

Article

Experimental Investigation of the Vibration Reduction of the Pipeline System with a Particle Impact Damper under Random Excitation

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Abstract: In the engineering field, severe vibration of the pipeline system occurs under random excitation, which leads to vibration failure of the pipeline system due to overload. The traditional method is to increase the rigidity of the pipeline system, and to avoid low-frequency resonance by using clamps or damping materials. However, due to structural limitations, it is difficult to apply clamps and damping materials. Particle damping technology has been applied in many fields, and the vibrational energy in the broadband frequency domain could be dissipated based on nonlinear particle collision damping. In this paper, a particle impact damper is designed for vibration reduction of the pipeline system. The damping capability is identified to investigate the effects of particle material, filling rate, particle size, damper structure, and boundary conditions. The results indicate that the ideal damping performance can be obtained by properly selecting particle parameters. Based on applying particle damping on the pipeline system, the proposed particle impact damper showed excellent damping capability under random excitation.

Keywords: pipeline system; particle impact damper; vibration reduction; random excitation



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1. Introduction

Pipeline systems are mainly used for fluid energy transmission and generally consist of pumps, valves, pipelines, clamps, joints, etc. They are widely used in many engineering fields, such as aerospace, petrochemistry, nuclear power, etc. The excitation of the pump source fluid and the base of the mechanical equipment can cause severe vibration in the pipeline system. Therefore, effective methods are highly recommended to reduce the vibration of pipeline systems.

In the past half-century, the vibration problems of pipeline systems have attracted great attention and many remarkable achievements have been made. According to the characteristics of the fluid, these problems are divided into ones dealing with the coupling of constant flow with pipelines and ones dealing with the coupling of non-constant flow with pipelines. In the area of coupled vibration problems between constant flow and pipelines, Paidoussis [1,2] had long been devoted to the study of nonlinear dynamical behaviors such as instability, bifurcation, and chaos of the pipeline system caused by the fluid under the action of steady flow. Ni et al. [3] studied flow-bend bifurcation and chaotic motion under nonlinear constraints using the cantilever flow convolution tube as a model, and their experimental results showed that in certain parameter regions, the path to chaos is through double-period bifurcation. Wang et al. [4] made a detailed review of the pipeline vibration and stability due to flow around the infusion tube structure at macro, micro, and nano scales. Tan et al. [5] established a nonlinear Timoshenko model for coupled vibration of flow transmission pipelines and concluded that the coupled Timoshenko theory is applicable to simulate fluid pipelines with high speed, high amplitude, or short pipeline conveyance. The coupling problem of unsteady flow and pipelines is mainly based on the classical water

hammer theory. Wiggert et al. [6] and Tijsseling [7] revealed the vibrational mechanism of coupling between unsteady fluid and pipeline systems generated by the water hammer effect, and proposed a 4-equation model, an 8-equation model, and a 14-equation model for fluid–structure interaction. Zhang et al. [8] provided a detailed review and discussion of the research content and progress of linear and nonlinear pipelines in the field of mechanics. Liu et al. [9] proposed a frequency-domain transfer matrix method for fluid–solid coupling considering an elastically constrained liquid-filled pipeline based on pipeline vibration and verified the effectiveness of the method by means of measurement and simulation data. Based on the Tijsseling method, Xu et al. [10] proposed to replace the recursively accelerated fluid–solid interacted quaternary model with time-line interpolation, and concluded that the quadratic linear interpolation scheme is the best.

Many scholars have made rich research achievements on the fluid–solid coupling vibration of the pipeline system. Since the vibration problems of the pipeline system are prominent, more effective damping methods are urgently needed to suppress pipeline vibration. The particle impact damping technique is an effective damping method to achieve vibration reduction in structural systems, which is based on the principle of collision and frictional energy dissipation between particles. This technique has the advantages of wide temperature tolerance, wide frequency domain, radiation resistance, and high reliability [11–13]. In recent years, many scholars have conducted a lot of fruitful work on particle damping. Zhao et al. [14] designed a particle damper based on aircraft duct damping, explored the mechanism and the influencing factors of vibration damping, and verified the effectiveness and practicality of the aircraft duct particle damper through experiments and finite element simulations. Jin et al. [15] proposed a tuned particle impact damper, analyzed the interaction between the transverse vibration and the additional damper, analyzed the damping performance using the damping coefficient predicted by the least-squares and Prony’s methods, and verified the effects of the excitation force and restitution coefficient on damping capacity. N. Meyer et al. [16] combined the discrete element model with a simplified finite element model and compared it with experiments to obtain the validity of the method and revealed the influence of the position and filling rate of the particle dampers on different modal parameters of the structure. Xiao et al. [17–19] explored gears filled with damped particles or powder boreholes in a centrifugal force field, established an energy dissipation model of the particle system considering friction and inelastic collision based on the discrete element method, analyzed the energy consumption and damping characteristics of the system, and characterized particle filling rate and material as important parameters related to energy dissipation. Lu et al. [20] provided an in-depth discussion of the stochastic response control of equivalent simplified particle damped systems under seismic excitation and combined numerical analysis as well as experimental studies to verify the feasibility of stochastic vibration analysis of particle damped systems. Based on the analysis of PCB dynamic characteristics, Xiao et al. [21,22] proposed a new structural design for the vibration reduction of extension housing for PCB, in which the discrete element method is used to calculate the system energy consumption of particles, optimize the particle size, filling rate and other parameters, and is combined with experiments to study the influence of particle damping configuration schemes on PCB motion characteristics. Żurawski et al. [23] introduced a new type of tuned particle impact damper (TPID) and the proposed semi-active damping methodology was confirmed in the cantilever beam vibration experiment, and various damping characteristics captured by the mass of the particle container and particle material with different volumes were given. Lu et al. [24] proposed an energy evaluation model of a particle tuned mass damper (PTMD) attached to a Multi Degree of Freedom (MDOF) structure under wind excitation which is established based on the equivalent simplification method, and the simulation results are verified through wind tunnel tests. It is concluded that the combination of parameters has a significant impact on the energy dissipation performance of PTMD. Prasad et al. [25] proposed the concept of a honeycomb damping plate (HCDP) based on particle damping technology to reduce the low-frequency vibration response of wind turbines. The effects

of four different particle materials and HCDP positioning on damping, and the effects of single-unit (SU) and multi-unit (MU) HCDP on the frequency response of the generator were also studied. The authors obtained good damping performance in reducing vibration amplitude when using the HCDP concept.

Although some research results have been achieved in particle damping, the literature on the damping of pipeline systems is relatively small. According to the structure and load characteristics of the pipeline system, it is of great research significance and important for engineering applications to introduce particle damping technology into vibration damping. In this study, a new particle impact damper for the pipeline system is proposed, and the effect of particle material, filling rate, particle size, damper structure and boundary conditions are investigated experimentally under random excitation. This paper provides an efficient tool for the design and maintenance of pipelines for vibration reduction, which is of great significance and value for pipeline vibration reduction in harsh vibration environments such as ocean engineering, aerospace, etc.

2. Energy Dissipation Mechanism of Particle Collisions

Particle damping technology seeks to fill the damper cavity with a certain number of particles, using the collision and friction energy between the particles to attenuate the vibration of the pipeline system caused by external excitation. Among them, the particle collision mode is mainly divided into normal and tangential collision.

2.1. Analysis of Energy Consumption of Normal Particle Collisions

The normal collision between particles can be roughly divided into three parts [26]: the elastic compression phase, the elastoplastic compression phase, and the elastic recovery phase. When the particle impact damper vibrates with the pipeline system, periodic collisions occur between particles in it. The particle normal collision contact model and diagram are shown in Figures 1 and 2, respectively.

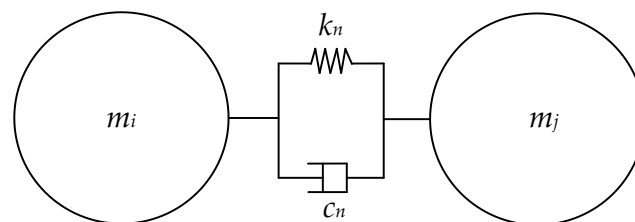


Figure 1. Particle normal collision contact model.

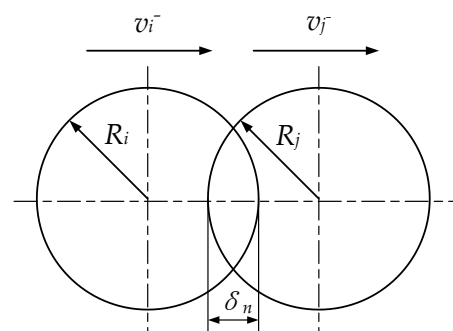


Figure 2. Schematic diagram of particle normal collision.

Where m , R , k_n , c_n , v_n^- , and δ_n are the particle mass, radius, normal stiffness, damping coefficient, velocity before the collision, and relative displacement, respectively. The energy consumption of particles in the normal direction is expressed as

$$\Delta E_n = \frac{1}{2} \frac{m_i m_j}{m_i + m_j} (1 - e_n^2) |v_{rn}^-|^2 \quad (1)$$

The normal coefficient of restitution is expressed as

$$e_n = \frac{v_{jn}^+ - v_{in}^+}{v_{in}^- - v_{jn}^-} \quad (2)$$

Herein, v_{in} and v_{jn} are the velocities of particles; the superscripts ‘−’ and ‘+’ represent the conditions before and after normal collisions, respectively.

2.2. Analysis of Energy Consumption of Tangential Particle Collisions

The particle tangential collision contact model is shown in Figure 3.

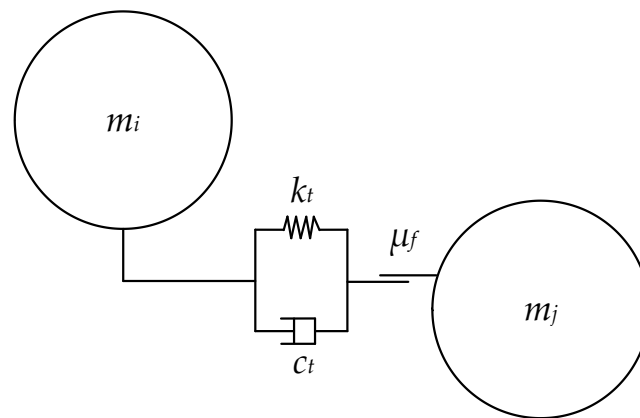


Figure 3. Particle tangential collision contact model.

Where k_t , c_t , and μ_f are the tangential stiffness, damping coefficient, and friction coefficient between particles, respectively. When the particles collide only in the tangential direction without relative sliding, the energy consumption in the tangential direction is expressed as

$$\Delta E_t = \frac{1}{2} \frac{m_i m_j}{m_i + m_j} (1 - e_t^2) |v_{rt}^-|^2 \quad (3)$$

The tangential coefficient of restitution is expressed as

$$e_t = \frac{v_{jt}^+ - v_{it}^+}{v_{it}^- - v_{jt}^-} \quad (4)$$

Herein, v_{it} and v_{jt} are the velocities of the particles; the superscripts ‘−’ and ‘+’ represent the conditions before and after tangential collisions, respectively.

When the tangential force between particles is greater than the maximum static friction, relative sliding between the particles begins to occur. The friction energy consumption will replace the tangential collision energy consumption, and its friction energy consumption is expressed as

$$\Delta E_f = \mu_f |F_n \delta_t| \quad (5)$$

where δ_t is the tangential relative displacement between particles, and F_n is the normal force between particles, the expression of which is obtained from Hertz contact theory [27] as

$$F_n = \frac{4}{3} E^* \sqrt{R^*} \delta_n^{\frac{3}{2}} \quad (6)$$

where $E^* = E_i^* E_j^* / (E_i^* + E_j^*)$, $R = R_i R_j / (R_i + R_j)$, E_i and E_j are the modulus of elasticity, and μ_i and μ_j are the Poisson’s ratio of the particles, respectively. The total quantity of dissipated energy is achieved by normal and tangential collisions; the total energy consumption can be expressed as

$$E = \Sigma \Delta E_n + \Sigma \Delta E_t + \Sigma \Delta E_f \quad (7)$$

3. Experimental Verification on the Damping Performance of the Pipeline System

To investigate the damping performance of the particle impact damper, a random excitation experiment was conducted. Random excitation is a kind of uncertain excitation; the application of random excitation on the test pipeline can better simulate the working conditions of the actual pipeline so that the test results are more practical. The schematic diagram of the vibration damping test system is shown in Figure 4.

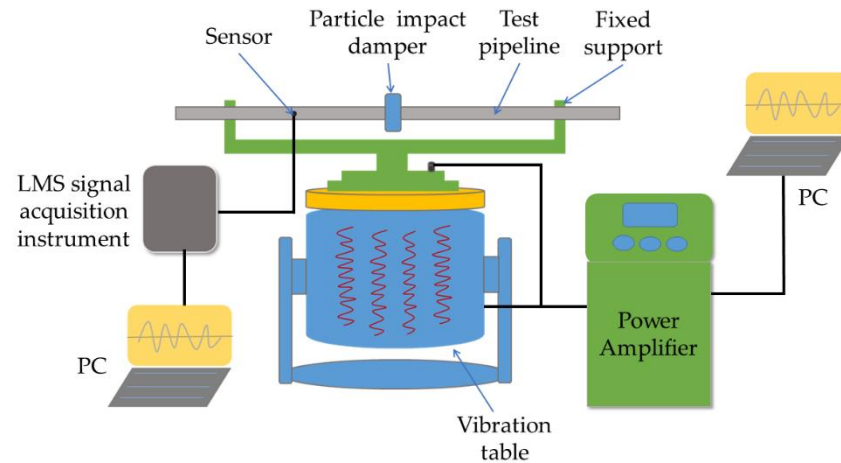


Figure 4. Schematic diagram of the vibration damping test system.

This paper refers to the vibration mode of the test pipeline (external diameter $\phi = 16$ mm, wall thickness $t = 1$ mm) with a length of 50 mm, where the measuring point of the sensor (PCB, model 352C22) was 12.5 cm away from the left end of the pipeline, and the particle impact damper was selected at the middle of the pipeline. The instruments required for the test and the test layout of the vibration table (ES-10-240, frequency range 2–5000 Hz) are shown in Figure 5.

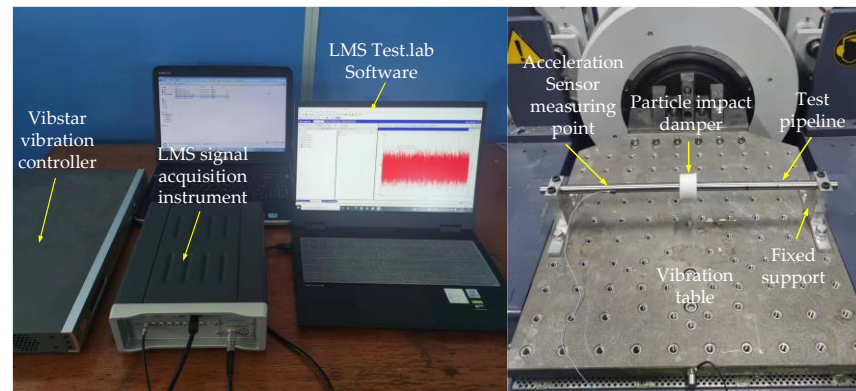


Figure 5. Experimental setup of the vibration test.

The vibration table can output a set random excitation signal. The frequency domain of random excitation is 10–2000 Hz. The load spectrum curve of random excitation is shown in Figure 6. Figure 6 represents the spectrum setting of random vibration excitation, which is the data that must be input for random excitation. After the random excitation signal is input, the vibration table starts to work and obtains the response signal of the pipeline through the acceleration sensor. The excitation conditions in Figure 6 are used for all tests.

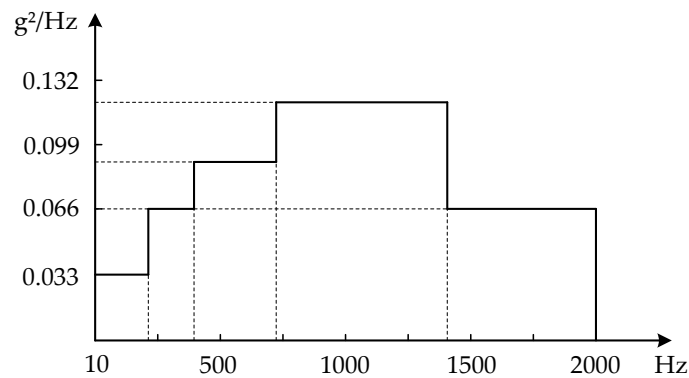


Figure 6. Load spectrum curve of random excitation.

During the test, the vibration table is loaded along the X direction (horizontal and vertical to the pipeline). An acceleration sensor was placed 12.5 cm away from the left end of the pipeline to measure the vibration acceleration. Two experiments are conducted under each experimental working condition, and the average of the results of the two experiments is taken as the experimental results under each experimental working condition.

The energy level of structural vibration is evaluated by the root-mean-square value of the damping effect of random excitation [28]; the expression is

$$E = \sqrt{\frac{1}{N} \sum_{i=1}^N y_i^2} \quad (8)$$

where N and y_i are the total numbers of discrete signals and vibrational signals. During the test, the formula of the damping effect of the particle impact damper is expressed as follows:

$$\Delta = \frac{E_a - E_b}{E_a} \times 100\% \quad (9)$$

where the subscripts 'a' and 'b' represent the RMS values of the bare pipeline and damped pipeline at a certain point, respectively.

4. Investigation of the Influence of Major Parameters on the Pipeline Damping Performance

4.1. Design of Particle Impact Damper

The test pipeline with an outer diameter of 16mm is selected to design a six-cavity particle impact damper. The outer diameter of the damper is 46 mm, the inner diameter is 16.5mm, the height of the damper is 28 mm, and the wall thickness is 3 mm. The particle impact damper cavity is filled with particles added to the test pipeline to perform the vibration reduction test.

4.2. Effect of Particle Materials on the Pipeline Damping Performance

The six-cavity structure of the particle impact damper was filled with 1 mm steel, aluminum, and glass particles, as shown in Figure 7. Random excitation tests were carried out at 20% and 80% filling rates, respectively. The effects of the three particle materials on the vibration damping performance of the particle impact damper were analyzed.

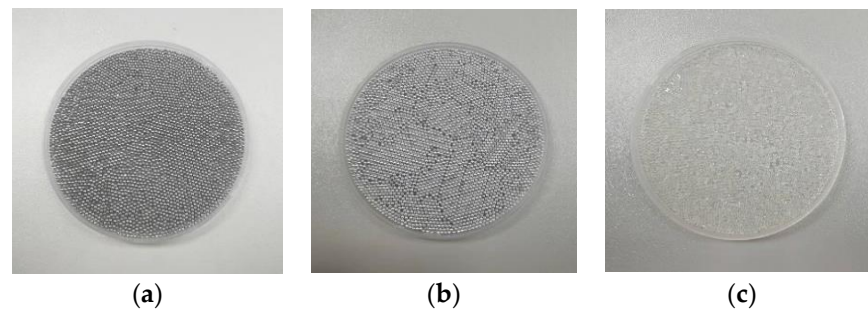


Figure 7. Three kinds of particle materials. (a) Steel ball; (b) Aluminum ball; (c) Glass ball.

4.2.1. Comparison of Three Particle Materials at a 20% Filling Rate

Figure 8 and Table 1 show the responses in the time domain and RMS values of the damped pipeline. When the cavity was filled with steel particles, the RMS of the response decreases by 35.7% compared with that of the bare pipe. Meanwhile, when filling with steel balls, the damping effect was improved by 10.4% and 25.3% compared to filling with aluminum and glass balls, respectively.

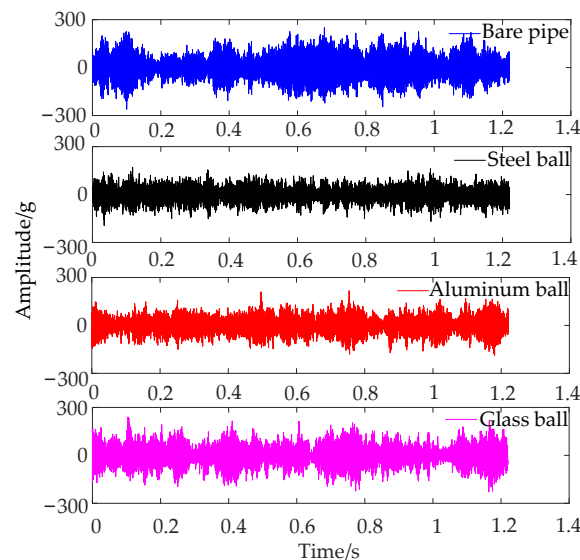


Figure 8. Time responses of damped pipeline with different materials at a 20% filling rate.

Table 1. Three materials with 20% filling rate under random excitation.

Pilot Protocol	RMS/g	Vibration Reduction Effect Δ
Bare pipe	78.7	—
Steel ball	50.6	35.7%
Aluminum ball	56.5	28.2%
Glass ball	67.7	14.0%

Figure 9 shows a comparison of the vibrational response of different particle materials with the bare pipe. Compared with the bare pipe, the particle impact damper filled with 20% steel balls, aluminum balls, and glass balls showed a shift in the first-order resonance frequency, and the resonant amplitude was significantly reduced. Among them, the resonant frequency shifts of the damped pipeline filled with steel balls were about 60 Hz, and the corresponding resonant amplitude was reduced by 68.8%. When the damped pipeline system was filled with aluminum and glass balls, the resonant amplitudes were reduced by about 55.9% and 26.3%, respectively. It is concluded that the vibration reduction effect of the particle impact damper filled with steel balls is the best due to the low value of the restitution coefficient and the relatively high mass effect.

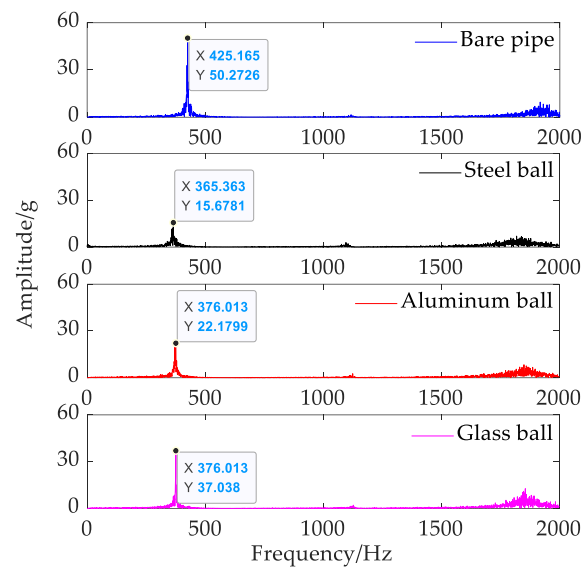


Figure 9. Spectral responses of damped pipeline with different materials at a 20% filling rate.

4.2.2. Comparison of Three Particle Materials at an 80% Filling Rate

Figure 10 shows the spectral responses of damped pipelines with different materials at an 80% filling rate. When the cavity of the damper was filled with steel balls, the corresponding resonant amplitude was reduced by 88.8%, while the resonant amplitude was reduced by 70.0% and 61.4% due to aluminum and glass, respectively. The RMS values of responses in the time domain are compared in Table 2. The experimental phenomenon was similar to that observed with the 20% filling rate.

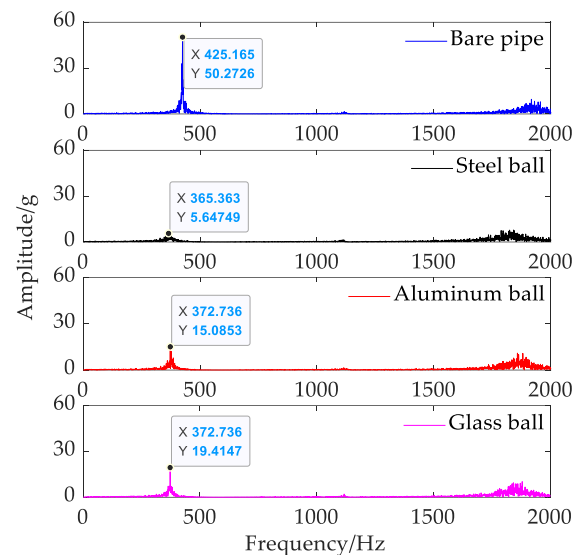


Figure 10. Spectral responses of damped pipeline with different materials at an 80% filling rate.

Table 2. Three materials with an 80% filling rate under random excitation.

Pilot Protocol	RMS/g	Vibration Damping Effect Δ
Bare pipe	78.7	—
Steel ball	41.8	46.9%
Aluminum ball	50.5	35.8%
Glass ball	54.2	31.1%

The test results show that particles of different materials have a great impact on the vibration reduction effect of the particle impact damper at the two filling rates of 20%

and 80%. The first-order amplitude and root mean square value of filled steel balls are the smallest, which means that the vibration reduction effect is the best. The first-order amplitude and root mean square value of filled aluminum balls are next, which implies that the vibration reduction effect is second. However, the first-order amplitude and root mean square value of filled glass balls are the largest, which means that the vibration reduction effect is relatively poor. Table 3 shows that the steel ball mass of the three kinds of particles is large at the same filling rate, which has a certain impact on the energy dissipation of vibration reduction. However, the mass of glass and aluminum is a little different, and the difference in vibration reduction effect between glass balls and aluminum balls is mainly due to the coefficient of restitution of the particles. According to the experimental results and Table 3, the smaller the coefficient of restitution of the particle materials, the better the vibration reduction effect.

Table 3. Parameters of different particle materials.

Particle Material	Coefficient of Restitution	Mass of 20% Filling Rate/g	Mass of 80% Filling Rate/g
Steel	0.56	15.4	61.6
Aluminum	0.75	5.1	20.9
Glass	0.94	4.9	19.8

4.3. Effect of Filling Rate on Damping Performance of the Pipeline System

The six-cavity particle impact damper is filled with steel balls with a particle size of 1 mm and a filling rate of 20, 40, 60, 80, 90, and 100% respectively. This paper judges the size of the filling rate by weighing the mass. The specific method is to fill the cavity with particles, weigh the filled particles with an electronic scale and consider that the filling rate corresponding to the weight at this time is 100%, then multiply this weight by the filling rate selected in the test, and add a certain mass of particles corresponding to the filling rate to the cavity. The RMS values of responses under different filling rates are shown in Figure 11.

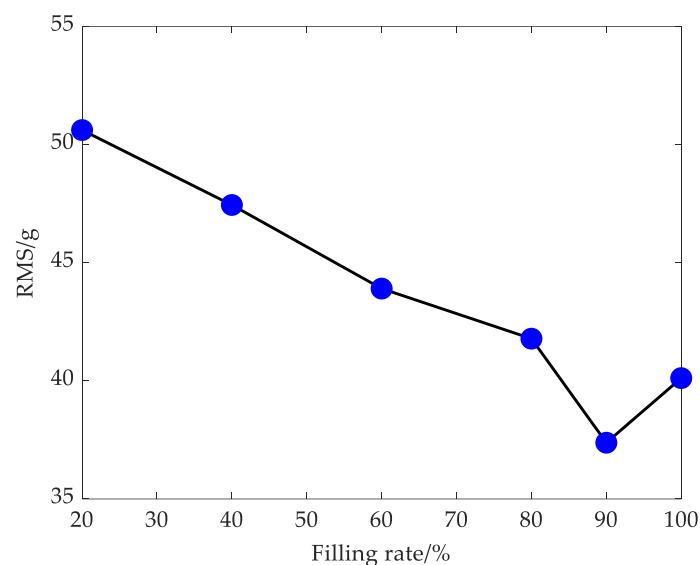


Figure 11. Influence of different filling rates on vibration reduction effect.

Figure 11 indicates that the vibration reduction effect of the particle impact damper increases and then decreases with the increase in the filling rate, and the best damping effect of the particle impact damper is achieved when the filling rate reaches 90%, and there exists an optimal filling rate for the particle impact damper. When the particle filling rate is small, the damping effect is not obvious due to the small proportion of particles in the

cavity, in which the number of particle–particle and particle–cavity collisions is limited. Thus, the energy dissipation through collision and friction is lower. With the increase in filling rate, the momentum exchange due to the collision and the particle–particle and particle–container wall friction are more sufficient. When the particle filling rate is large, the space for particle movement is restricted, the free movement stroke of the particles becomes smaller and the ability to dissipate energy by collision and friction is reduced. Therefore, the particle impact must have an optimum filling rate, damper size, particle size and other factors related to the particle impact damper. In practice, a good damping effect can be achieved when the particle filling rate is controlled within the range of 70–90%.

4.4. Effect of Particle Size on Damping Performance of the Pipeline System

To investigate the effect of particle size on damping performance, steel balls with particle sizes of 1, 2, and 3 mm were selected for the damping test as shown in Figure 12. A single variable is controlled and the filling rates were set to 20% and 80%. The frequency domain comparison diagram of different particle sizes filled in the particle impact damper is obtained as follows.

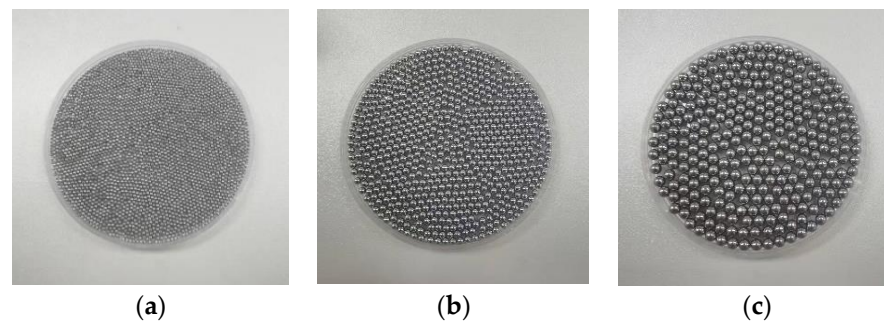


Figure 12. Filling materials of three kinds of particle size. (a) 1mm; (b) 2mm; (c) 3mm.

Figure 13a shows that the first-order resonant frequencies of the bare pipe in the particle impact damper filled with 20% steel balls of three particle sizes are shifted compared to Figure 8. The corresponding amplitudes are significantly reduced. Among them, the resonant frequency offset of the pipe filled with 1 mm steel balls was about 60 Hz, the corresponding amplitude was reduced by 68.8%. While the resonance frequency offset of the pipe filled with 2 and 3 mm steel balls was about 52 Hz, the corresponding amplitudes were reduced by 56.3% and 64.9%, respectively. According to the comparison of the first-order resonance amplitudes of the three particle sizes, the particle impact damper filled with 1 mm steel balls has the best damping effect at a 20% filling rate, followed by that filled with 3 mm balls, and by that filled with 2 mm balls. Similarly, the particle impact damper filled with 2 mm steel balls has an excellent damping effect, followed by that filled with 3 mm balls, and by that filled with 1 mm balls at an 80% filling rate in Figure 13b.

At the same filling rate, the smaller the particle size, which involves a greater number of particles, the more the momentum exchange of particle–particle and particle–container wall interactions is relatively adequate, which means that the energy dissipation is relatively high, and the vibration reduction effect is relatively adequate. At a different filling rate, the vibration reduction effect of particles with different diameters is different due to the high nonlinearity of particle damping, so there is no obvious pattern in the damping effect of three sizes at the two filling rates.

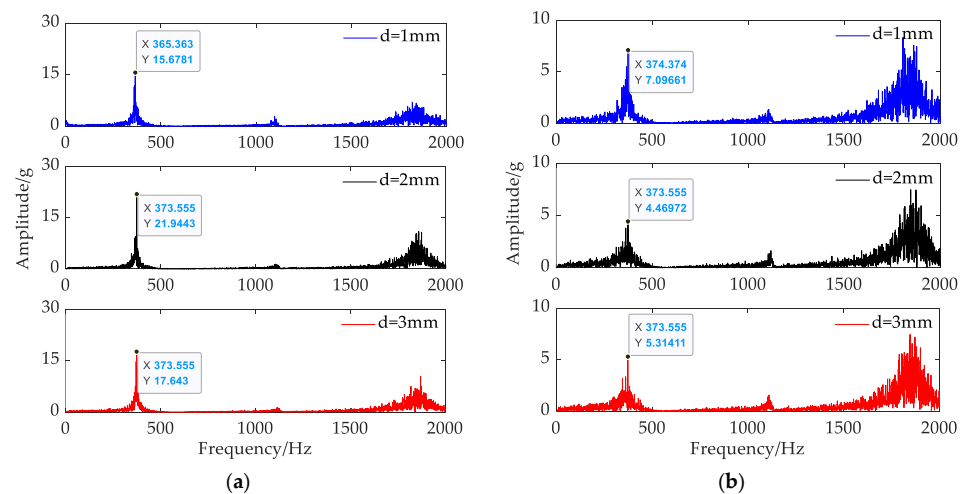


Figure 13. Comparison of frequency response with three particle sizes at the (a) 20%, (b) 80% filling rate.

4.5. Effect of Particle Impact Damper Structure on Damping Performance of the Pipeline System

A test pipeline with a diameter of 16 mm was selected and three kinds of particle impact dampers were designed according to the pipeline diameter, as shown in Figure 14. To investigate the effect of the different number of cavities on the vibrational damping performance, three types of particle impact dampers with two, four, and six cavities were selected.

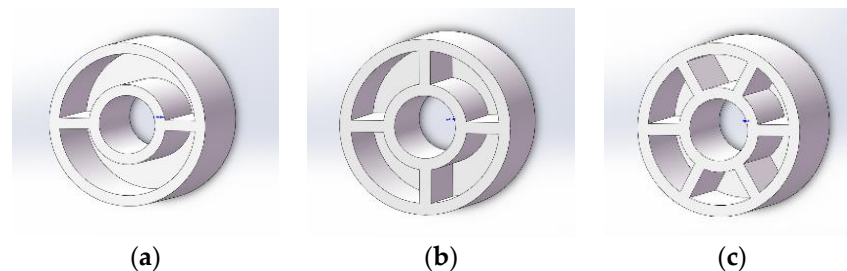


Figure 14. Three particle impact damper structures. (a) Two cavities; (b) Four cavities; (c) Six cavities.

Figure 15a shows the comparison frequency responses with different cavities with 1 mm steel balls. The resonant amplitude of the pipeline was reduced by 47.5% with the two-cavity damper, while the corresponding amplitudes in the other cases were cut down by 70.1 and 57.8%, respectively. When filled with 1 mm steel balls, the four-cavity damper has an excellent damping effect at the 20% filling rate. A similar damping effect occurs at the 80% filling rate, as shown in Figure 15b.

Figure 16 shows the RMS values of pipelines with two-, four-, and six-cavity dampers under two filling rates. When the number of damper cavities is small, the space of the damper cavity is larger, and the free motion stroke between particles becomes larger. As the number of particle–particle and particle–cavity collisions is limited, the energy dissipated by collision and friction is lower, so the damping effect is not obvious. With the increase in damper cavities, the space of the damper cavity becomes smaller, which means that the movement stroke of the particles will be shorter; the more contact between the particles and the particle impact damper, the more sufficient the momentum exchange between the particles and the particle impact damper will be. Therefore, with the increase in particle–particle and particle–cavity collision and friction, the vibration damping effect will improve. However, when the number of damper parts is large, the space of the damper cavity is small, and the movement space of particles is limited, which means that the collision and friction energy dissipation capacity of particle–particle and particle–cavity interactions decreases. Therefore, there must be a reasonable number of damper cavities.

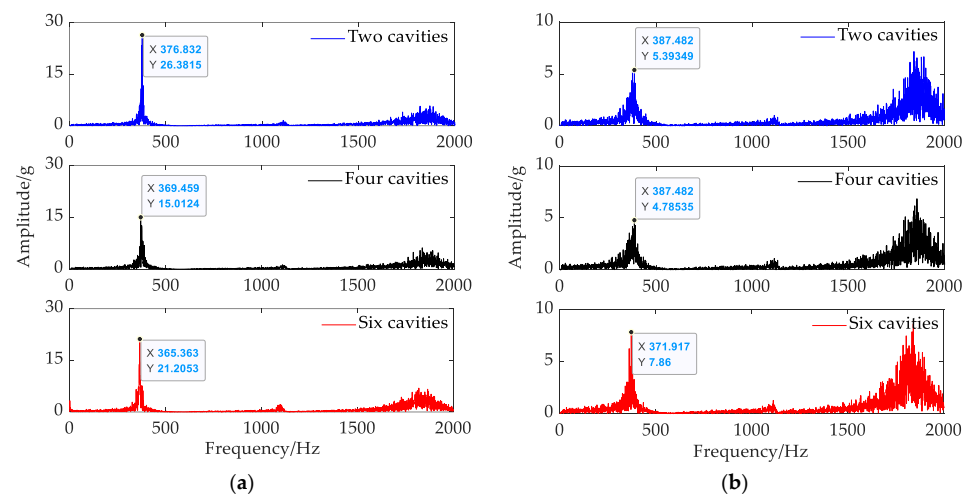


Figure 15. Comparison of frequency response with different cavities at the (a) 20%, (b) 80% filling rate.

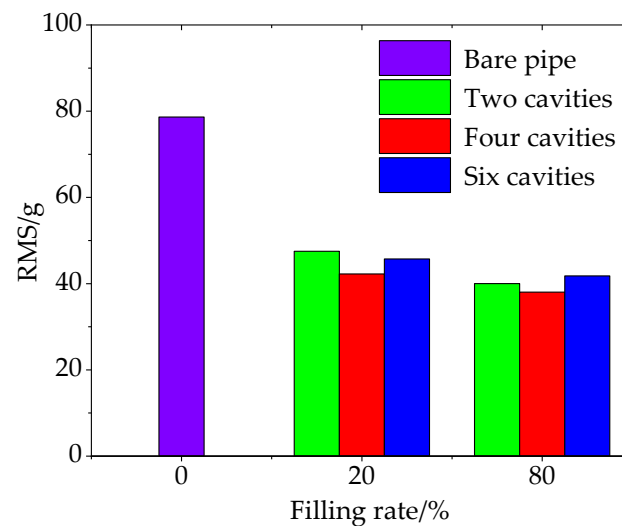


Figure 16. Influence of damper cavity on damping effect.

4.6. Effect of Boundary Conditions on Damping Performance of the Pipeline System

To investigate the effect of the boundary conditions on the damping performance of the pipeline system, for the six-cavity damper, two boundary conditions were selected: fix-free and fix-fix, with 1 mm steel balls shown in Figure 17.

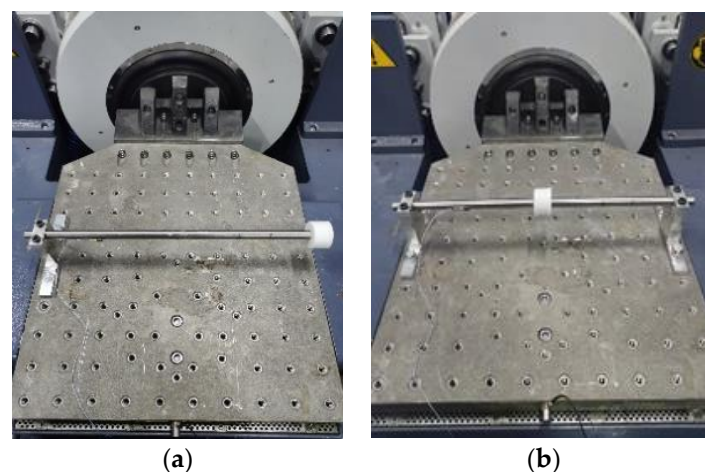


Figure 17. Two kinds of boundary conditions. (a) Fix-free; (b) Fix-Fix.

Figure 18a shows the fix-free pipeline with an additional particle impact damper, where the first- and second-order resonant frequencies at 20% and 80% are offset from the bare pipe by 41 and 75 Hz, respectively. The first- and second-resonant amplitudes are reduced by 48.1%, 89.2% and 42.6%, 59.6%, respectively. When the boundary condition is fix-fix, the corresponding resonance amplitudes are reduced by 68.8% and 88.8%, respectively. The particle impact damper has superb damping performance regardless of the fix-free or fix-fix boundary conditions.

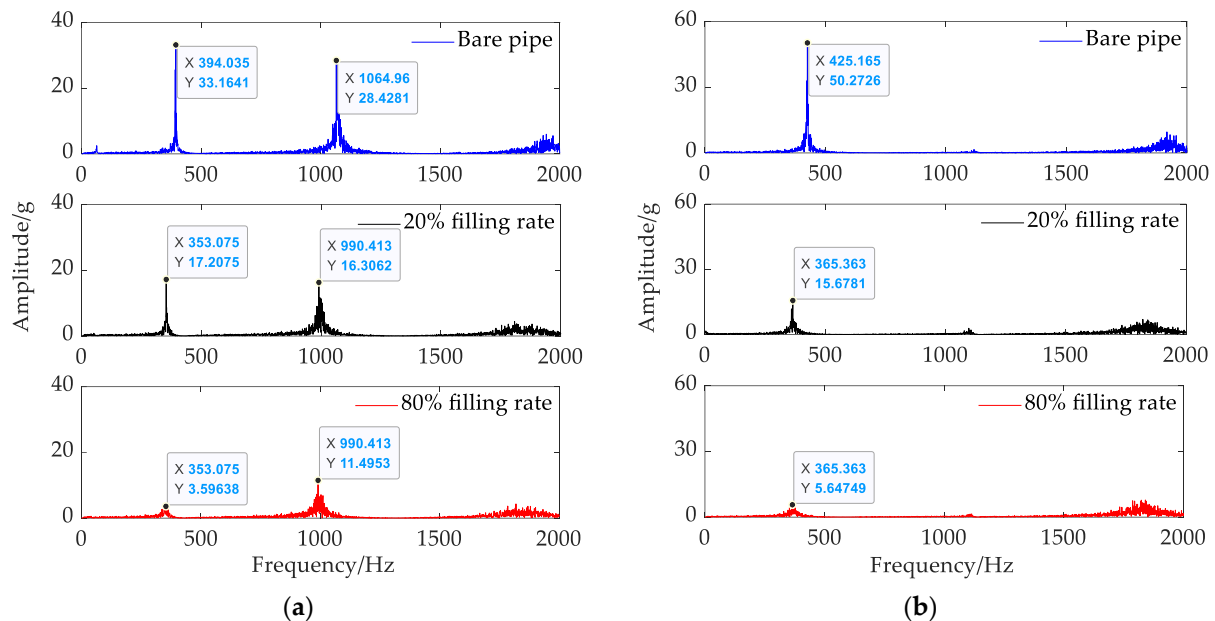


Figure 18. Comparison of damping performance with different boundary conditions; (a) fix-free, (b) fix-fix boundary condition.

Figure 19 shows that the RMS value of the pipeline with the particle impact damper displays a decreasing trend with the filling rate for both boundary conditions. Compared to the bare pipeline, the RMS values of the fix-free condition with 20% and 80% fill rates decreased by 42.68% and 58.14%. Similarly, the RMS values of the fix-fix pipe decreased by 35.65% and 46.87%, respectively. This indicates that different boundary conditions do not affect the damping effect of the particle impact damper, and the particle impact damper provides a good damping effect under different boundary conditions. When the filling rate is 0, it can be seen that the root mean square value of the fix-free bare pipe is larger than that of the fix-fix bare pipe, which is because there is no fixed configuration and the structure is less rigid, so it is more affected by vibration. At the filling rates of 20% and 80%, the root mean square value of the fix-free pipe is slightly lower than that of the fix-fix pipe, mainly because the particle impact damper is attached to the end of the fix-free pipe with the largest vibration amplitude. The more serious the pipe vibration, the more serious the particle collision in the particle impact damper. Therefore, the more energy consumed by the collision, the better the vibration reduction effect.

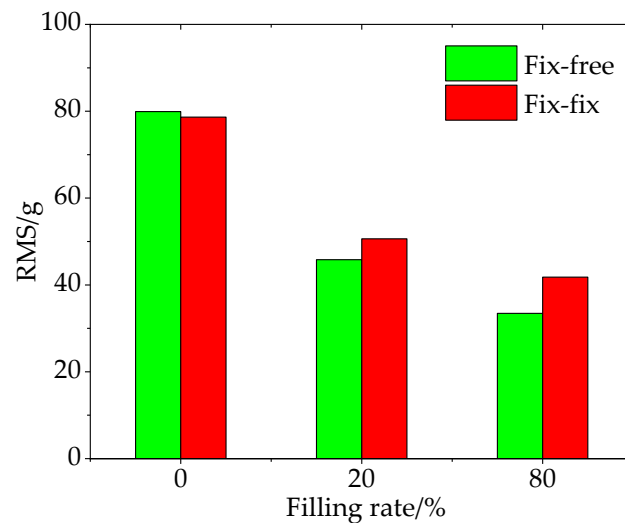


Figure 19. Influence of boundary conditions on vibration reduction effect under three filling rates.

5. Conclusions

In this paper, the vibration characteristics of the pipeline system with a particle impact damper under random excitation are investigated. The effects of parameters such as particle material, filling rate, particle size, damper structure and boundary conditions on the vibration damping performance are investigated. Due to the lower restitution coefficient, the impact damper with steel particles has a more effective vibration reduction effect compared to the damper filled with aluminum and glass particles. When the filling rate was 20%, the damping effect of the steel balls increased by 10.4% and 25.3% compared to the aluminum and glass balls, respectively. At an 80% filling rate, the damping effect of the steel balls increased by 17.2% and 22.9%. When the filling rate of the particles was about 90%, the damping capability of the pipeline system was excellent. The effect of particle size on the pipeline system varies with the filling rate. When the filling rates are 20% and 80%, the four-cavity damper has an excellent damping effect compared to the two- and six-cavity dampers. The effect of boundary conditions on the damping effect is inconsiderable. The proposed particle impact damper can achieve a superior vibration reduction effect in the broadband frequency range, which is expected to reduce pipeline vibration under random excitation, provide an efficient tool for pipeline vibration reduction design and maintenance, and have important significance and value for pipeline vibration reduction in harsh vibration environments such as ocean engineering, aerospace, etc. In the future, the combination of testing and simulation, multiple particle damping, and active control damping will also be considered.

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