THEORETICAL AND EXPERIMENTAL INVESTIGATIONS OF PARTICLE IMPACT DAMPER WITH ELASTIC RESTRAINT

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Compared with traditional impact damping devices, particle impact damper under elastic restraint, a new impact damper with double damping structure, has better damping performance. For the purpose of further studying its damping effects on cantilever beam, this paper comes up with both the dynamic model and the movement differential equation of the particle impact damper system with elastic restraint, and stimulates the damping effects of cantilever beam under the influence of this device. Simultaneously, based on experiments on the damping effects of the particle impact damper with elastic restraint under five different stiffness conditions, it is concluded that: (1) results from the theoretical calculation basically agree with those from experiments, which verifies the reliability of the calculation model of the particle impact damper with elastic restraint built within this paper, and (2) in the system of the particle impact damper with elastic restraint, the influence of stiffness ratio on the damping effects is nonlinear, and the spring stiffness also affects the point of resonance of this impact system.

Key words: elastic restraint; particle impact damper; dynamic model

1. Introduction

The damping technology, capable of transferring vibration into thermal or other types of energy through the energy consumption process in order to realize vibration and noise reduction, is widely applied into such fields as aviation, machine, automobile, and civil engineering. The impact damper, the most classic type in the traditional damping theory, conducts momentum exchange by using the constant, non-elastic collisions between the impactor and the chamber, and hereby consistently absorbs, diffuses, and dissipates energy to inhibit the responses of the primary system [1-4]. However, as part of the energy would return to the primary system, the effect of energy dissipation is anything but satisfactory. In the end of the 20th century, Panossian firstly proposed the conception of particle damper and conducted experiments on particle damping [5] by referring to aluminum cantilever beam as the study subject. Later, the concepts of flexible particle damper [6],
particle damper [7,8] and particle impact damper [9-11] were put forward successively. The principle of particle impact damper is to add particle damping agent on the basis of impact damper, to trigger plastic transformation via the inter-collision between the steel ball inside the chamber and the particle damping agent, and thereby to absorb and consume the system energy. The experiments [12-17] testify that, compared with traditional impact damper, in the process of free damping and forced excitation vibration, both the damping performance and the impulsive noise reduction effects of the particle impact damper are more remarkable and effective. However, there were still a series of problems; for example, the loose particles of the damping agent inside the chamber and the uncertainty of the movement make the system too complex to accomplish accurate calculations or real-time simulation. On the other hand, the experiments have discovered that the energy storage property of the spring can cut down the acceleration rapidly; also, a better damping performance is surly possible if the elastic energy storage property and the plastic energy consumption property can be organically combined.

2. The structure and damping mechanism of the particle impact damper with elastic restraint

The impact damper with particle damping agent is added with elastic restraint to form the particle impact damper with elastic restraint, which is a new impact damper combining elastic restraint with plastic collision (see Figure 1). This damper consists of a two-layer structure. The inside-layer chamber is equipped with fine particle damping agent as well as steel ball, and the inter-collision of both generates plastic transformation of the particles; at the same time, the inner friction helps permanent energy dissipation. For the outside layer, there is attached spring restraint. Due to the dynamic amplification effects of the spring, the inter-collision and plastic transformation between the particles inside the chamber are intensified; simultaneously, the spring could mount up and transfer the energy to the chamber, and therefore could realize the maximum of the momentum exchange between the damper and the primary system for the purpose of double damping effects[18]. Compared with the impact damper with particle damping agent, such device with a two-layer structure has more abundant dynamic movements, more precious original study value, and a wider range of application prospect.

Figure 1: 3D figure of particle impact damper with elastic restraint.
3. Calculation model of the particle impact damper with elastic restraint

3.1 The dynamic model

In order to further analyze the dynamic characteristics of the vibration system in the particle impact damper with elastic restraint, a dynamic model (see Figure 2) is established. The system is constituted by the primary vibration mass body M, the equivalent stiffness K, and the system damping c. Under the influence of the constant external force $F_0\sin(wt)$, the primary vibration body engenders vibration.

![Simplified model of the particle impact damper with elastic restraint](image)

Figure 2: Simplified model of the particle impact damper with elastic restraint.

3.2 Movement differential equation

In the model in Figure 2, the steel ball and the primary vibration body are seen as two complete individual subjects, whose laws of motion do not interrupt with each other and whose relationship only exists under inter-collision. It is supposed that collision energy consumption is the major means of energy dissipation during the entire experiment process, and the friction among each component in the damper is neglectable; the collision is a non-elastic one and only the vibration in horizontal direction is considered. Thus, when there is no collision, the movement differential equation of the primary vibration body is[19]:

$$M\ddot{x}+c\dot{x}+Kx=F_0\sin(wt) \quad (1)$$

From the equation (1), the steady-state response of the primary system is:

$$x = B \sin(wt - \psi) \quad (2)$$

Also,

$$B = \frac{F_0}{k} \frac{1}{\sqrt{(1 - \lambda^2)^2 + (2\xi\lambda)^2}} \quad (3)$$

$$\psi = \tan^{-1}\frac{2\xi\lambda}{1-\lambda^2} \quad (4)$$

In the formula, $w$ represents the frequency of the excitation force, $\lambda = w/w_n$ is the frequency ratio, and $\xi = c/2m_\omega w_n$ is the damping ratio of the system.

3.3 Solution method and process

1) The calculation of the system equivalent mass and equivalent stiffness.

① Independently, the mass of the cantilever beam $m_a$ and the terminal concentrated mass $m_b$ are weighed, and therefore the equivalent mass[20] is,

$$M = 0.23m_a + m_b \quad (5)$$

② The size of the cantilever beam is measured, and according to the formula, the stiffness of the cantilever beam is calculated as:

$$k_1 = 3EI/L^3 \quad (6)$$
2) The calculation of the system equivalent damping. Under the elastic restraint, the first-order damping coefficient $c$ of the particle impact damper system is rounded as:

$$c = \frac{\psi_b + \psi_p}{2\pi} \sqrt{KM} \quad (7)$$

(1) $\psi_b$ stands for the inherent damping of the cantilever beam, which can be measured by attenuation experiment:

$$\delta = \frac{1}{n} \frac{A_1}{A_n} \quad (8)$$

The damping ratio is:

$$\xi_1 = \frac{\delta}{2\pi} \quad (9)$$

$$\psi_b = 4\pi \xi_1 \quad (10)$$

(2) In the impact damper system, the specific volume of the damping $\psi_p$ is defined as the ratio of the elastic energy storage and the maximum elastic energy during the circulation period, which is:

$$\psi_p = \frac{\Delta T}{T} \quad (11)$$

In this formula, $\Delta T$ is the kinetic energy dissipation in a single circulation process, and $T$ is the maximum kinetic energy for the entire circulation.

It is supposed that the friction between the steel ball and the chamber is ignorable, that the instantaneous velocity of the steel ball before the collision, $v_i^-$, is zero, and that the chamber is in constant motion, illustrated by $v_j^-$. The value of $\Delta T$ can be calculated through the following formula:

$$\Delta T = \frac{1}{2} (1 - e^2) \frac{m_p m_\Delta}{m_p + m_\Delta} (v_j^- - v_i^-)^2 \quad (12)$$

And the restitution coefficient $e$ during the entire impact process can be obtained through the empirical formula[21]:

$$e = 1 - 0.115 |v_j^-|^{0.2} \quad (13)$$

In the circulation process, the maximum kinetic energy $T$ reaches its highest value as the velocity of the primary system increases to the highest value. It is calculated as follows:

$$T = \frac{1}{2} m v_1^2 \quad (14)$$

4. The comparison and analysis of the numerical calculation and the experimental results

4.1 The experiment device

This experiment makes the cantilever beam an equivalent counterpart of the spring-particle system, and, by comparing and analyzing results from the simulation calculation and those from the experiments, investigates the one-dimension impact model proposed by this paper. During the experiment, one end of the cantilever beam is fixed, and this end has gone through sine excitation
vibration by the high-frequency electromagnetic vibrator. The particle impact damper with elastic restraint is placed at the free end of the cantilever beam, with the accelerometer fixed opposite to the damper (see Figure 3). The acceleration signal is collected by the signal acquisition device, and hence the time-displacement diagram or the frequency-displacement diagram is obtained by quadratic integral or Laplace transform.

The size of the cantilever beam used in the experiment is 315mm×45mm×2.1mm, and the material is A3 steel with a density of 7.8×10³kg/m³. The damping chamber is a cylinder, with the inner diameter of 12mm and the height of 20mm; inside the chamber, there are 8 steel balls (5mm in diameter), filled with zinc powder granules, 56µm in grain size and 20% filling rate.

![Figure 3: Schematic diagram of experiment device.](image)

There are two parts: One is free damping experiment. The acceleration signal of the cantilever beam under the influence of the particle impact damping with damping and elastic restraint is collected, and the data will be analyzed and disposed. The other is forced vibration experiment. Under the action of harmonic excitation force, on conditions of diverse damping (see Table 1) and 5 different stiffness ratios of the particle impact damping with elastic restraint, the maximum amplitudes of the cantilever beam are gathered, transferred, and analyzed comparatively. In this case, stiffness ratio is defined as the ratio of the spring stiffness value and the stiffness value of the main cantilever beam. In the early stage of the experiment, the system inherent frequencies in the two forced vibration experiments are pre-measured respectively by the swept frequency. Then, the experiment frequency is set up in accordance with the measured inherent frequency, so that the maximum amplitude value can be obtained.

<table>
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<tr>
<th>No.</th>
<th>Name</th>
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<td>No</td>
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### 4.2 Results and discussion

Figure 4 indicates the free damping curves (calculation results and experiment results) of the cantilever beam under no influence of the additional damping or particle impact damping with elastic restraint. It can be gleaned from the figure that, for the particle impact damper with elastic restraint, the calculation result curve and the experimental one reach their peak values at the same or similar time point, and their basic tendencies go and match each other. However, in the early
damping stage, the calculation value is higher than the experiment one, which can be attributed to the simplicity of the theoretical model and the inevitable friction as well as resistance forces occurring during the real experiment process. As for the later damping stage, the calculation value becomes lower than the experiment one, predominantly because of the inertia force of the primary system, which leads to the decline of cantilever beam’s damping speed. The discussion above has justified that the dynamic model established by this paper can be applied to the simulation of the particle impact damper with elastic restraint.

After a comparison of the free damping curves of the cantilever beam under the particle impact damping with no additional damping and that with elastic restraint (Figure 4), there is a remarkable discrepancy between the two curves. Under the circumstance of the same initial acceleration, with the effects of the particle impact damping with elastic restraint, the damping has a notable downward trend; at the end of 1.8s, the damping ratio of the particle impact damping with elastic restraint is 94.8%, far higher than that of the cantilever beam without additional damping, 67.9%. Therefore, it can be concluded that the particle impact damper with elastic restraint can effectively reduce the response amplitude of the cantilever beam with fine damping performance.

![Figure 4](image.png)

**Figure 4:** The free damping of the cantilever beam and the particle impact damper with elastic restraint.

In Figure 5, it shows the comparison of the theoretical calculation results and the experiment results of the cantilever beam’s forced vibration, respectively in the condition of no damping, impact damper, and particle impact damper with elastic restraint. It can be obtained from Figure 5 that the curves of both results, under all three damping conditions, appear basically the same variation trend. The experiment result indicates that the maximum amplitude of the impact damper decreases by 43.6% than that of no damping condition, and in comparison, the maximum amplitude of particle impact damper with elastic restraint declines by 74.8%, suggesting that the damping mechanism of particle impact damper with elastic restraint is to transfer, store, and dissipate energy by elastic restraint and particle plastic transformation; as a result, it can foster a higher damping speed of the cantilever beam and achieve a more outstanding damping performance. The reasons are concerning two aspects: (1) After the spring is added, the number of collision between the impactor in the damper and the two ends of the chamber increases and the number of momentum exchange increases as well. (2) Due to the introduction of spring, the impactor conveys energy to the spring and as the spring start to transfer energy, there is friction between the spring and the frame as well as between the spring and the cantilever beam, and a small part of system energy will be dissipated
in form of thermal energy. In the calculation and experiment results of the particle impact damper with elastic restraint, the maximum amplitude reaches its peak value respectively at 12.2Hz and 12.1Hz with their corresponding amplitudes of 5.25mm and 5.60mm, and the error is less than 7%. Therefore, it can be verified that the movement model and the movement differential equation built in this paper are reliable and can be used to conduct theoretical simulation specific to particle impact damper with elastic restraint.

![Figure 5: Comparison of the theoretical calculation results and experiment results during forced vibration.](image)

5. Conclusion

Compared with traditional impact damper, particle impact damper with elastic restraint has a two-layer damping structure, which achieves better damping performance under the double influences of spring energy storage and plastic transformation. Therefore, this paper proposes the dynamic model and movement differential equation of the particle impact damper with elastic restraint in order to simulate and anticipate the cantilever beam’s damping performance under the effects of different dampers, and verifies the validity of the model by experimental study. On top of that, the damping properties of particle impact damper with elastic restraint under different spring stiffness ratio conditions are compared and analyzed to reach the following conclusions:

(1) Results from theoretical calculation and the experiment basically match each other, and the calculation model of particle impact damper with elastic restraint, built in this paper, is therefore reliable.

(2) In the system of particle impact damper with elastic restraint, the influence of stiffness ratio on the damping performance is non-linear, and the spring stiffness can affect the resonance frequency point in the impact system.

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References


