

Metastructured Drill Pipe and Its Three-Directional Coupled Vibration Damping Mechanism

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Abstract: To address the problem that longitudinal, lateral, and torsional vibrations of drill pipes during oil and gas well drilling, as well as their coupled interactions, are difficult to effectively control, this paper proposes a novel drill pipe structure based on the principle of local resonance--the metastructured drill pipe. Through finite element analysis, this study calculated the band structure, characteristic modal displacement fields, and vibration transmission characteristics under finite periodicity, systematically explaining its bandgap properties. The research results show that the designed locally resonant metastructured drill pipe opens a complete three-directional bandgap in the range of 44.30 Hz to 81.14 Hz, which can effectively suppress the propagation of three types of vibrations, including longitudinal, lateral, and torsional vibrations. Mechanism analysis indicates that this bandgap originates from the simultaneous suppression of the three primary modes of the host shaft by the local resonators, thereby hindering the propagation of the three wave modes, forming a complete bandgap. Further parameter studies show that by adjusting the structural parameters of the local resonators, the position and width of the bandgap can be effectively tuned. The metastructured drill pipe concept proposed in this paper provides a new theoretical approach to address the shortcomings of traditional methods in controlling multi-directional coupled vibrations of drill pipes, offering a new guided solution for drill pipe vibration control under complex downhole conditions in oil wells.

Keywords: Low-frequency Vibration Reduction; Metastructure; Bandgap Characteristics; Oil Drill Pipe; Metamaterial.

1. Introduction

During oil and gas well drilling, the drill pipe operates for extended periods in a long, narrow wellbore filled with drilling fluid, subjected to complex loads such as bottom-hole pressure, friction, and variations in rock hardness, which easily excite longitudinal, lateral, and torsional vibrations as well as their coupled interactions[1][4]. Such vibrations not only accelerate the fatigue damage of drill pipe connection threads but may also lead to serious accidents such as downhole tool failure and wellbore trajectory loss of control, directly affecting the service life of drilling tools and drilling efficiency[5][7]. Existing vibration damping methods mostly target vibrations in a single direction, making it difficult to effectively suppress coupled longitudinal-torsional-lateral vibrations, which has become a key technical bottleneck in the safe operation of drill pipes[8][10]. In recent years, metastructures have attracted widespread attention due to their unique bandgap characteristics, i.e., the ability to inhibit the propagation of elastic waves within specific frequency ranges. By rationally designing structural parameters, the position and width of bandgaps can be actively controlled, thereby achieving effective management of elastic wave propagation behavior within specific frequency ranges[11][14]. This provides a new approach to address the problem of controlling low-frequency multi-directional coupled vibrations of drill pipes under complex working conditions. Based on the bandgap regulation mechanism of metastructures, scholars have systematically explored the structure-property relationships of bandgaps in one-dimensional elastic components like rods and shafts by integrating wave propagation characteristics design with traditional structural load-bearing functions. In recent years, extensive research has been conducted on one-dimensional metastructures suppressing lateral, torsional, and longitudinal

vibrations. For longitudinal vibration control, Li Mengchang et al. proposed a novel pipeline metastructure that generates a Bragg scattering bandgap and a local resonance bandgap, effectively suppressing longitudinal vibration in the medium-frequency range[15]; Wei Zhendong et al. designed a one-dimensional periodic metastructure isolator composed of metal and rubber, which utilizes bandgap characteristics to achieve longitudinal vibration control in ship hydraulic pipelines[16]; Wang Kexin et al. introduced tunable-frequency local resonance units into the same fluid-filled pipeline metastructure and optimized their installation positions, successfully achieving suppression of axial vibration in multiple target frequency bands[17]. For torsional wave vibration control, Chen et al. studied the tunability of bandgaps in a stepped shaft with periodically attached piezoelectric rings, suppressing torsional wave propagation in different frequency ranges by changing the electrical parameters of shunt circuits[18]; Zhou et al. proposed a quasi-zero-stiffness local resonance oscillator, which demonstrates good suppression effects on low-frequency torsional vibration[19]. For transverse wave vibration control, Li Suobin et al. proposed a sandwich metastructure beam-plate structure, which can effectively suppress longitudinal and transverse waves in the low-frequency range[20][21]. Fu Qiang et al. proposed a novel locally resonant sandwich metastructure beam, consisting of a sandwich beam host and local resonance units composed of mass blocks wrapped in soft material, capable of meeting low-frequency and high-bandwidth transverse wave damping requirements[22]; Zhao Feng et al. constructed a constant-value quasi-zero-stiffness isolator based on a double-pair inclined rod negative stiffness mechanism. This structure can conveniently achieve the desired constant quasi-zero stiffness using rods and springs, exhibiting superior low-frequency transverse wave isolation performance[23].

This paper addresses the control requirements for coupled longitudinal-torsional-lateral vibrations in drill pipes. Based on the local resonance principle, a metastructured drill pipe with multi-directional vibration suppression capabilities is designed. The finite element method is used to systematically analyze the band structure characteristics, characteristic modal shapes, and vibration transmission laws of longitudinal, transverse, and torsional waves in finite structures. The formation mechanism of the multi-directional coupled vibration bandgap is revealed, and the influence of structural parameters on bandgap characteristics is explored, providing a theoretical basis for the vibration damping application of metastructures in petroleum engineering.

2. Model and Band Structure Calculation Method

Based on the bandgap formation mechanism of locally resonant metastructures, this paper proposes a locally resonant metastructured drill pipe model. As shown in Figure 1, the local resonance unit of this model consists of three parts: the outer scattering ring (red part), the soft material ring coating the outer side of the host rod (green part), and the hard ring transversely embedded between the two soft material rings (brown part). This unit is periodically arranged along the axial direction (x-direction) to form the metastructured drill pipe. Its schematic diagram and cross-sectional view are shown in Figure 2.

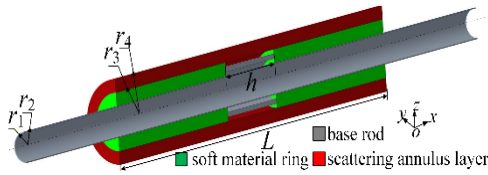


Figure 1. Front view structural diagram of the locally resonant metastructured drill pipe unit cell

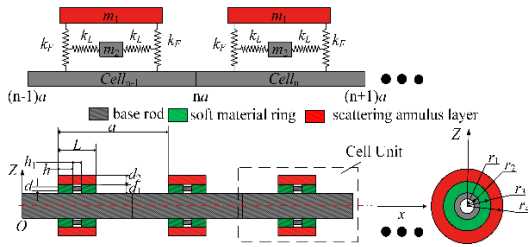


Figure 2. Schematic diagram and cross-sectional view of the locally resonant metastructured drill pipe

This study is based on periodic structure theory, taking the unit cell shown in Figure 1 as the research object. Through finite element simulation calculations, the band structure characteristics and characteristic modes of the locally resonant metastructured drill pipe are analyzed. In the calculation, Bloch periodic boundary conditions are introduced on the periodic boundaries of the unit cell to characterize its infinite periodicity. The mathematical expression for this boundary condition is

$$u(x+a) = u(x)e^{i(ka)} \quad (1)$$

By introducing the periodic condition (1) into the finite element characteristic equation for free vibration, we obtain:

$$(K - \omega^2 M)u = 0 \quad (2)$$

For each given Bloch wave vector k , the corresponding set of eigenfrequencies can be obtained by solving the eigenvalue problem. Based on this, by scanning the wave vector k across

the boundary of the first irreducible Brillouin zone, the band structure of the drill pipe metastructure is ultimately assembled (Figure 3). This band structure exhibits bandgaps at specific frequency bands. These bandgaps can inhibit the propagation of vibration within the structure, thereby achieving vibration reduction.

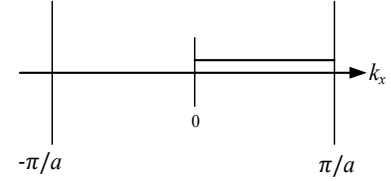


Figure 3. The First Irreducible Brillouin Zone

To evaluate the low-frequency vibration attenuation characteristics of the metastructured drill pipe, this study constructed a finite periodic structure consisting of 1×3 units arranged along the x-direction and calculated its vibration transmission spectrum. In the finite element model, an acceleration excitation is applied at one end of the structure, and the acceleration response is collected at the other end. The vibration transmission loss is ultimately calculated using Equation (3):

$$T_L = 20 \lg \left(\frac{a_o}{a_i} \right) \quad (3)$$

Equation (3): a_o and a_i represent the output and input accelerations, respectively. Through frequency sweep calculations, the transmission characteristic curve reflecting the structure's vibration attenuation capability is ultimately obtained.

3. Bandgap Characteristic Analysis

The main structural dimension parameters involved in the calculations of this section are as follows: The host rod (lattice constant a) length is 4000 mm. The soft material ring (green part) length h is 967.5 mm, thickness d_1 is 55 mm; the scattering ring layer (red part) length L is 2365 mm, thickness d_2 is 55 mm. The host rod outer radius r_2 is 127 mm, inner radius r_1 is 120 mm; the soft material ring outer radius r_3 is 237 mm, inner radius r_2 is 127 mm; the scattering ring layer outer radius r_4 is 347 mm, inner radius r_3 is 237 mm. The length h_1 of the hard ring set in the middle is 430 mm, thickness d is 20 mm. The material selection for each component of the structure is as follows: The host rod and the hard ring embedded between the two soft material rings are made of steel; the soft material ring layer located between the host rod and the outermost scattering ring layer is made of rubber; the outermost scattering ring layer is made of copper. The basic mechanical parameters of each material are listed in Table 1.

Table 1. Structural Material Parameters

Material	Density ($\text{kg} \cdot \text{m}^{-3}$)	Elastic Modulus (Mpa)	Poisson's Ratio
Steel	7780	216000	0.33
Rubber	1300	2.05	0.43
Copper	8950	110000	0.34

The infinite periodic structure band structure diagram and the finite periodic structure transmission characteristic curves were finally calculated for the metastructured drill pipe unit

cell shown in Figure 1. The results are shown in Figures 4~9. From the band structure, it can be seen that within the 0~180 Hz range, the band structure is mainly composed of four types of modes: the rod interior wave band for structural longitudinal vibration, the rod exterior wave band for lateral and torsional vibrations, and the flat resonance bands of the local resonators. This indicates that longitudinal, lateral, and torsional vibration modes can form in the locally resonant metastructured drill pipe. Among them, the vibration mode of band L_2 in Figure 4 is the longitudinal vibration mode of the metastructured drill pipe, the vibration mode of band F_2 in Figure 6 is the transverse vibration mode of the metastructured drill pipe, and the vibration mode of band T_2 in Figure 8 is the torsional vibration mode of the metastructured drill pipe.

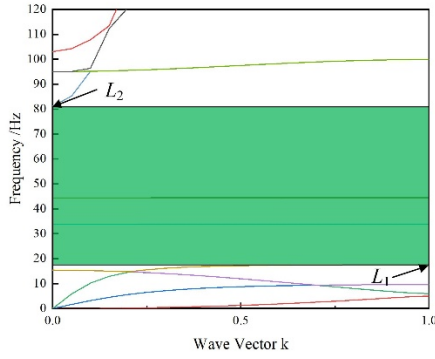


Figure 4. Longitudinal wave bandgap band structure

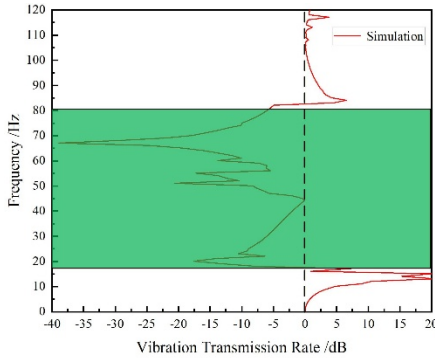


Figure 5. Longitudinal excitation transmission characteristics

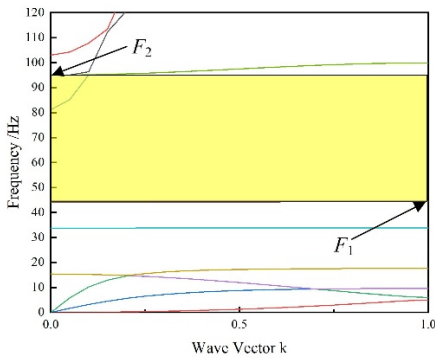


Figure 6. Transverse wave bandgap band structure

The two vibration modes of the metastructure host rod and the local resonators couple with each other according to the modal superposition principle while dominating the system's primary modes. During the coupling process, the vibration modes of the local resonators suppress the dominant modes of the metastructure host, respectively inducing sub-bandgaps that inhibit longitudinal, lateral, and torsional vibrations.

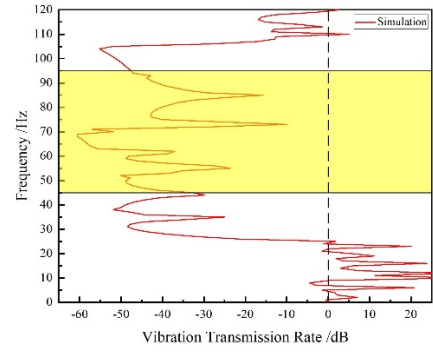


Figure 7. Transverse excitation transmission characteristics

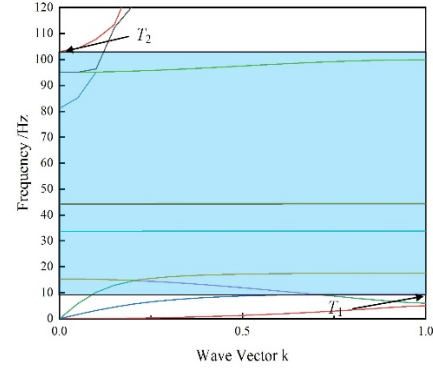


Figure 8. Torsional wave bandgap band structure

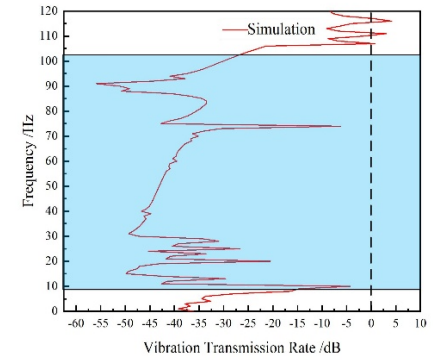


Figure 9. Torsional excitation transmission characteristics

These sub-bandgaps correspond to the green area in Figure 4, the yellow area in Figure 6, and the blue area in Figure 8, respectively. These three bandgaps overlap and ultimately form a complete bandgap. Within the complete bandgap, all vibration modes (longitudinal-transverse-torsional coupling) in the metastructured drill pipe are suppressed. In Figure 4, the longitudinal wave bandgap in the metastructured drill pipe is formed by the coupling between the host rod's own L_2 vibration mode and the local resonator's L_1 mode, with a frequency range of 17.59Hz~81.14Hz. Figure 5 shows that longitudinal vibration in the finite periodic structure is significantly attenuated within this bandgap. In Figure 6, the transverse wave bandgap in the metastructured drill pipe is formed by the coupling between the host rod's own F_2 vibration mode and the local resonator's F_1 mode, with a frequency range of 44.30Hz~95.02Hz. Figure 7 shows that transverse vibration in the finite periodic structure is significantly attenuated within this bandgap. In Figure 8, the torsional wave sub-bandgap formed by the coupling between the host rod's exterior vibration mode T_2 and the local resonance mode T_1 of the resonator is 9.60Hz~103.03Hz. Figure 9 shows that torsional vibration in the finite periodic structure is also effectively attenuated within this bandgap.

range.

4. Formation Mechanism of Low-Frequency Broad Bandgap

To explore the formation mechanism of the low-frequency broad bandgap in the locally resonant metastructured drill pipe, this study extracted the vibration modes of the super cell at the boundaries of its key sub-bandgaps, specifically including longitudinal waves (L1, L2), transverse waves (F1, F2), and torsional waves (T1, T2). By analyzing these modes, the aim is to systematically analyze the formation process and mechanism of the low-frequency broad bandgap. and the theoretical model derived based on the equivalence of these two modes is shown in Figure 10. The vibration modes corresponding to the lower and upper boundary energy bands are shown in Figures 11a and 11b, respectively, That is, the rubber and steel block are connected in parallel, where the steel block and rubber are equivalent to a spring K_L

The total stiffness of the sandwich resonator K is:

$$K = 2K_L \quad (4)$$

When the excitation frequency approaches the natural frequency of the local resonator, its vibration mode L1 is fully excited and becomes the dominant mode, exhibiting significant vibration along the x-direction, as shown in Figure 11a. This mode couples with the vibration mode of the metastructure host rod and applies a reaction force to the host, effectively suppressing the host rod's vibration along the x-direction. This ultimately prevents the longitudinal wave from propagating further in the host rod. The host rod remains in a static state, forming the longitudinal wave bandgap. Under longitudinal excitation, the longitudinal vibration mode L2 of the metastructure host rod is excited as the dominant mode, manifesting as the base unit vibrating along the x -direction, as shown in Figure 11b. At this time, the local resonator is in a static state, the wave mode of the novel locally resonant drill pipe host rod dominates the response of the super rod, so the longitudinal wave can propagate in the locally resonant drill pipe according to this mode, and the longitudinal wave bandgap closes.

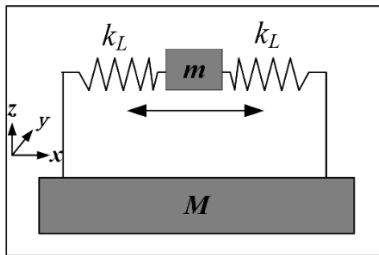


Figure 10. Longitudinal vibration Theoretical model

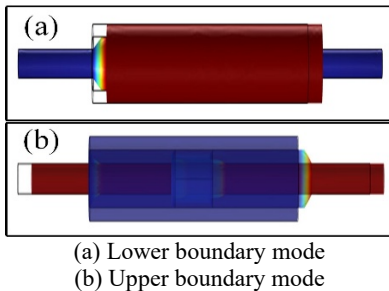


Figure 11. Longitudinal vibration modes of the locally resonant metastructured drill pipe unit cell

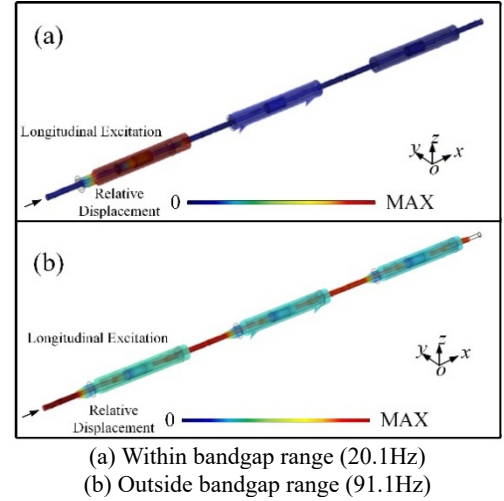


Figure 12. Excitation transmission process inside and outside the longitudinal wave sub-bandgap range

The vibration of the local resonator along the vertical direction (x-direction) generates a coupling force on the host rod unit through the rubber ring, calculated by the formula:

$$F = K|A_1| = 2k_L|A_1| \quad (5)$$

In the formula: $|A_1|$ is the dominant modal displacement of the local resonator, which is an inherent property of the system. Therefore, the magnitude of the coupling force between the local resonator and the host rod mainly depends on the equivalent stiffness of the local resonator. The opening position of the longitudinal bandgap is determined by the natural frequency f of the local resonator. The formula for calculating f is as follows:

$$f = \frac{1}{2\pi} \sqrt{\frac{K}{m}} \quad (6)$$

To clarify the formation mechanism of this longitudinal wave bandgap, a finite periodic structure consisting of 3 metastructure unit cells arranged along the x-direction was constructed. In the finite element simulation, a longitudinal acceleration excitation was applied at one end of the structure, and its acceleration response was calculated at the other end. The modal shapes corresponding to typical frequencies within the bandgap (20.1Hz) and outside the bandgap (91.1Hz) were then extracted from the transmission characteristics, as shown in Figures 12a and 12b, respectively. As shown in Figure 12a, within the bandgap frequency range, the host of the metastructured drill pipe remains essentially static, while the local resonance unit undergoes significant vibration in the x-direction. This indicates that the excitation energy is effectively absorbed and dissipated, thereby suppressing vibration propagation. In stark contrast, Figure 12b shows that at frequencies outside the bandgap, vibrational energy is distributed throughout the entire drill pipe, and the structure vibrates according to its overall mode, indicating that vibration can propagate unimpeded at this frequency without effective bandgap attenuation.

Similarly, Among them, the theoretical model shown in Figure 13 is obtained. the vibration mode corresponding to the lower boundary of the bandgap is shown in Figure 14a, and the vibration mode corresponding to the upper boundary is shown in Figure 14b. By equivalently processing the two vibration modes, Compared with the equivalent model of the local resonator when the longitudinal wave bandgap is formed, the equivalent mass and spring connection method in this mass-spring system remain unchanged, but during the

vibration of the local resonator, the resonator mainly exhibits lateral vibration.

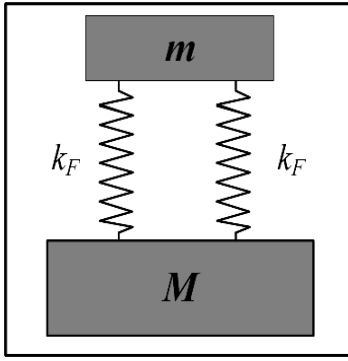


Figure 13. Transverse vibration theoretical model

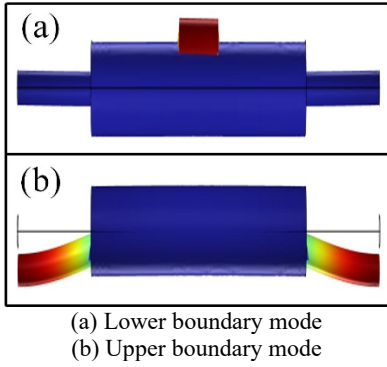


Figure 14. Transverse vibration modes of the locally resonant metastructured drill pipe unit cell

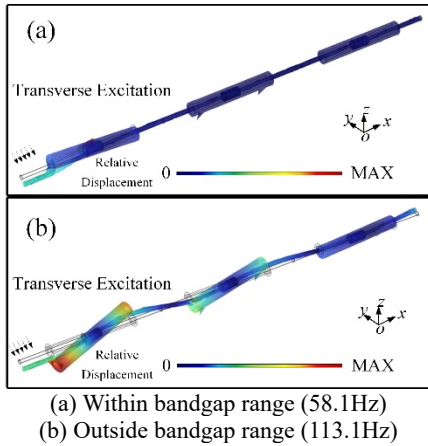


Figure 15. Excitation transmission process inside and outside the transverse wave sub-bandgap range

To clarify the formation mechanism of this transverse wave bandgap, a finite periodic structure consisting of 3 metastructure unit cells arranged along the x-direction was constructed. In the finite element simulation, a lateral acceleration excitation was applied at one end of the structure, and its acceleration response was calculated at the other end. The modal shapes corresponding to typical frequencies within the bandgap (58.1Hz) and outside the bandgap (113.1Hz) were then extracted from the transmission characteristics, as shown in Figures 15a and 15b, respectively. As shown in Figure 15a, within the bandgap frequency range, the host of the metastructured drill pipe remains essentially static, while the local resonance unit undergoes significant lateral vibration. This indicates that the excitation energy is effectively absorbed and dissipated, thereby suppressing vibration propagation. In stark contrast, Figure 15b shows that

at frequencies outside the bandgap, vibrational energy is distributed throughout the entire drill pipe, and the structure vibrates according to its overall mode, indicating that vibration can propagate unimpeded at this frequency without effective bandgap attenuation.

respectively; the equivalent theoretical model established based on this is shown in Figure 16. the modes corresponding to the lower and upper boundaries of the bandgap are shown in Figures 17a and 17b, Similar to the models for longitudinal and transverse wave bandgaps, the equivalent mass and spring connection form in this equivalent mass-spring system remain unchanged. During vibration, the local resonance unit mainly exhibits torsional vibration.

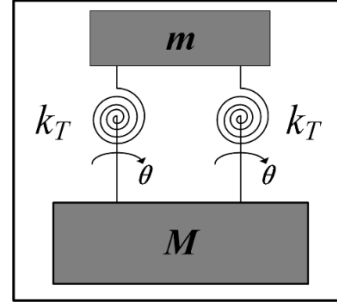
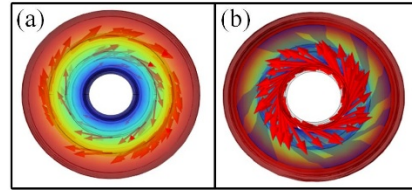


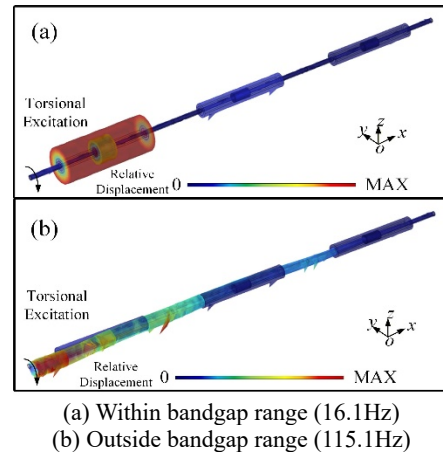
Figure 16. Torsional vibration Theoretical model



(a) Lower boundary mode (b) Upper boundary mode

Figure 17. Torsional vibration modes of the locally resonant metastructured drill pipe unit cell

To clarify the formation mechanism of this torsional wave bandgap, a finite periodic structure consisting of 3 metastructure unit cells arranged along the x-direction was constructed. In the finite element simulation, a torsional acceleration excitation was applied at one end of the structure, and its acceleration response was calculated at the other end.



(a) Within bandgap range (16.1Hz)
(b) Outside bandgap range (115.1Hz)

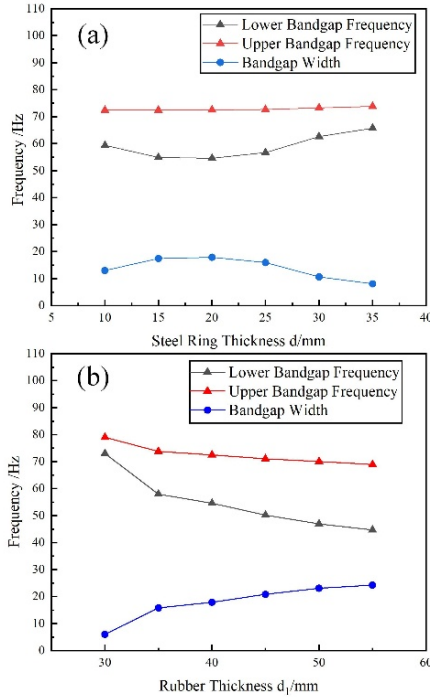
Figure 18. Excitation transmission process inside and outside the torsional wave sub-bandgap range

The modal shapes corresponding to typical frequencies within the bandgap (16.1Hz) and outside the bandgap (115.1Hz) were then extracted from the transmission characteristics, as shown in Figures 18a and 17b, respectively.

As shown in Figure 18a, within the bandgap frequency range, the host of the metastructured drill pipe remains essentially static, while the local resonance unit undergoes significant torsional vibration. This indicates that the excitation energy is effectively absorbed and dissipated, thereby suppressing vibration propagation. In stark contrast, Figure 18b shows that at frequencies outside the bandgap, vibrational energy is distributed throughout the entire drill pipe, and the structure vibrates according to its overall mode, indicating that vibration can propagate unimpeded at this frequency without effective bandgap attenuation.

5. Influence Laws on Bandgap Characteristics

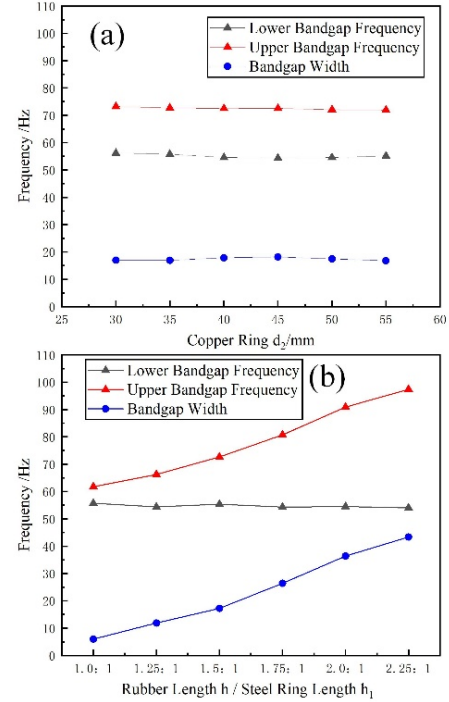
The above analysis indicates that the local resonance oscillator is the core element for regulating the bandgap characteristics of the metastructured drill pipe, and its natural frequency directly determines the starting position of the bandgap. Based on this, this study provides a theoretical basis for precise bandgap tuning by systematically revealing the influence laws of oscillator parameters on the bandgap. Taking the steel ring thickness d , rubber thickness d_1 , copper ring thickness d_2 , and the ratio of rubber length to steel ring length h/h_1 as key parameters, the influence laws of these four parameters on bandgap characteristics were deeply analyzed.



(a) Influence laws of steel ring thickness d
(b) Influence law of rubber thickness d_1 on bandgap characteristics
Figure 19. Influence laws of steel ring thickness d and rubber thickness d_1 on bandgap characteristics

As shown in Figure 19a, under the condition that other parameters of the locally resonant metastructured drill pipe remain unchanged, as the steel ring thickness d increases, the complete bandgap width of the novel metastructured drill pipe model first increases and then decreases. Simultaneously, the lower boundary frequency of the complete bandgap first shifts to lower frequencies and then gradually shifts to higher frequencies, while the upper boundary frequency remains basically stable. When the steel ring thickness is 20mm, the complete bandgap width reaches its maximum, and the

starting frequency is the lowest. As shown in Figure 19b, under the condition that other parameters of the locally resonant metastructured drill pipe model remain unchanged, as the rubber thickness d_1 increases, both the starting frequency and the lower boundary frequency of the bandgap shift to lower frequencies, and the rate of decrease of the lower boundary frequency is faster than that of the upper boundary, resulting in a gradual increase in bandgap width. The widest bandgap and the lowest starting bandgap frequency are achieved when the rubber thickness is 55mm.



(a) Influence law of copper ring thickness d_2 on bandgap characteristics

(b) Influence law of the ratio of rubber length to steel ring length h/h_1 on bandgap characteristics

Figure 20. Influence laws of copper ring thickness d_2 and the ratio of rubber length to steel ring length h/h_1 on bandgap characteristics

As shown in Figure 20a, under the condition that other parameters of the locally resonant metastructured drill pipe remain unchanged, as the copper ring thickness d_2 increases, the bandgap width of the metastructure model first increases and then decreases. During this process, both the upper and lower boundary frequencies of the bandgap first shift to lower frequencies and then gradually shift to higher frequencies. When the copper ring thickness is 40 mm, the bandgap width reaches its maximum, and the starting frequency is the lowest. As shown in Figure 20b, under the condition that other parameters of the locally resonant metastructured drill pipe remain unchanged, as the ratio of rubber length h to steel ring length h_1 increases, the upper boundary frequency of the bandgap gradually shifts towards higher frequencies, while the lower boundary frequency remains basically unchanged. Therefore, the bandgap width increases step by step. When the h/h_1 ratio is 2.25, the bandgap width reaches its maximum, and the starting frequency is the lowest

6. Conclusion

Based on the bandgap formation mechanism and method of locally resonant metastructures, and aiming to suppress coupled longitudinal, lateral, and torsional vibrations in oil

drill pipes, this paper constructs a novel locally resonant metastructured drill pipe. Using the finite element method, the band structure characteristics of this structure are systematically calculated. The bandgap boundary modal shapes of the three elastic waves and the corresponding vibration transmission characteristics of the finite periodic structure are analyzed, revealing the bandgap generation mechanism and vibration attenuation laws. On this basis, the influence laws of key structural parameters on bandgap characteristics are further explored. The main conclusions are as follows:

(1) A novel locally resonant metastructured drill pipe is proposed. This structure opens a complete bandgap in the frequency range of 44.30~81.14 Hz, which can simultaneously suppress longitudinal, lateral, and torsional vibrations. Vibration transmission curve analysis further indicates that this structure has good control effects on the above three vibration modes in the low-frequency band.

(2) Regarding the bandgap formation mechanism, when the excitation frequency approaches the natural frequency of the local resonator, the resonator's vibration mode is excited and dominates the system response, coupling with the host rod's vibration modes. The resonator exerts a reverse force on the host, suppressing all its wave modes, leading to the formation of a complete bandgap for elastic waves in all directions.

(3) The structural parameters of the metastructured rod have a significant influence on bandgap characteristics and vibration transmission behavior. By adjusting the steel ring thickness d , rubber thickness d_1 , copper ring thickness d_2 , and the ratio of rubber length to steel ring length h/h_1 , the bandgap position and attenuation performance can be effectively tuned, enhancing the structure's ability to suppress vibrations in the target frequency band.

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