the vibration reduction and isolation design of the foundation structure [3,4].

To enhance the vibration isolation performance of equipment foundations, Peng [5] proposed an impedance matching design method for ship foundations. This approach modifies the structural characteristic parameters and shapes of the foundation to achieve mutual matching between its impedance and that of the internal excitation

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source, thereby achieving low radiation noise levels for ships. Li [6] compared the vibration acceleration and underwater radiation noise of the foundation structure before and after the installation of damping materials, which provided support for the low-noise optimization design of the surface ship structure. Wang et al. [7] found through research that the application of damping materials can reduce the value of equipment foundation vibration amplitude in the intermediate frequency range above 60 Hz. Yang et al. [8,9] proposed a unified impedance model for ship vibration reduction that comprehensively optimized the structural dynamic layout of stiffness, damping mass and damping material to enhance the vibration reduction capability of the foundation structure. Ling and Wu [10] used the finite element method to study the suppression effect of multi-stage isolation mass on structural sound propagation. Liu et al. [11] further revealed the suppression mechanism of vibration damping mass on structural sound transmission through case analysis and experimental verification. Yuan et al. [12] discussed the two indirect force estimation approaches, and experiments showed that indirect approaches could be good choices for determining the output forces of machinery in ships. Chen et al. [13] established an isolation vibration system with distributed dynamic absorbers and found that it could increase the frequency range of the absorbers. Ye et al. [14] combined a mathematical model of particle damping, developed a design method of particle damping optimization, solved the problem of high-frequency vibration in the power device, proposed to combine it with active control technology, and verified that it can achieve low-medium-high broadband vibration control of ship equipment. Based on scaled model experiments, Wu et al. [15] proposed a hysteresis nonlinear foundation structure with MRD and verified its effectiveness in low-frequency line spectrum vibration. Gong et al. [16] discussed the effect of damping mass on the propagation of vibration waves in pipelines based on the impedance mismatch principle and numerical analysis methods, and the results showed that damping mass has a beneficial damping effect in the medium to high frequency range. To achieve the purpose of impedance mismatch, Qi et al. [17] used a modern type of vertically symmetric foundation with low stiffness isolators and high input impedance to control the coupled vibration and noise radiation of the propeller shaft system. Wang [18] proposed the combination of active or semi-active control with dynamic absorbers to reduce the vibration transmitted to the deck and hull from power equipment and piping systems. Chen et al. [19] derived the expression of pressure-resistant strength of airbag isolators from the thin shell non-distance theory and verified the reliability of airbag isolators. Du and Li [20] investigated the nonlinear vibration mechanism of the ship rotating machinery with an airbag isolator under heaving motion. Bu et al. [21] proposed a multi-objective collaborative attitude control method for double-layer airbag isolator devices under flexible support conditions. To effectively reduce the vertical and horizontal stiffness of the airbag isolator, Yin et al. [22] adopted a composite airbag structure with serial hard-elastic layers. Li et al. [23] designed a highly adjustable magnetorheological elastomer-based isolator for real-time adaptive control, which can change the lateral stiffness of the isolator under moderate magnetic field levels. For complex mechanical systems, Wu et al. [24] analyzed the quantitative relationship between the impedance of the two transmission channel systems and the isolation effect of the mechanical system and the transmission loss of the pipeline system based on the hammer test method. The experimental results show that the impedance can be increased and the isolation effect can be improved by strengthening the foundation reinforcement or changing the elastic element properties/layout of the pipeline system. Ye [25] proposed a method to improve the impedance of the foundation by optimizing the structural variables of the foundation without altering the structural shape of the foundation and verifying its effectiveness. Dario et al. [26] developed an isolation system to optimize the tuned mass damper inertial device, which allows the inertial instrument and damper to be installed in series, resulting in a lower mass and more effective alternative than conventional tuned mass dampers. Maciejewski et al. [27] conducted numerical simulation and optimization design of a vibration isolation system. They established a mathematical model for vibration reduction and obtained an optimal method for high-efficiency vibration isolation by simulating the dynamic behavior of the system under diverse working conditions.

In light of the research summarized in this review, it is apparent that improving the mechanical impedance matching or impedance mismatch by increasing the damping mass, changing the shape or material properties of the foundation structure, etc. [28], has improved the vibration reduction and isolation performance of the system. It may be necessary to increase foundation mass or decrease foundation stiffness in order to further extend the isolation frequency range of the foundation using the method to lower frequencies, but doing so could result in issues like excess foundation mass or inadequate stiffness, which are detrimental to the lightweight design of ship structures and structural safety. Therefore, this paper proposes a foundation impedance-balanced method, which uses a vibration isolation liquid layer instead of the traditional foundation support structure in the design of the foundation structure to transform the excitation force point and line transmission into surface transmission. To improve the vibration isolation performance of the foundation, the impedance of the foundation is balanced and distributed by interrupting the continuous propagation of vibration waves through the discontinuous panel structure. The vibrational isolation effect of the proposed method is calculated using the finite element method, and the effect of the device foundation panel structural parameters on the vibrational properties is investigated.

2. Principles and Characterization Methods of Impedance Balancing

2.1 Impedance-balanced Principle

Assuming that the total force F and total impedance Z transmitted to the foundation structure by the same equipment are constant, the equipment is connected to the foundation structure through machine feet. The equipment excitation is transmitted only through the foot of the machine to the foundation structure. If the number of machine feet is n, the force transmitted to the foundation through the k-th machine foot is F_k, and the input impedance at the k-th machine foot is Z_k, so we have:

$$F=\sum_{k=1}^{n}F_k=\sum_{k=1}^{n}x_kF,\sum_{k=1}^{n}x_k=1 \tag{1}$$

$$Z=\sum_{k=1}^{n}Z_k=\sum_{k=1}^{n}y_kZ,\sum_{k=1}^{n}y_k=1 \tag{2}$$

where $x_k=\frac{F_k}{F},y_k=\frac{Z_k}{Z}$, the total power flowing into the foundation is P.

$$P=\sum_{k=1}^{n}P_k=\sum_{k=1}^{n}\frac{F_k^{\ 2}}{Z_k} \tag{3}$$

From Equations (1)-(3), it can be concluded that:

$$P=\left(\sum_{k=1}^{n}\frac{x_k^{\ 2}}{y_k}\right)\frac{F^2}{Z} \tag{4}$$

When $x_k=y_k$, the system can obtain the minimum input power, that is, when the force/impedance distribution of the foundation is balanced, the energy transmitted from the equipment to the foundation is the lowest. Figure 1 compares the vibration response of the foundation structure under different loading modes. It can be seen that when the excitation force is the same, the vibrational response of the base structure is weaker when the force is uniformly distributed over the surface compared to the case of concentrated point force loading. Therefore, if the unbalanced excitation force of the equipment can be transformed into a distributed force, the transmission of vibration energy can be effectively reduced and the vibration isolation level of the foundation can be improved.

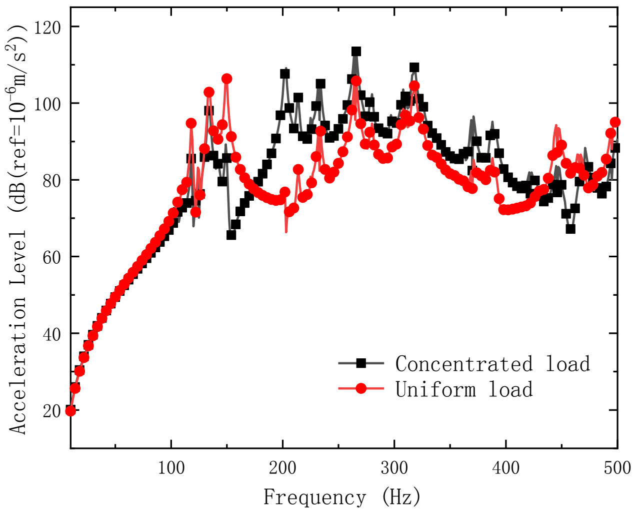


Figure 1. Comparison of average vibration acceleration levels of structures under different loading forms.

2.2 Impedance-balanced Characterization Method

This paper proposes the concept of impedance-balanced design for the foundation, which reflects the level of impedance balancing of the foundation under the current structure form through the difference of input impedance curves at several points in a certain frequency range. The specific definition is as follows.

Assuming that n loading points are uniformly selected on the surface of the foundation structure, each loading point has an input impedance $Z_0^i(f)$ at frequency f, and the standard deviation S_i of the n loading points on the foundation at frequency i is expressed as:

$$S_i=\sqrt{\frac{\sum_{i=1}^{n}(Z_0^i-\overline{Z_0^i})^2}{n}} \tag{5}$$

$\overline{Z_0^i}$ represents the average input impedance of each loading point at frequency i.

In order to eliminate the effect of high or low levels of data values on the dispersion of the sample values, the dispersion coefficient is calculated, which is defined as follows:

$$V_i=\frac{S_i}{\overline{Z_0^i}} \tag{6}$$

The ratio of the standard deviation to the mean of the data. Therefore, within the [a, b] frequency band, impedance standard deviation curve $R(S_i)$ and discrete coefficient curve $D(V_i)$, average the curve values at each frequency point, get foundation impedance discretization coefficient *ZDC*, defined as:

$$ZDC = \frac{\sum_{i=1}^{m} V_i}{m} \tag{7}$$

where *m* is the number of analysis frequencies in the [a, b] frequency band.

Similarly, take the reciprocal of the foundation impedance discretization coefficient to obtain the foundation impedance-balanced coefficient ZSC, which represents the degree of equipment foundation impedance balancing, defined as:

$$ZSC = \frac{1}{ZDC} = \frac{m}{\sum_{i=1}^{m} V_i} \tag{8}$$

3. Impedance-balanced Ship Equipment Foundation Model and Vibration Reduction Effect

3.1 Impedance-balanced Ship Equipment Foundation Model

This article proposes a new type of ship equipment foundation structure with impedance-balanced, as shown in Figure 2. Replace the complete continuous panel with a discontinuous foundation panel, and replace the traditional support structure with a vibration isolation liquid layer, so that the surface waves transmitted to the structure surface undergo waveform conversion at the fluid solid interface, diminishing in the form of liquid surface waves, so as to balance the distribution of input impedance at various locations of the foundation panel. Keeping the impedance dispersion coefficient curve of the foundation at a low level effectively reduces the vibrational response under the excitation force of the device.

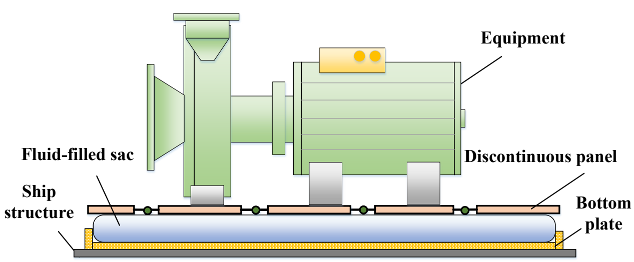


Figure 2. Schematic diagram of impedance-balanced foundation structure.

3.2 FEM Model of Impedance-balanced Ship Equipment Foundation

For complex structures such as the ship foundation, the finite element method is commonly used for numerical analysis. In order to improve the efficiency of simulation calculations, the paper proposes to use the structure-acoustic coupling finite element method for analysis. The liquid is assumed to be ideal fluid and the influence of the fluid-filled sac on the isolation characteristics of the foundation is ignored. The sonic wave is a small amplitude sonic wave and there is no energy loss during the propagation process. The structure-acoustic coupling dynamic equation is expressed as follows:

$$\begin{bmatrix} M & 0 \\ -\rho_a \bar{Q}^T & M_a \end{bmatrix} \begin{bmatrix} \ddot{X} \\ \ddot{P} \end{bmatrix} + \begin{bmatrix} C & 0 \\ 0 & C_a \end{bmatrix} \begin{bmatrix} \dot{X} \\ \dot{P} \end{bmatrix} + \begin{bmatrix} K & \bar{Q} \\ 0 & K_a \end{bmatrix} \begin{bmatrix} X \\ p \end{bmatrix} = \begin{bmatrix} F \\ F_a \end{bmatrix} \tag{9}$$

M_a, C_a and K_a represent the mass matrix, damping matrix, and stiffness matrix of the fluid, respectively. p is the acoustic pressure vector, and K_a is the load vector of the acoustic field excitation. $\bar{Q}$ is the structure-acoustic coupling matrix, and ρ is the density of the fluid.

Equation (9) can be rewritten as follows utilising the modal superposition principle and the Helmholtz equation:

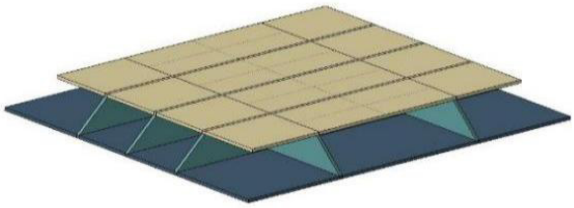
$$\begin{bmatrix} K + j\omega C - \omega^2 M & \bar{Q} \\ \rho_a \omega^2 \bar{Q}^T & K_a + j\omega C_a - \omega^2 M_a \end{bmatrix} \begin{bmatrix} X \\ p \end{bmatrix} = \begin{bmatrix} F(\omega) \\ F_a(\omega) \end{bmatrix} \tag{10}$$

where ω is the circular frequency, and j = 1, $F(\omega)$ represents the modal load.

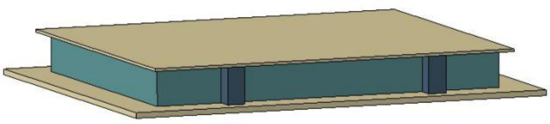
Equation (10) is the solution equation for structural vibration and radiated acoustic field based on structure-acoustic coupling theory. By solving the above equation, the structural vibration and radiated noise under a given excitation load can be calculated.

Establish finite element models for traditional foundation and impedance-balanced foundation structures respectively. The computational model is shown in Figure 3, where the bottom boundary condition of the foundation is fixed on all four sides. The load is applied to the foundation panel in the form of a unite excitation force. Spring elements are used to connect each adjacent foundation panel. After the convergence calculation, the finite element mesh size of the structure was set as 0.005 m while the acoustic mesh size was 0.01 m. The total number of finite element meshes is about 280,000.

The main structural parameters and material properties of traditional and impedance-balanced foundation are shown in Table 1. The main material parameters are shown in Table 2.



(a) Traditional foundation structure model



(b) Impedance-balanced foundation structure model

Figure 3. Schematic diagram of foundation structure.

Table 1. Main structural parameters of traditional and impedance-balanced foundation.

Panel size	2.0 m × 1.6 m	**Panel thickness**	**0.02 m**
Foundation plate thickness	0.03 m	**Web plate thickness**	0.01 m
Total height of foundation	0.2 m	**Liquid layer thickness**	0.2 m
Foundation material	Q235 Steel	**Liquid layer material**	Water

Table 2. Main material parameters.

Material	Steel	**Material**	Water
Density	7850 kg/m^3	**Density**	1000 kg/m^3
Elastic module	2.1×10^{11} Pa	**Bulk volume**	2.2×10^9 Pa
Poisson ratio	0.3		

3.3 Impedance-balanced Foundation Isolation Effect

As shown in Figure 4, to verify the isolation effect of the impedance-balanced foundation, the concentrated force of 1 N and moment load of 1 N·m were applied at the midpoint and both sides of the panels of impedance-balanced foundation and traditional foundation respectively. The calculation and analysis frequency band was 10-500 Hz. Set evenly distributed assessment points on the surface of the panel and bottom plate on the foundation, and use the average vibration acceleration level of the assessment points as the evaluation standard. The calculation results are shown in Figures 5-6.

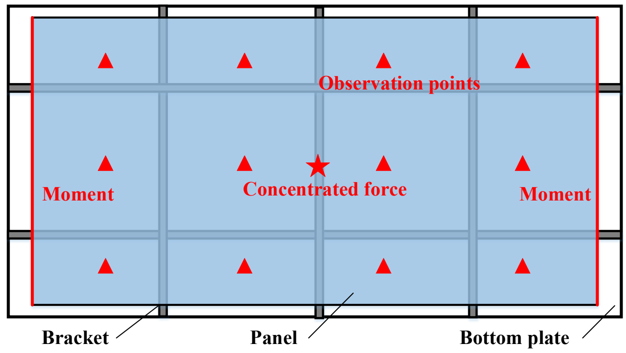


Figure 4. Schematic diagrams of measurement point layout and the loading situation.

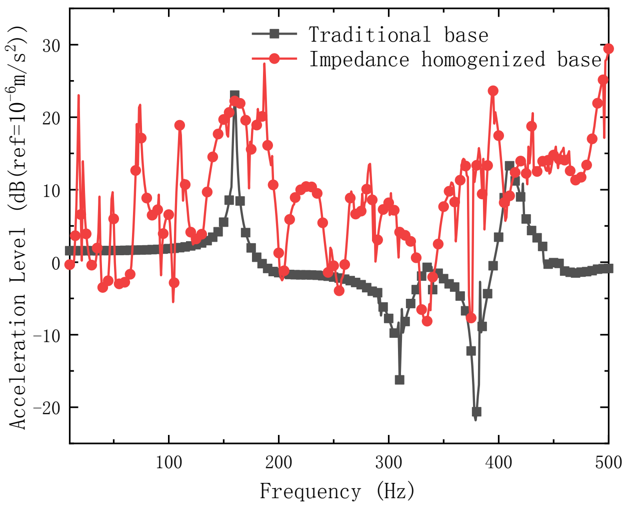


Figure 5. Comparison of average vibration level difference between two types of foundations subjected to concentrated force.

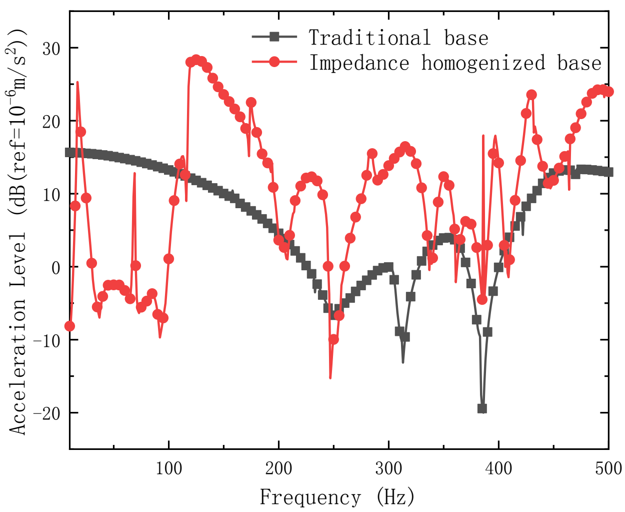


Figure 6. Comparison of average vibration level difference between two types of foundations subjected to the combined action of concentrated force and moment.

Figures 5-6 show that the impedance-balanced foundation performs better than the traditional foundation in the frequency range of 0-500 Hz when the foundation structure is subjected to a concentrated force, with an average isolation level of 10 dB higher than that of the traditional foundation. However, the isolation level of the impedance-balanced foundation in the frequency range of 0-100 Hz is lower than that of the conventional foundation when the focused force and moment load are coupled to the foundation. The impedance-balanced foundation's isolation level, which is more than 12 dB higher than that of the conventional foundation in the frequency range of 100-500 Hz, can reach up to 30 dB at the 125 Hz frequency point. Therefore, it can be seen that the impedance-balanced foundation has better isolation performance in a wide frequency range.

4. Analysis of the Impedance-balanced Foundation Isolation Characteristics

4.1 The Influence of the Structural Form of the Foundation Panel

The Influence of Panel Thickness on the Isolation Characteristics of the Impedance-balanced Foundation

Based on the above structural model, analyze and calculate the impact of changes in the thickness of the foundation panel on the vibration isolation characteristics of the foundation structure. To improve computational efficiency, the above model is further simplified into a shell structure model. The thickness of the foundation panel is 10 mm, 15 mm, and 20 mm, respectively. The calculation results of the average vibration acceleration level of the lower surface of the foundation are shown in Figure 7, and the difference in the foundation vibration level is shown in Figure 8.

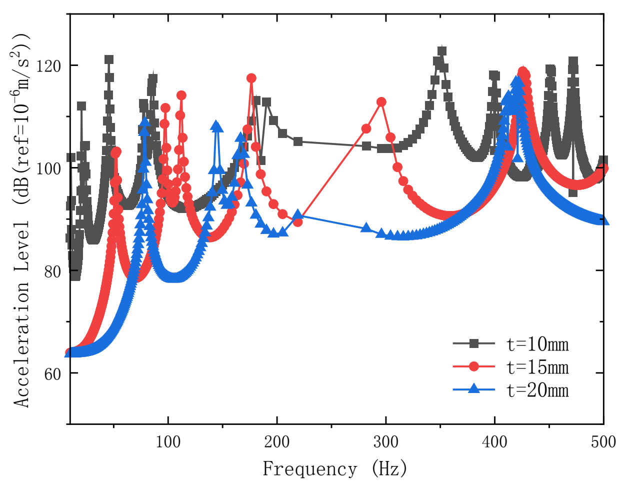


Figure 7. Average vibration acceleration level curve of assessment points with different thicknesses of foundation panels.

From Figures 7-8, it can be seen that as the thickness of the foundation panel increases, the average level of the assessment points of the hull structure under the foundation decreases overall. When the thickness is greater than 15 mm, further increasing the thickness does not reduce the system's vibration level. As the frequency gradually increases, the peak acceleration response shifts to the high frequency. This is because the increase in thickness increases the stiffness of the foundation system. By comparing the results in Figure 8, it is found that, although the increase in thickness makes the foundation exhibits a stronger vibration isolation effect at most frequency points, not all frequency point positions within the analysis frequency band have increased vibration level difference, and even negative vibration level difference have been calculated at some frequency points. Therefore, in the design process of the impedance-balanced foundation, it is necessary to combine the excitation load characteristics of the equipment with adjusting the panel thickness.

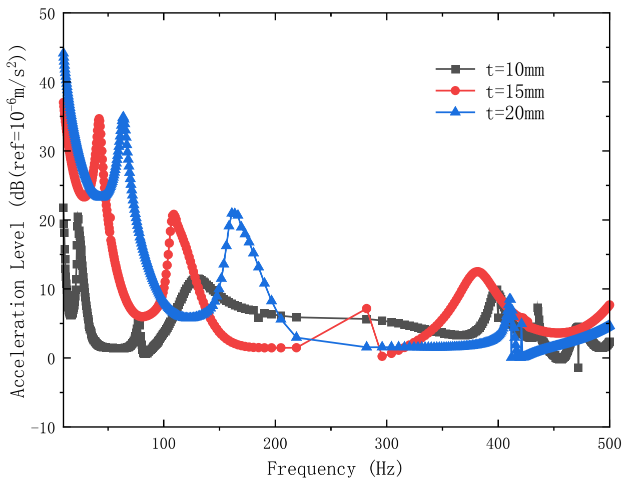


Figure 8. Average vibration level difference curve of assessment points with different thicknesses of foundation panels.

The Influence of Panel Layout on the Vibration Isolation Characteristics of the Impedance-balanced Foundation

With a reasonable discussion of the foundation panel, the elastic waves in the response plane of the panel can be effectively isolated and controlled, thus effectively increasing the vibration reduction and isolation level of the foundation. To investigate the influence of panel layout on the vibration characteristics of impedance-balanced foundation, taking the four layout schemes shown in Table 3 and Figure 9 as examples, the vibration response of the foundation under different panel layout modes was calculated, and the calculation frequency band and loading method were the same as the previous text.

The comparison of the vibration response and vibration level difference of different schemes of the foundation is shown in Figures 10-11. It can be seen that in the 10-500 Hz frequency band, after disassembling the foundation panel, the vibration isolation characteristics of the foundation will change. In the 10-500 Hz analysis frequency band, Scheme 4 causes the lowest level of structural vibration response. In each scheme, as the number of sub-panels increases, the number of peaks in the response curve will decrease, and the curve has a tendency to shift towards high frequencies. From the vibration level difference curves of each scheme, it can be observed that Scheme 1 has a higher vibration isolation effect at 10-100 Hz, the average isolation level is about 10 dB.

Table 3. Size parameters of fluid-filled sac under different layout schemes of the foundation.

Disassembly scheme	Number of panels/piece	Single foundation panel size/m
Scheme 1	2	0.90 × 1.60
Scheme 2	3	0.60 × 1.60
Scheme 3	4	0.90 × 0.70
Scheme 4	6	0.60 × 0.70

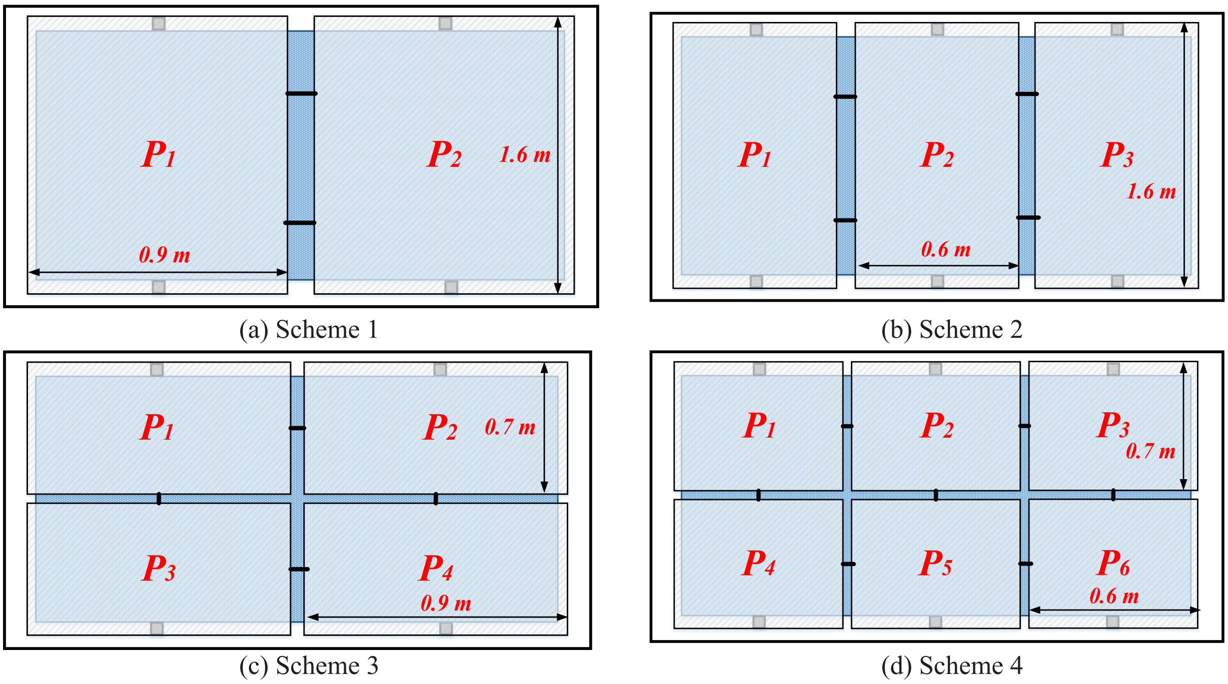


Figure 9. Schematic diagrams of different layout schemes for the foundation panel.

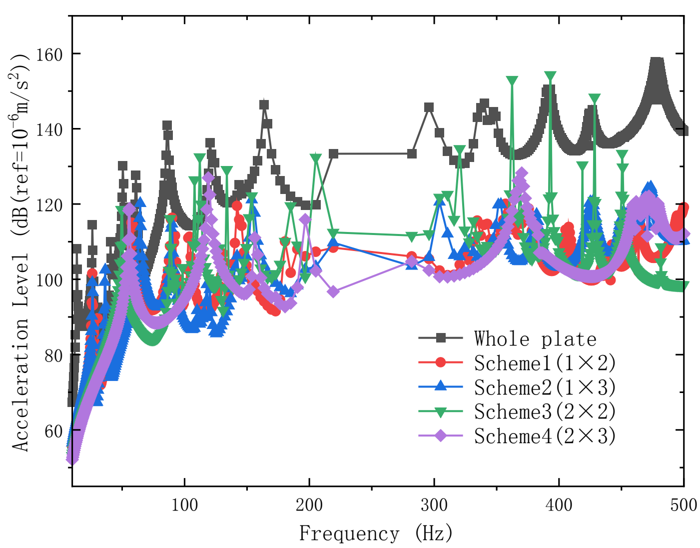


Figure 10. Average vibration acceleration level curve of the bottom plate with different layout schemes of the foundation panel.

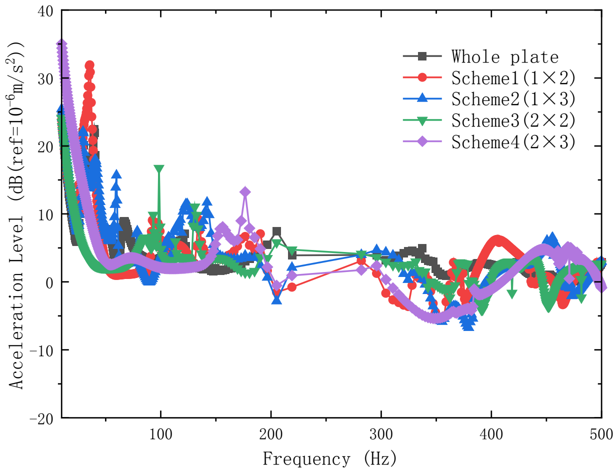


Figure 11. Vibration level difference curve of assessment points with different layout schemes of foundation panels.

4.2 Influence of Foundation Panel Connection Stiffness

To investigate the influence of the stiffness of the foundation panel connection on the vibration reduction and isolation characteristics of the foundation, based on the foundation model of Scheme III mentioned above, the average vibration acceleration level of the foundation plate was calculated when the hinge stiffness between the foundation panels was 500 N·m^2, 1000 N·m^2 and 1500 N·m^2, respectively. The calculation results are shown in Figures 12-13.

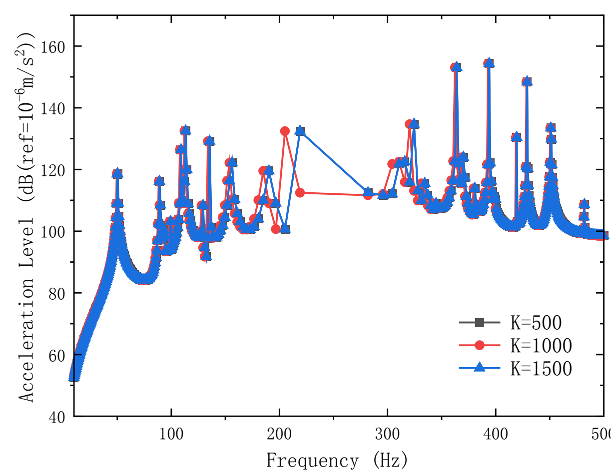


Figure 12. Average vibration acceleration level curve of the foundation plate with different connection stiffness of the foundation panel.

From Figures12-13, it can be seen that in the frequency band of 10-500 Hz, when the stiffness of the hinge connections among the panels increases, the acceleration response curves of each structure remain basically consistent, and the frequencies corresponding to the positions with larger responses in the curves remain basically unchanged. The maximum isolation level in the frequency range of 10-500 Hz is 25 dB. This is because the increase in the stiffness of the connections between the foundations has a limited effect on the overall natural character of the foundations. The lower the stiffness, the more pronounced the oscillation of the vibration level difference curve in the frequency band. However, as the stiffness increases, the change in the vibration level difference curve is relatively stable.

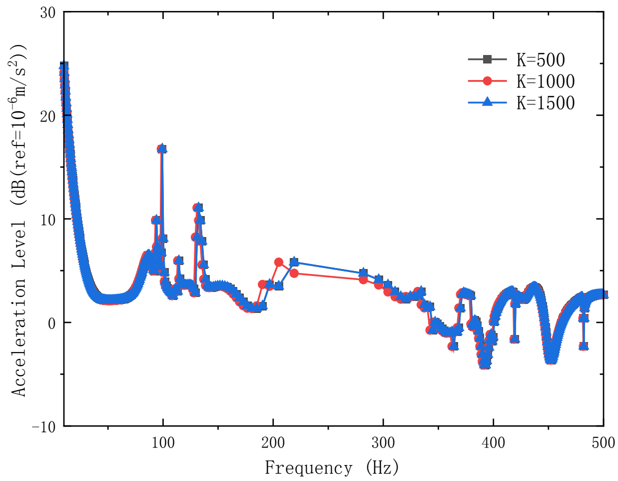


Figure 13. Average vibration acceleration level difference curve of foundation panel with different connection stiffness.

4.3 The Vibration Isolation Property of the Impedance-balanced Foundation Subjected to White Noise Excitation

Using white noise excitation in the calculation of isolation performance is of significant importance. White noise excitation is a signal with constant average power spectral density across all frequencies. By containing components of various frequencies, the use of white noise excitation allows for a more comprehensive evaluation of the performance of the isolation system, providing a valuable reference for isolation design and optimization. Therefore, this paper conducts the calculation of impedance-balanced foundation isolation performance under white noise excitation based on the aforementioned model. The calculation results are shown in Figure 14.

From Figure 14, it can be observed that the impedance-balanced foundation isolation performance, under white noise excitation, exhibits a similar curve trend to that under unit force excitation. Both show effective isolation in the frequency range of 10-150 Hz, with maximum isolation of 18 dB at 100 Hz. However, the isolation effectiveness is weaker in the frequency range greater than 300 Hz. Therefore, it can be concluded that the impedance-balanced foundation possesses favorable low-frequency isolation performance.

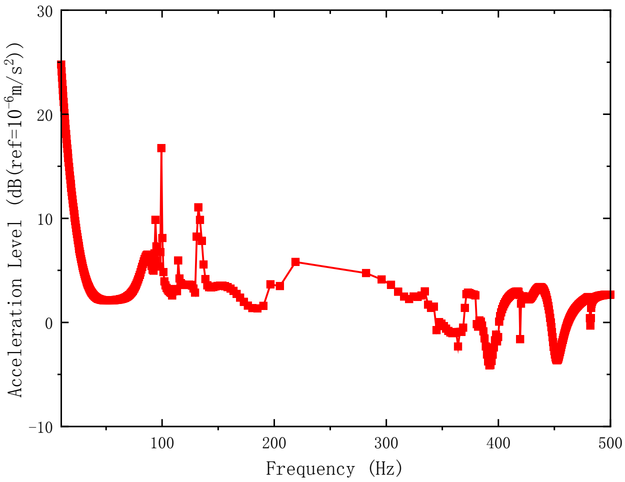


Figure 14. Average vibration acceleration level curve of the foundation plate with different connection stiffness of the foundation panel.

5. Conclusions

This paper proposes a vibration reduction method based on the principle of impedance balancing and designs an impedance-balanced foundation with a "discontinuous panel-vibration isolation liquid layer-foundation structure". Based on the structure-acoustic coupling finite element method, the vibration reduction characteristics of the impedance-balanced foundation under unbalanced excitation of the equipment are studied, and the influence of the structural parameters of the foundation panel on its vibration reduction characteristics is explored. The main conclusions are as follows:

(1) The vibration level difference of the impedance-balanced foundation is higher than that of the traditional foundation with 10 dB in the low-frequency band of 10-500 Hz subjected to the combined action of unbalanced excitation force and moment.

(2) The thickness and quantity of the panel have an influence on the isolation performance of the impedance-balanced foundation. Furthermore, the impedance-balanced foundation exhibits superior vibration isolation performance within the low-frequency range of 10-150 Hz. When the number of sub-panels is 4 and the arrangement is 2 * 2, the isolation performance of the foundation is better among the four layout schemes considered in this paper. The effect of panel connection stiffness on the isolation performance of the foundation is not obvious.

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Data Availability Statement

The data used to support the findings of this study are included within the article.

Conflict of Interest

The authors declare that there is no conflict of interest.

References

[1] Yao, Y.R., Zhu, Sh.J., 2003. Li yong pin lv xiang ying han shu qiu she bei dui ji zuo de ji li (Chinese) [On determination of the exciting force of the equipment from the frequency-response function]. Chuan Hai Gong Cheng. (3), 5-8.

[2] Česnik, M., Slavič, J., Čermelj, P., et al., 2013. Frequency-based structural modification for the case of base excitation. Journal of Sound and Vibration. 332(20), 5029-5039.
DOI: https://doi.org/10.3390/MACHINES11020229

[3] Zhao, F., Li, H., Li, H., et al., 2023. Experimental investigation of vibration reduction effect of high-pressure air compressor using composite damping base. Machines. 11(2), 229.
DOI: https://doi.org/10.3390/MACHINES11020229

[4] Tan, X.X., 2022. qian shui zhuang bei nei bu ji zuo zu kang fen xi ji you hua she ji yan jiu (Chinese) [Research on impedance analysis and optimization design of diving equipment internal foundation] [Master's thesis]. Chengdu: University of Electronic Science and Technology.
DOI: https://doi.org/10.27005/d.cnki.gdzku.2022.001819

[5] Peng, D.W., 2020. Chuan bo ji zuo zu kang pi pei she ji yan jiu (Chinese) [Research on impedance matching design of ship foundation] [Master's thesis]. Harbin: Harbin Engineering University.
DOI: https://doi.org/10.27060/d.cnki.ghbcu.2020.000083

[6] Li, H., 2022. Da gong lü jian chuan yong chi lun xiang xiang ti jie gou de jian zhen jiang zao fang fa yan jiu (Chinese) [Research on vibration and noise reduction method for high power marine gearbox housing structure] [Master's thesis]. Harbin: Harbin Institute of Technology.
DOI: https://doi.org/10.27061/d.cnki.ghgdu.2020.001018

[7] Wang, G.Zh., Hu, Y.Ch., Chou, Y.W., 2012. Ji zuo can shu dui jian chuan jie gou zhen dong yu sheng

fu she de ying xiang (Chinese) [Effects of the foundation parameters on ship structural vibration and acoustic radiation]. Jiang Su Ke Ji Da Xue Xue Bao (Zi Ran Ke Xue Ban). 26(03), 222-225.

[8] Yang, D.Q., Yang, K., Wang, B.H., 2020. Gang duzhi liang-zu ni zong he you hua de chuan bo jian zhen tong yi zu kang mo xing fa (Chinese) [A unified impedance modeling method for ship structural dynamics synthetic layout optimization design]. Zhen Dong Gong Cheng Xue Bao. 33(3), 485-493. DOI: https://doi.org/10.16385/j.cnki.issn.1004-4523.2020.03.006

[9] Yang, K., Yang, D.Q., Wu, B.H., 2019. gao chuan di sun shi ji zuo zu kang you hua she ji fa (Chinese) [Impedance optimization design of foundation structures with high transmission loss]. Zhen Dong Yu Chong Ji. 38(6), 7-14. DOI: https://doi.org/10.13465/j.cnki.jvs.2019.06.002

[10] Lin, Y.Sh., Wu, W.G., 2015. Zu zhen zhi liang zu yi jie gou sheng chuan di fen xi fang fa ji bo zu te xing (Chinese) [Method for solving problems about impeding structure-borne sound transmission from blocking masses and wave impedance characteristics]. Hua Zhong Ke Ji Da Xue Xue Bao (Zi Ran Ke Xue Ban). 43(10), 30-36. DOI: https://doi.org/10.13245/j.hust.151007

[11] Liu, J.H., Jin, X.D., Li, Z., 2003. Zu zhen zhi liang zu yi jie gou sheng de chuan di (Chinese) [Impediment to structure-borne sound propagation from vibration isolation mass]. Shanghai Jiao Tong Da Xue Xue Bao. 37(8), 1201-1204. DOI: https://doi.org/10.16183/j.cnki.jsjtu.2003.08.015

[12] Yuan, C., Zhu, X., Zhang, G., et al., 2007. Indirect engineering estimation of force excited by machinery vibration sources of ship. Journal of Ship Mechanics. 11(6), 961.

[13] Chen, R., Liu, Sh.J., 2015. Dai fen bu shi dong li xi zhen qi ji zuo zhen dong chuan di te xing yan jiu (Chinese) [Study on vibration transmission characteristics of foundation system with distributed dynamic absorbers]. Chuan Bo Gong Cheng. 37(06), 50-53+74. DOI: https://doi.org/10.13788/j.cnki.cbgc.2015.06.050

[14] Ye, L.C., Xiao, W.Q., Shen, J.P., et al., 2021. Ji yu li zi zu ni de dong li zhuang zhi ji zuo jian zhen you hua she ji yan jiu (Chinese) [Vibration reduction optimization design of power plant installation foundation based on particle damping]. Zhen Dong Yu Chong Ji. 40(03), 40-47. DOI: https://doi.org/10.13465/j.cnki.jvs.2021.03.006

[15] Wu G.X., Jia, X.G., Zhang, Y., et al., 2022. Ji yu zhi hui fei xian xing ji zuo jie gou de jian chuan di pin xian pu zhong gou shi yan yan jiu (Chinese) [Low frequency line spectrum reconstruction tests of ship vibration based on hysteretic nonlinear foundation structure]. Zhen Dong Yu Chong Ji. 41(19), 122-128. DOI: https://doi.org/10.13465/j.cnki.jvs.2022.19.016

[16] Gong, Y.F., Peng, W.C., Zhang, J.J., et al. (editors), 2019. Research on the impediment to vibration wave propagation of pipe from a vibration isolation mass. 2019 5th Asia Conference on Mechanical Engineering and Aerospace Engineering; 2019 Jun 1-3; Wuhan, China. 288, 01002. DOI: https://doi.org/10.1051/matecconf/201928801002

[17] Qi, L.B., Zou, M.S., Liu, S.X., et al., 2019. Use of impedance mismatch in the control of coupled acoustic radiation of the submarine induced by propeller-shaft system. Marine Structures. 65, 249-258. DOI: https://doi.org/10.1016/j.marstruc.2019.02.001

[18] Pei, Y., Liu, Y., Zuo, L., 2018. Multi-resonant electromagnetic shunt in base isolation for vibration damping and energy harvesting. Journal of Sound and Vibration. 423, 1-17. DOI: https://doi.org/10.1016/j.jsv.2018.02.041

[19] Chen, Y.Q., Shuai, Ch.G., Xu, G.M., 2021. Qi nang ge zheng qi nai ya qiang du yan jiu (Chinese) [Research on the strength of air spring isolator]. Journal of Ship Mechanics. 25(07), 956-962.

[20] Du, X., Li, M., 2021. Nonlinear vibration mechanism of the marine rotating machinery with airbag isolation device under heaving motion. Shock and Vibration. 1-15. DOI: https://doi.org/10.1155/2021/8816723

[21] Bu, W.J., Shi, L., He, L., et al., 2019. Multi-objective coordinated attitude control method fordual layer air spring vibration isolation mounting. Journal of National University of Defense Technology. 41(06), 70-74.

[22] Yin, L.H., Xu, W., Liu, S., et al., 2022. Ji yu you xian yuan de fu he jie gou qi nang ge zhen qi jing tai te xing yan jiu (Chinese) [Research on static characteristics of compound structure air spring based on finite element]. Chuan Jian Ke Xue Ji Shu. 44(04), 38-42.

[23] Li, Y., Li, J., Tian, T., et al., 2013. A highly adjustable magnetorheological elastomer base isolator for applications of real-time adaptive control. Smart Materials and Structures. 22(9), 095020. DOI: https://doi.org/10.1088/0964-1726/22/9/095020

[24] Wu, W.H., Xiang, Y., Luo, W., et al., 2019. Fu za ji xie ge zhen xi tong zu kang yu chuan di sun shi guan lian xing yan jiu (Chinese) [Research on correlation between transmission loss and impedance of complex

mechanical isolation systems]. Zao Sheng Yu Zheng Dong Kong Zhi. 39(1), 224-229.

[25] Ye, Zh.X., 2019. Ji zuo she ji dui ge zhen xiao guo de ying xiang fen xi yu you hua fang fa yan jiu (Chinese) [The influence and optimization of foundation design to the performance of vibration isolation system]. Chuan Jian Ke Xue Ji Shu. 41(17), 48-51.

[26] De Domenico, D., Ricciardi, G., 2018. An enhanced base isolation system equipped with optimal tuned mass damper inerter (TMDI). Earthquake Engineering & Structural Dynamics. 47(5), 1169-1192. DOI: https://doi.org/10.1002/eqe.3011

[27] Maciejewski, I., Zlobinski, M., Krzyzynski, T., 2021. Optimal design of vibration-isolation systems by means of a numerical simulation. Journal of Mechanical Science and Technology. 35, 3887-3894. DOI: https://doi.org/10.1007/S12206-021-0802-Y

[28] Li, X.Zh., Lu, J., Li, M.Zh., 2022. Ban ke jie gou hou du dui zu kang te xing ying xiang fen xi yan jiu (Chinese) [Analysis and research on influence of plate-shell structure thickness on impedance characteristics]. He Dong Li Gong Cheng. 43(S1), 137-141. DOI: https://doi.org/10.13832/j.jnpe.2022.S1.0137