Study on vibration characteristics of periodic truss structure of offshore platform

Xia Zhaowang¹,², Xu Xiangxi¹, Ju Fuyu¹, Wang Zongyao¹, Lu Zhiwei¹ and Cao Rui¹

Abstract
Using the band gap properties of the periodic structure, the truss structure of an offshore platform is designed as a one-dimensional periodic conduit structure, and the band gap characteristics are used to realize the vibration control of the truss structure of the offshore platform. The finite element method is used to simulate the vibration characteristics of the periodic conduit, and the influence of the structural parameters (length and wall thickness) of the periodic conduit on the vibration band gap of the periodic conduit is analysed. The frequency response characteristics of the periodic truss structure of an ocean platform are calculated and compared with those of a traditional truss structure. The results show that the periodic truss exhibits better suppression of vibration transmission than the traditional truss, especially for the vibration in the band gap, which is greatly attenuated. This study shows that the periodic structure has broad application prospects in vibration isolation design of truss structures for offshore platforms. The research provides a new technical approach for vibration control of truss structures on offshore platforms.

Keywords
Periodic structure, offshore platform, vibration control, band gap, truss

Date received: 29 May 2020; accepted: 16 October 2020

Handling Editor: James Baldwin

Introduction
In the field of marine engineering equipment, with the rapid development of China’s economy in recent years, the demand for oil and gas resources has become increasingly tense, and the development of offshore oil and gas resources is becoming increasingly important. As a basic facility for the development of marine oil and gas resources, the offshore platform is the base for offshore production operations and life, and its safety is of paramount importance. Offshore platform truss structures are inevitably affected by the combined effects of wind, waves, ocean currents and even ice seismic loads.¹,² Due to the long-term exposure in such harsh external environments, offshore platform³–⁵ trusses experience obvious vibration, which aggravates the fatigue damage of the platform, reduces the reliability of the system, and affects the safety and durability of the structure.⁷–⁹ The vibration control technology of offshore platforms has received increasing attention.⁹–¹¹

In recent years, it has been found that when elastic waves,¹² propagate in periodic composites or structures, the elastic waves are internally affected by the periodic

¹School of Energy and Power, Jiangsu University of Science and Technology, Zhenjiang, China
²School of Shipbuilding and Ocean Engineering, Jiangsu Maritime Institute, Nanjing, China

Corresponding author:
Xia Zhaowang, School of Energy and Power Engineering, Jiangsu University of Science and Technology, Mengxi Road 2, Zhenjiang 212003, China.
Email: dlxzw@163.com

Creative Commons CC BY: This article is distributed under the terms of the Creative Commons Attribution 4.0 License (https://creativecommons.org/licenses/by/4.0/) which permits any use, reproduction and distribution of the work without further permission provided the original work is attributed as specified on the SAGE and Open Access pages (https://us.sagepub.com/en-us/nam/open-access-at-sage).
structure and cannot propagate in a specific frequency range.\textsuperscript{13–15} This frequency range is called the band gap, and such periodic composites or structures with elastic band gaps are referred to as periodic structures.\textsuperscript{16–18}

At present, the band gap mechanism of periodic structures mainly consists of two kinds: the Bragg scattering mechanism\textsuperscript{19} and the local resonance mechanism.\textsuperscript{20} The reason why the band gap is generated is that when elastic waves propagate in the geometric or material medium of a periodic structure, the interaction between the periodic structure\textsuperscript{21–24} and the elastic waves causes the waves in some frequency bands to have no corresponding vibration modes in the periodic structure. That is, the elastic waves of a frequency band are greatly suppressed when propagating through the structure.

Therefore, by properly designing the periodic structure, it is possible to achieve effective suppression of vibration\textsuperscript{25,26} in a certain frequency range. At present, research on the theory of periodic structures has reached maturity. Shen et al. designed the conduit into a periodic structure and used the transfer matrix (TM) method to study the characteristics of steady-state waves in the system and the dynamic response of the periodic shell system.\textsuperscript{27,28} It is found that the periodic conduit has better vibration damping performance than the aperiodic conduit. Yu et al.\textsuperscript{29} founded the existence of the Bragg and locally resonant band gaps, corresponding to the velocity field, can exist in a periodic pipe system through experiments and analyzed the influence of relevant factors on the band gaps. In this paper, the mechanism of periodic structure damping\textsuperscript{30} is introduced into the design of truss structures of ocean platforms. The truss structures of ocean platforms are designed as a periodic conduit with wall thickness variation. The vibration characteristics of a periodic conduit are analysed by the finite element method. The influence of the structural parameters of the periodic conduit unit on the vibration band gap of the periodic conduit is analysed. The vibration band gap of the periodic conduit is used to suppress the vibration transmission of the truss structure of an ocean platform. It is found that the periodic truss structure of an ocean platform has better vibration damping performance than a traditional truss structure of an ocean platform in the periodic conduit band gap.

**Offshore platform truss structure and periodic conduit model**

Taking the structure of the offshore platform shown in Figure 1, the offshore platform is three layers, the height of each layer is 20 m, and the total height of the offshore platform with a bottom fixed pillar is 65 m. The top is a steel plate with a thickness of 0.02 m. The other parameters of the offshore platform are shown in Table 1:

An offshore platform truss structure is usually composed of steel conduits. Combined with the structural characteristics of the offshore platform and the periodic arrangement of the periodic structure, the four main conduits of the offshore platform are designed as a periodic conduit structure, as shown in Figure 2(a). Figure 2(b) shows the basic unit of the periodic conduit. The wall thicknesses of conduit sections A and B are 0.03 m and 0.08 m, respectively, the lengths of conduit sections

![Figure 1. Finite element model of offshore platform.](image)

![Figure 2. Periodic conduit diagram: (a) periodic conduit structure and (b) periodic conduit basic unit.](image)

| Table 1. Offshore platform conduit parameters. |
|-----------------------------------------------|
| Outer diameter (m) | Wall thickness (m) | Quantity |
|---------------------|-------------------|----------|
| Main conduit        | 1.35              | 0.05     | 4        |
| Horizontal conduit  | 0.7               | 0.02     | 16       |
| Oblique conduit     | 0.5               | 0.02     | 12       |
$a_1$ and $a_2$ are both 3 m, and the length $a$ of the basic unit of the conduit is 6 m. The following mainly studies the longitudinal vibration and bending vibration of the periodic conduit.

The bending vibration equation of the conduit is:

$$f_x - GA_y K_y \left( \frac{\partial^2 u_x}{\partial z^2} - \phi_y \right) = 0$$  \hspace{1cm} (1)$$

$$m_y - EI_y \frac{\partial^2 \phi_y}{\partial z^2} = 0$$  \hspace{1cm} (2)$$

$$\frac{\partial f_x}{\partial z} - (\rho_g A_p + \rho_f A_f) \frac{\partial^2 u_x}{\partial t^2} = 0$$  \hspace{1cm} (3)$$

$$\frac{\partial m_y}{\partial z} + f_x - (\rho_g A_p + \rho_f A_f) \frac{\partial^2 \phi_y}{\partial t^2} = 0$$  \hspace{1cm} (4)$$

Where $G = \frac{E}{2(1 + \nu)}$, $K_y = \frac{6E}{(1 + \nu)(1 - 2\nu)}$, $f_x$, $u_x$, $\phi_y$ and $m_y$ representing the shear force, displacement, rotation angle and torque of the cross section of the conduit along the $x$ direction; $I_p$, $I_f$ representing rotational inertia of conduit and fluid; $A_f$ is the cross-sectional area of the fluid.

Let the left end of the conduit be the zero end face, and the solution of two adjacent unit cells is as follows:

$$\Psi_y^{(n-1)a}(a_1) = H_1 \Psi_y^{(n-1)b}(a_1)$$  \hspace{1cm} (5)$$

$$\Psi_y^{(n-1)b}(0) = K_1 \Psi_y^{(n-1)b}(0)$$  \hspace{1cm} (6)$$

$$\Psi_y^{(n-1)b}(a_2) = K_2 \Psi_y^{(n-1)b}(a_2)$$  \hspace{1cm} (7)$$

$$\Psi_y^{(n)b}(0) = H_2 \Psi_y^{(n)a}(0)$$  \hspace{1cm} (8)$$

Where:

$$H_1 = \begin{bmatrix}
-B_1 \sinh \lambda_1 & -B_1 \cosh \lambda_1 & B_2 \sin \lambda_2 & -B_2 \cos \lambda_2 \\
-B_3 & 0 & -B_4 & 0 \\
0 & -B_5 & 0 & B_6 \cos \lambda_2 \\
0 & 1 & 0 & 0
\end{bmatrix}$$

$$H_2 = \begin{bmatrix}
0 & -B_1 & 0 & -B_2 \\
-B_3 & 0 & -B_4 & 0 \\
0 & -B_5 & 0 & B_6 \\
1 & 0 & 1 & 0
\end{bmatrix}$$

$$K_1 = \begin{bmatrix}
-B_1 \sinh \lambda_1 & -B_1 \cosh \lambda_1 & B_2 \sin \lambda_2 & -B_2 \cos \lambda_2 \\
-B_3 & 0 & -B_4 & 0 \\
0 & -B_5 & 0 & B_6 \\
1 & 0 & 1 & 0
\end{bmatrix}$$

$$K_2 = \begin{bmatrix}
-B_1 \sinh \lambda_1 & -B_1 \cosh \lambda_1 & B_2 \sin \lambda_2 & -B_2 \cos \lambda_2 \\
-B_3 \sinh \lambda_1 & -B_3 \cosh \lambda_1 & -B_4 \cos \lambda_2 & -B_4 \sinh \lambda_2 \\
-B_5 \sinh \lambda_1 & -B_5 \cosh \lambda_1 & -B_6 \sin \lambda_2 & B_6 \cos \lambda_2 \\
-B_1 \sin \lambda_1 & B_1 \cosh \lambda_1 & B_2 \sin \lambda_2 & -B_2 \cos \lambda_2
\end{bmatrix}$$

The longitudinal vibration equation of the conduit is:

$$\rho \frac{\partial^2 \mathbf{u}}{\partial t^2} = \frac{\partial}{\partial x} \left( E \frac{\partial \mathbf{u}}{\partial x} \right)$$  \hspace{1cm} (9)$$

Where $u$ is the displacement at $x$.

The amplitude of the first cell material $A$ is:

$$U_{n1}(x) = P_{n1}^+ e^{i \omega x} + P_{n1}^- e^{-i \omega x}$$  \hspace{1cm} (10)$$

The amplitude of the first cell material $B$ is:

$$U_{n2}(x) = P_{n2}^+ e^{i \omega x} + P_{n2}^- e^{-i \omega x}$$  \hspace{1cm} (11)$$

where $P_{n1}^+$ and $P_{n1}^-$ are the positive and negative directions along the axis, respectively. $a_1 = \sqrt{k_3 - \left( \frac{w}{c_{1f}} \right)^2}$ and $a_2 = \sqrt{k_3 - \left( \frac{w}{c_{1f}} \right)^2}$ represents the wave velocity in the $x$ direction.

The relationship between the ($n$–1)th cell and the $n$th cell is:

$$\psi_{n2} = T \psi_{(n-1)2}$$  \hspace{1cm} (12)$$

where $\psi_{ni} = \begin{bmatrix} P_{ni}^+ \\ P_{ni}^- \end{bmatrix}$

The periodic property of the periodic conduit in the $x$ direction is obtained by Bloch’s theorem:

$$\psi_{n2} = e^{ikx} \psi_{(n-1)2}$$  \hspace{1cm} (13)$$

Using equations (12)–(13), we can get the standard matrix eigenvalues:

$$|T - e^{ikx}I| = 0$$  \hspace{1cm} (14)$$

where $I$ is a $4 \times 4$ identity matrix, $k$ is the one-dimensional Bloch wave vector. By solving the matrix $T$, the dispersion relationship between the wave vector and frequency can be obtained.

The vibration band gap characteristics of the periodic conduit

**Longitudinal vibration characteristics of the periodic conduit**

A longitudinal harmonic excitation perpendicular to the end face of the conduit is applied to one end of the periodic conduit with an excitation frequency range of 0–1000 Hz, and the simulation analysis uses free vibration without any boundary constraints. The output response of the other end is obtained by calculation, and the longitudinal vibration characteristic curve of the periodic conduit is shown in Figure 3. Figure 3 shows that the periodic conduit has a significant band gap in the 295–580 Hz range with a maximum attenuation value of 88 dB compared to a conventional conduit with equal wall thickness.
A simple harmonic excitation parallel to the end face of the conduit is applied to one end of the conduit to obtain a periodic conduit bending vibration characteristic curve, as shown in Figure 4. Figure 4 shows that compared with the conventional conduit with equal wall thickness, there are obvious band gaps in the three frequency bands of 235–290 Hz, 430–520 Hz and 845–1000 Hz, and the bending vibration band gap of the periodic conduit is more dispersed than the longitudinal vibration band gap.

**Bending vibration characteristics of the periodic conduit**

The influence of structural parameters on the band gap of the periodic conduit

The influence of the geometric parameters of the periodic conduit (unit length and wall thickness) on the band gap is analysed.

**The influence of the basic unit length of the periodic conduit**

The wall thicknesses of conduit sections A and B are 0.03 m and 0.08 m, respectively. According to the actual engineering application, the total length of the conduit is constant. When the basic unit length of the periodic conduit is increased, the number of conduits is reduced. Therefore, the influences of the basic unit length and the number of cycles of the periodic conduit on the band gap are considered together. When the total length of the conduit is 60 m, the basic unit length of the periodic conduit is 6 m, 10 m and 20 m, and the number of cycles is 10, 6 and 3, respectively. The calculated influences of the basic length of the conduit on the longitudinal vibration band gap and the bending vibration band gap are shown in Figures 5 and 6.

Figure 5 shows that increasing the unit length can effectively lower the centre frequency of the longitudinal vibration band gap. But since the total length is constant, the unit length increases, and the number of cycles is reduced, resulting in a decrease in the vibration attenuation of the band gap.

Figure 6 shows that for the periodic conduit with unit length of 6 m and 10 m, increasing the length of the unit can shift the bending vibration band gap of the periodic duct to low frequency, but the vibration attenuation in the band gap is reduced. When the unit
length is increased to 20 m, the band gap characteristics are not obvious because the number of cycles is too small. The above analysis shows that the bending vibration band gap has higher requirements on the number of cycles than the longitudinal vibration band gap, and it is necessary to comprehensively consider the influence of the two factors of the unit length and the number of cycles in engineering practice.

**The influence of periodic conduit wall thickness**

The length of the basic unit of the periodic conduit is 6 m, and the wall thicknesses \( t_A \) and \( t_B \) of basic unit sections A and B, respectively, of the periodic conduit are set to (0.03 m, 0.05 m), (0.03 m, 0.08 m), (0.05 m, 0.10 m) and (0.05 m, 0.12 m), four combinations with different wall thicknesses, to study the influence of the wall thickness of the conduit unit on the vibration characteristics. The vibration characteristics of the periodic conduit with the four wall thickness combinations are shown in Figures 7 and 8.

**Vibration characteristics of periodic truss structures on offshore platforms**

Since periodic conduits have band gap characteristics, periodic conduits are used as the main conduit in the truss structure of an offshore platform to improve the vibration isolation effect of the offshore platform from bottom to top. The length of the periodic conduit unit is 6 m, and the wall thicknesses \( t_a \) and \( t_b \) are 0.03 m and 0.08 m, respectively. The vertical and horizontal excitations are applied at the intersection of the lowermost horizontal conduit and the four main conduits of the truss structure of the ocean platform. The excitation and response positions are shown in Figure 1. The acceleration vibration responses of the excitation and the centre of the upper panel are detected, and the vibration transmission characteristics of the offshore platform are obtained, as shown in Figures 9 and 10.

Figure 7. Longitudinal vibration characteristics of the periodic conduit with different wall thicknesses.

Figure 8. Bending vibration characteristics of the periodic conduit with different wall thicknesses.

Figure 9. Vibration transmission characteristics of the trusses under vertical excitation.

Figure 10. Vibration transmission characteristics of the trusses under horizontal excitation.
truss offshore platform increases significantly at 255–575 Hz, which is basically consistent with the longitudinal vibration band gap of the periodic duct at 290–580 Hz, indicating that the vibration attenuation of this frequency band is mainly due to the band gap characteristics of the periodic structure. The reason for the slight deviation between the two frequency bands is mainly due to the calculation of the longitudinal vibration of the periodic conduit, which is the free boundary condition. In the simulation analysis of the periodic conduit truss offshore platform, the boundary condition of the periodic conduit is constrained by the connected conduit.

Figure 10 shows that under horizontal excitation, the vibration isolation effect is improved to some extent in most frequency bands for 0–1000 Hz. In the 230–280 Hz frequency band, the vibration isolation effect is improved by an average of 16 dB. In the 425–490 Hz frequency band, the vibration isolation effect is improved by approximately 21 dB. In the 790–980 Hz frequency band, the vibration isolation effect of the periodic conduit truss offshore platform is significantly better than that of the traditional conduit truss offshore platform. The three bands and the bending vibration band gap of the periodic conduit have good consistency, indicating that the band gap characteristics of the periodic structure can be used for the vibration isolation of the offshore platform.

**Conclusion**

In this paper, the main conduits of an offshore platform truss structure are designed as periodic conduits, and the band gap characteristics of the periodic structure are utilized to improve the vibration isolation performance of the offshore platform truss. Some conclusions are made as follows:

1. The periodic conduits composed of different wall thicknesses have obvious longitudinal vibration and bending vibration band gaps.
2. When the length of the conduit is constant, the length of the periodic conduit unit increases, and the centre frequency band of the vibration band gap moves to low frequency; however, the vibration attenuation decreases due to the decrease in the number of cycles. When the basic unit of the periodic conduit is too long, the number of cycles is too small, and the periodic conduit structure does not exhibit the band gap characteristics well.
3. Different wall thickness combinations of periodic conduits have little effect on the centre frequency of the band gap but have a greater influence on the bandwidth of the band gap. Increasing the wall thickness difference can increase the band gap width. When there is no wall thickness difference, the small wall thickness of the periodic conduit has a wider band gap.
4. Under vertical and horizontal excitation, the periodic duct truss structure has more obvious vibration attenuation in some frequency bands than the traditional duct truss structure, and these frequency bands have good consistency with the vibration band gap of the periodic duct.

**Declaration of conflicting interests**

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

**Funding**

The author(s) disclosed receipt of the following financial support for the research, authorship, and/or publication of this article: The research reported in this paper was sponsored by the Natural Science Foundation of Jiangsu Province (BK20191462).

**ORCID iD**

Xu Xiangxi https://orcid.org/0000-0002-6381-1244

**References**

1. Shuai S, Guo-Feng Z, Shuai-Lin W, et al. Ice induced vibration of conical offshore platform structure based on discrete element model-finite element model. Chin J Comput Mech 2015; 32: 662–667.
2. Qiong W, Wei Z, Weiguo Z, et al. A tuned mass damper with nonlinear magnetic force for vibration suppression with wide frequency range of offshore platform under earthquake loads. Shock Vib 2018; 43: 1–18.
3. Punurai W, Azad MS, Pholdee N, et al. A novel hybridized metaheuristic technique in enhancing the diagnosis of cross-sectional dent damaged offshore platform members. Comput Intell 2020; 36: 34–52.
4. Shen Y, Sahoo PK and Pan Y. A study of micro-arc oxidation coatings on aluminum alloy drill pipe for offshore platform. Mar Technol Soc J 2017; 51: 16–22.
5. Shi J, Li J, Yuan Z, et al. A simplified statistic-based procedure for gas dispersion prediction of fixed offshore platform. Process Saf Environ Prot 2018; 114: 48–63.
6. Viola SM, Page HM, Zaleski SF, et al. Anthropogenic disturbance facilitates a non-native species on offshore oil platforms. J Appl Ecol 2018; 33: 232–245.
7. Xia ZW, YuanQL, Mao KJ, et al. Vibration characteristics analysis of auxiliary mono-layer semi-active isolation system. J Ship Mech 2017; 21: 69–75.
8. Fang Y, Zuo Y and Xia Z. Vibration transmission analysis of nonlinear floating raft isolation system with magneto-rheological damper. J Low Freq Noise V A 2018; 37: 700–710.
9. Krishnamoorthy P, Chin CS, Gao Z, et al. A multi-hop microprocessor based prototype system for remote
vibration and image monitoring of underwater offshore platform. In: IEEE 7th international conference on cybernetics and intelligent systems (CIS) and IEEE conference on robotics, automation and mechatronics (RAM), Siem Reap, Cambodia, 15–17 July 2015, pp.268–275. IEEE.
10. Liu F, Li H, Wang W, et al. Frequency variation and sensor contribution assessment: Application to an offshore platform in the South China Sea. *J Sound Vib* 2015; 337: 218–232.
11. Bian J and Jing X. Superior nonlinear passive damping characteristics of the bio-inspired limb-like or X-shaped structure. *Mech Syst Signal Process* 2019; 125: 21–51.
12. He ZC, Li E, Wang G, et al. Development of an efficient algorithm to analyze the elastic wave in acoustic metamaterials. *Acta Mech* 2016; 227: 3015–3030.
13. Zhao TT, Lin SY and Duan YL. Suppression of lateral vibration in rectangular ultrasonic plastic welding tool based on phononic crystal structure. *Acta Phys Sin* 2018; 67: 280–285.
14. Chang IL, Liang ZX, Kao HW, et al. The wave attenuation mechanism of the periodic local resonant metamaterial. *J Sound Vib* 2018; 412: 349–359.
15. Shen H, Jen W, Yu D, et al. The vibrational properties of a periodic composite pipe in 3D space. *J Sound Vib* 2009; 328: 57–70.
16. Wen J, Wang G, Yu D, et al. Theoretical and experimental investigation of flexural wave propagation in straight beams with periodic structures: application to a vibration isolation structure. *J Appl Phys* 2005; 97: 114907.
17. Massidda S, Continenza A, Freeman AJ, et al. Structural and electronic properties of narrow-band-gap semiconductors: InP, InAs, and InSb. *Phys Rev B Condens Matter* 2016; 41: 12079–12085.
18. Liu C, Jing X and Chen Z. Band stop vibration suppression using a passive X-shape structured lever-type isolation system. *Mech Syst Signal Process* 2016; 68: 342–353.
19. Sigalas M and Economou EN. Band structure of elastic waves in two dimensional systems. *Solid State Commun* 1993; 86: 141–143.
20. Liu Z, Zhang X Mao., et al. Locally resonant sonic materials. *Science* 2000; 289: 1734–1736.
21. Chigrin DN, Lavrinenko AV, Yarotsky DA, et al. All-dielectric one-dimensional periodic structures for total omnidirectional reflection and partial spontaneous emission control. *J Light Technol* 2018; 17: 2018–2024.
22. McGrath DT and Pyati VP. Periodic structure analysis using a hybrid finite element method. *Radio Sci* 2016; 31: 1173–1179.
23. Shaw AD, Hill TL, Neild SA, et al. Periodic responses of a structure with 3:1 internal resonance. *Mech Syst Signal Process* 2016; 61: 19–34.
24. Lin Z, Ramezani H, Eichelkraut T, et al. Unidirectional invisibility induced by PT-symmetric periodic structures. *Phys Rev Lett* 2011; 106: 213901.
25. Lin CY, Huang YH and Chen WT. Multimodal suppression of vibration in smart flexible beam using piezoelectric electrode-based switching control. *Mechatronics* 2018; 53: 152–167.
26. Ou J, Long X, Li QS, et al. Vibration control of steel jacket offshore platform structures with damping isolation systems. *Eng Struct* 2007; 29: 1525–1538.
27. Shen HJ, Wen JH, Yu DL, et al. Coupled flexural-longitudinal vibration in a curved periodic pipe conveying fluid. *Adv Mater Res* 2011; 328: 1734–1738.
28. Shen HJ, Wen JH, Yu DL, et al. Stability of fluid-conveying periodic shells on an elastic foundation with external loads. *J Fluids Struct* 2014; 46: 134–148.
29. Yu D, Wen J, Shen H, et al. Propagation of steady-state vibration in periodic pipes conveying fluid on elastic foundations with external moving loads. *Phys Lett A* 2012; 376; 3417–3422.
30. Xia Z, Mao K, Wei S, et al. Application of genetic algorithm-support vector regression model to predict damping of cantilever beam with particle damper. *J Low Freq Noise V A* 2017; 36: 138–147.