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Article

Research on intelligent vibration damping base of washing machine based on a stiffness-variable magnetorheological elastomer

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Abstract: Traditional washing machine vibration-damping bases have a fixed stiffness, which can lead to structural resonance when the motor's excitation frequency aligns with the machine's inherent vibration frequency during the washing and spinning processes. This not only amplifies the noise caused by vibrations but also accelerates the wear and tear of the internal components. In this study, a pioneering approach has been introduced, developing an intelligent vibration-damping base for drum washing machines based on the dynamics of a mass-spring-damped single-degree-of-freedom system. This innovative base is designed with variable stiffness magnetorheological elastomer, utilizing the dynamics of the mass-spring-damped system to adaptively counteract vibrations. A vibration transmission rate curve specific to drum washing machines has been derived, and an intelligent control strategy for the drum washing machine's vibration-damping base has been proposed. Dynamic testing of the drum washing machine's vibration-damping base was conducted to verify the effectiveness of the intelligent damping base. The intelligent damping base addresses the unavoidable low-frequency resonance issues of traditional passive damping bases in washing machines and overcomes the drawback that the performance parameters of traditional passive isolation structures cannot be changed once set, providing a new direction for the damping of household appliances.

Keywords: control strategy; drum washing machine; intelligent vibration damping base; resonance; variable stiffness magnetorheological elastomer; household appliances damping; vibration transmission

1. Introduction

Vibration and noise are a common phenomenon in daily production and life, from train operation, building construction, to the smallest washing machine rotation, in most cases vibration and noise are harmful, so vibration and noise reduction to provide people with more comfortable living and working conditions, it has become scientists and engineers have been trying to do the work.

Viscoelastic vibration damping structure has excellent energy dissipation performance and fatigue performance, is commonly used in engineering applications as an energy-consuming vibration damping device. Its basic principle is that, under the action of external vibration, the use of special vibration-damping materials or structure of the hysteresis energy dissipation characteristics, increase its damping effect, the energy of mechanical vibration into energy that can be dissipated, thereby reducing the structure of the vibration under the action of the external force or noise and other mechanical response, so as to achieve to ensure that the system works properly, and to improve the service life of the engineering purposes. Viscoelastic vibration damping structure is suitable for all kinds of engineering structures to reduce wind-induced vibration, seismic vibration damping, and other engineering fields [1,2]. In engineering vibration damping, reasonable use of passive control can effectively avoid the inherent defects of active and semi-active control [3,4]. Different active and passive control methods can be used to reduce structural hazards in terms of spacecraft micro vibration [5], or a maximum reduction ratio of 69.2% can be achieved by selecting a reasonable installation location for additional viscoelastic damping layer [6]. The new vibration-damping mechanism model Inerter-spring-damper structure (ISD structure) has a very good vibration reduction effect [7], expanding the direction for the application of vibration-damping structure. Magnetorheological (MR) materials are a class of smart materials whose material properties can be rapidly changed under the action of a magnetic field, and the process is controllable and reversible, i.e., the magnetorheological fluids can be changed back to the initial state in an instant after the magnetic field is withdrawn [8–13]. The concept of magnetorheological fluids (MRFs) was first introduced by Rabinow [14] in 1948. Due to the nature of magnetorheological fluids, they have shown utility in a variety of applications, such as dampers, clutches, and brakes [15–19]. In daily life, vibration damping structures have a wide range of applications. They can be used effectively to control vibration or noise in various equipment. For instance, common kitchen appliances like blenders and household washing machines benefit from specialized vibration damping structures.

Researchers both domestically and internationally have conducted in-depth studies on vibration isolation technologies based on passive and semi-active variable stiffness. Luo [20] and colleagues developed a novel Maxwell-negative stiffness damper (MNSD) that realizes the conceptual MNS model, effectively controlling the displacement and acceleration of low-frequency structures under strong ground motions. The study introduced a design method for MNSD that takes into account its nonlinear characteristics, and systematic research has shown that compared to traditional dampers, MNSD has a significant advantage in improving the performance of seismically isolated buildings. Luo [21] and colleagues also compared three types of negative stiffness dampers (NSDs) and found that the viscoelastic damper (NSVeD) performs best in reducing the floor response acceleration of base-isolated structures without increasing isolator displacement. Through multi-objective optimization, the seismic isolation efficiency of the structure was effectively enhanced.

Wang [22] and his team have achieved significant results in the field of intelligent control and structural vibration control, particularly in the development of new types of Tuned Mass Dampers (TMD). Their VMD-STMD and BSTMD, which adjust mass and damping in real time, have enhanced the vibration control and seismic performance of footbridges and building structures. Furthermore, their APVS-TMD, featuring variable stiffness technology, effectively addresses vibration issues on footbridges, offering new ideas for the application of intelligent control technology.

In order to analyze the vibration isolation performance of offshore platform mounting pedestal, Man et al. [23] used the variable density method to optimize the topology of the double-layer bottom structure with two schemes of open holes and open holes with reinforcement, and also carried out experiments to validate the optimization, and the results showed that the vibration level falloff of the optimized pedestal was improved by 3.41 dB compared with that of the original pedestal. Huang

[24] will use electromagnetic damping elements to replace the viscous damping elements in the traditional tuned mass damper, and design an electromagnetic resonant tuned mass damper (EMS-TMD) that combines both structural damping control and energy harvesting. Yin [25] developed a magnetically stiffened eddy current inertia damper (MSEID) prototype, and carried out theoretical analysis and experimental research on the single-mode vibration control of MSEID on inclined cables, obtained the influence of MSEID parameter variations on the modal damping ratio of the cables, and revealed the upgrading mechanism of the vibration-damping effect of MSEID on the cables. Zhang [26] researched the harmonic suppression of the magnetic gear, reduced the torque fluctuation measures, and established a magnetic gear system dynamics model taking into account the torque fluctuation of the outer rotor and the magnetorheological damper. The dynamic response of torsional vibration acceleration of the magnetic gear prototype before and after the installation of the damper is compared, and the torsional vibration control effect of the rotary magnetorheological damper is verified. Hao [27] studied the nonlinear dynamics and vibration control of the magnetic gear drive system, and verified the vibration suppression effect of the magnetorheological damper on the magnetic gear drive system by comparing and analyzing the vibration response of the magnetic gear prototype with and without the magnetorheological damper.

Drum washing machine in the work of the internal motor drives the inner cylinder rotation as shown in **Figure 1a,b**, the inner cylinder, during high-speed rotation, generates significant centrifugal force leading to up-and-down vibrations [28]. To minimize these vibrations on the floor and reduce noise impact on neighbors, in order to reduce the vibration of the washing machine work to the floor, reduce the noise impact on the neighbors, through knowledge of vibration theory, placing a softer, more elastic base under the washing machine can significantly reduce the vibration and consistent noise produced by the washing machine. By learning about vibration theory, placing a softer flexible base underneath the washing machine can significantly reduce the vibration and secondary noise transmitted to the floor during constant power operation. However, the situation is more complicated, to achieve better washing effect, most of the drum washing machines are driven by variable frequency, and in a complete washing process requires many times of forward and reverse operation, which makes the excitation frequency of the washing machine in the process of work is constantly changing. When the excitation frequency coincides with the intrinsic frequency of the washing machine, it will inevitably cause the structure of the washing machine to resonate, which will greatly aggravate the vibration of the structure of the washing machine, and adversely affect people's life and work. Therefore, designing a washing machine vibration damping base with fixed stiffness alone cannot adequately address the requirements for minimal vibration and low noise. It is necessary to design the base with adjustable stiffness.

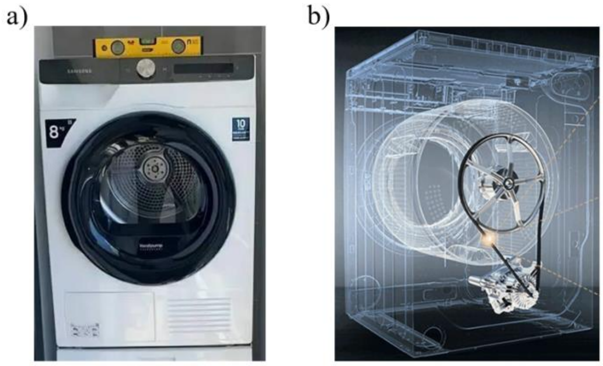

Figure 1. (a) Physical picture of drum washing machine; **(b)** drum washer working principle diagram.

It was found that magnetorheological elastomers may be able to solve the above problems, and magnetorheological elastomers can fit well into the vibration environment of washing machine operation with little increase in cost compared to traditional vibration damping materials. Zhu et al. [29] and Kumbhar [30] described the characterization, synthesis, and application of MR fluids. Magnetorheological dampers contain a smart fluid known as magnetorheological fluid (MRF). The change in the applied excitation current changes the strength of the magnetic flux density of the electromagnet, which in turn changes the rheological properties of the magnetorheological fluid. This fluid contains micron-sized magnetic particles (5–50 μm), such as iron, suspended in a carrier fluid, typically oil. In the absence of an applied magnetic field the magnetorheological fluid exhibits the properties of a Newtonian fluid [31–34], with the soft magnetic particles in the base carrier fluid exhibiting an irregular and haphazardly distributed arrangement. With the increase of the applied magnetic field, the soft magnetic particles are arranged perpendicular to the direction of the magnetic induction line, and then the magnetorheological fluid changes from the state of Newtonian fluid to the state of semi-solid of Bingham [34–36]. With the increase of the magnetic field strength, the magnetorheological fluid changes and the shear yield strength of the magnetorheological fluid increases continuously until it reaches the magnetic saturation. increases until magnetic saturation is reached. If the magnetic field is removed, the shear yield strength of the magnetorheological fluid decreases rapidly, and its fluidity rapidly returns from the Bingham semi-solid state to the Newtonian fluid state, as shown in **Figure 2**. Magnetorheological elastomers are micron-scale ferromagnetic particles doped into polymers such as silica gel, rubber, etc., which are cured in a magnetic field environment so that the particles within the matrix have a chain or columnar structure. Magnetorheological elastomers not only have high technical characteristics such as controllability, reversibility, and rapid response, but also have the advantages of low energy consumption, easy control, and high stability due to the highly sensitive properties of magnetorheological elastomers, with magnetic particles resistant to settling.

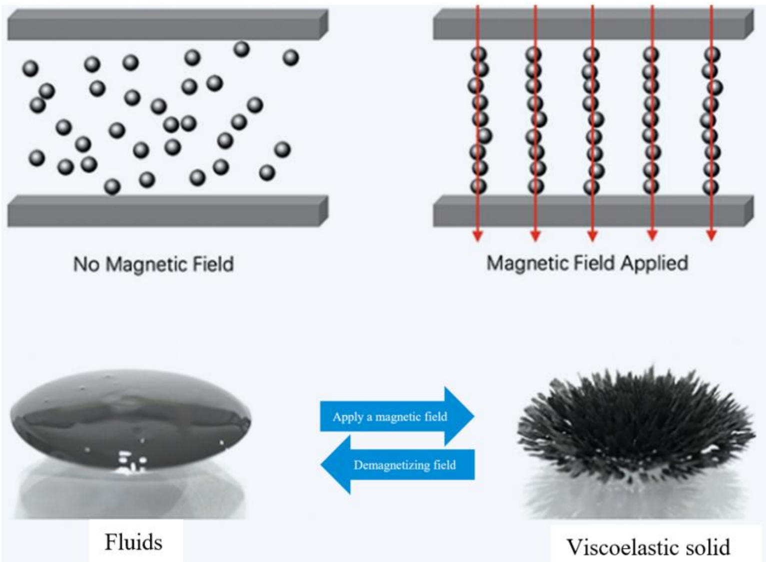

Figure 2. Working principle of magnetorheological elastomer.

In summary, magnetorheological materials are a new type of intelligent material whose rheological properties can be controlled by an external magnetic field. They are characterized by rapid response times (in the millisecond range), good reversibility (returning to their initial state once the external magnetic field is removed), and adjustable mechanical properties via the external magnetic field. These materials have been extensively applied in various fields such as automotive, bridges, robotics, and construction. However, their application in household appliances is still very limited. This study integrates magnetorheological materials with washing machines, addressing the unavoidable low-frequency resonance issue of traditional passive damping bases in washing machines and overcoming the drawback of traditional passive isolation structures, where the performance parameters of the isolation layer cannot be changed once set. This provides a new direction for the damping of household appliances.

Therefore, based on the magnetorheological elastomer material, this project will design the intelligent vibration-damping base for washing machine based on the full study and analysis of the dynamics of mass-spring-damping single-degree-of-freedom system, and propose the vibration control strategy to realize the better vibration and noise control of the washing machine in all kinds of working scenarios, so as to solve the problem that the vibration-damping base for the existing washing machine can't meet the problem of the whole process of washing and dewatering with small vibration and low noise control.

2. Analytical models and methods

2.1. Analytical modeling of drum washing machine vibration

The vibration-damping base of a drum washing machine is considered as a mass-spring-damping system as in **Figure 3**. During high-speed operation, the clothes inside the drum of a washing machine act as an eccentric mass block. The centrifugal force generated by this eccentric mass block is the primary source of excitation for the washing machine. For simplicity, we define the total mass of the drum washing machine as *M*, the rotating uneven mass of the rotor as *m*, the distance of the center of the rotor from the center of mass as *e*, the rotating angular velocity of the rotor as *ω*, and the bottom connected to an ideal spring *k*, and a damper *c*. Taking the initial position of the mass block as the origin, and the positive direction is set to be vertically upward, the vertical displacement of the washing machine away from the equilibrium position can be expressed as the coordinates *x*. The mechanical model of this is simplified as follows diagram is shown in **Figure 3a,b**.

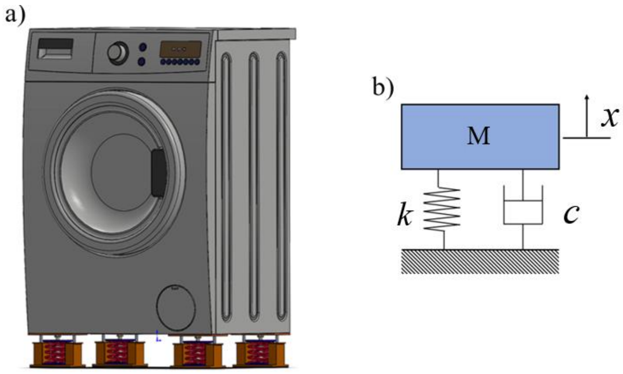

Figure 3. (a) Drum washing machine model drawing; **(b)** vibration resolution model.

According to Newton's second law, write down the equilibrium equation. we can get:

$$M\ddot{x} + c\dot{x} + kx = me\omega^2 sin\omega t \quad (1)$$

vide both sides of Equation (1) by the mass *M* while defining the following symbols:

$$\omega_n = \sqrt{\frac{k}{M}}, \zeta = \frac{c}{2M\omega_n} \quad (2)$$

solve for：

$$\begin{cases} X = \frac{me\omega^2}{M}\frac{1}{\sqrt{({\omega_n}^2-\omega^2)^2+(2\zeta\omega_n\omega)^2}} \\ \quad = \frac{me}{M}\frac{\lambda^2}{\sqrt{(1-\lambda^2)^2+(2\zeta\lambda)^2}} \\ \varphi = arctan\frac{2\zeta\lambda}{1-\lambda^2} \end{cases} \quad (3)$$

λ denotes the ratio between the frequency of the external excitation and the intrinsic frequency of the system, often referred to as the frequency ratio, i.e.,

$$\lambda = \frac{\omega}{\omega_n} \quad (4)$$

Rewriting Equation (4) into dimensionless form as：

$$\beta = \frac{MX}{me} = \frac{\lambda^2}{\sqrt{(1-\lambda^2)^2+(2\zeta\lambda)^2}} \quad (5)$$

where *M* is the total mass of the drum washer, *m* is the uneven mass of the rotor rotation, and e is the rotor eccentricity.

2.2. Derivation of vibration characteristics of drum washing machine

The amplitude-frequency characteristics and phase-frequency characteristics are analyzed as shown in **Figure 4**. The relationship between β and the frequency ratio λ is called amplitude-frequency characteristics, and the corresponding curve is the amplitude-frequency characteristic curve.

The variation of phase φ with frequency ratio λ is called phase-frequency characteristic and the corresponding curve is called phase-frequency characteristic curve, as shown in **Figure 5**.

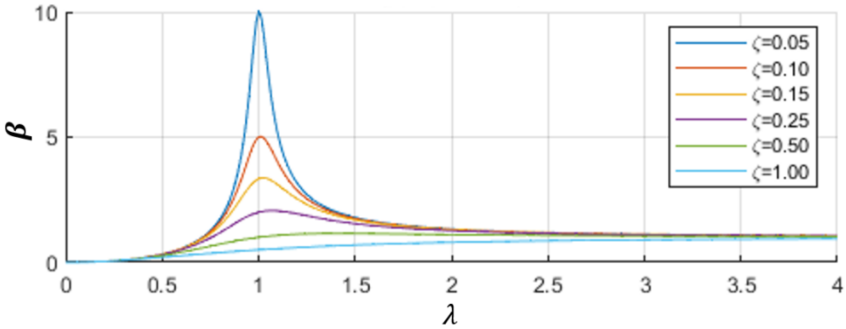

Figure 4. Magnitude-frequency characteristic curve.

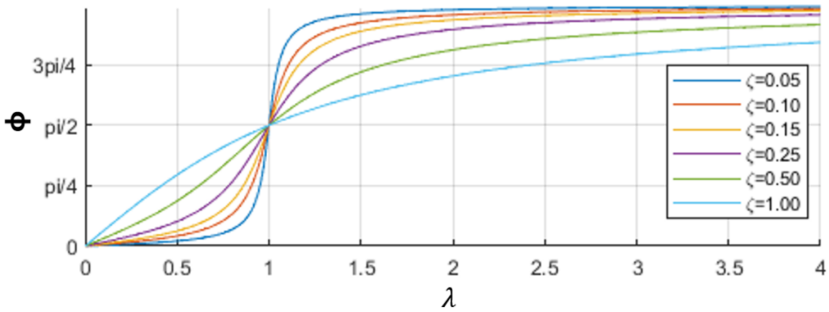

Figure 5. Phase-frequency characteristic graph.

From the amplitude-frequency characteristic curve, when λ > 2.5, with the constant change of damping ratio ζ, β curve is basically unchanged, tends to a constant $\frac{me}{M}$, currently the system vibration frequency is basically independent of the system damping. Near λ = 1, with the constant change of the damping ratio ζ, the β curve changes drastically, currently the system is greatly affected by the damping, and the vibration is drastic when the damping is small [37].

From the phase-frequency characteristic curve, the phase difference φ increases gradually with the increase of the frequency ratio λ. When λ > 2.5 and the damping ratio is relatively small, the phase difference is close to 180° indicating that the phase difference between the external excitation and the response of the system is large, meaning that the system's response to external excitation is relatively inverted, and currently, the system has a better vibration damping effect. Because the system response tends to cancel the external excitation, so that the vibration is reduced.

3. Research on intelligent vibration isolation of drum washing machine based on variable stiffness control

3.1. Vibration transmission rate and vibration isolation analysis of drum washing machine

To reduce the forces transmitted to the foundation by the vibrating washing machine, we introduce vibration isolation pads consisting of spring dampers, which are placed between the vibrating washing machine and the foundation to block direct contact, a method known as positive vibration isolation [38]. The effect of vibration isolation is described by comparing the amplitude of the force transmitted to the foundation after vibration isolation with the amplitude of the force transmitted to the foundation without vibration isolation. This ratio, also known as the transmittance, is denoted by *Tf*, which expresses the performance of the isolation system in terms of the degree of transmission of vibration energy to the foundation and is defined as:

$$T_f = \frac{P_T}{P_0} \tag{6}$$

where P_0 and P_T represent the amplitude of the force transmitted to the foundation before and after vibration isolation, respectively. These force amplitudes are used to measure the effectiveness of the vibration isolation system.

In the study of this problem, we assume that the displacement amplitude of the washing machine *M* is *X*. With active vibration isolation, the amplitude of the force transmitted to the foundation through the spring is kX, and the amplitude of the force transmitted to the foundation through the damper is $c\omega X$. On the other hand, the force transmitted to the foundation after active vibration isolation is equal to the combined force transmitted to the foundation by the spring and the damper, and as a result, we obtain the following description of the amplitude of the total transmitted force:

$$P_T = \sqrt{(kX)^2 + (c\omega X)^2} = kX\sqrt{1 + (2\zeta\lambda)^2} \tag{7}$$

Among them:

$$X = \frac{me\omega^2}{M}\frac{1}{\sqrt{({\omega_n}^2-\omega^2)^2+(2\zeta\omega_n\omega)^2}} = \frac{me\omega^2}{k}\frac{1}{\sqrt{(1-\lambda^2)^2+(2\zeta\lambda)^2}} \tag{8}$$
$$P_0 = me\omega^2$$

Thus, the force transmission rate is:

$$T_f = \frac{P_T}{P_0} = \frac{\sqrt{1+(2\zeta\lambda)^2}}{\sqrt{(1-\lambda^2)^2+(2\zeta\lambda)^2}} \tag{9}$$

Based on MATLAB, the relationship between force transmission rate and frequency can be obtained from Equation (9) as shown in **Figure 6**.

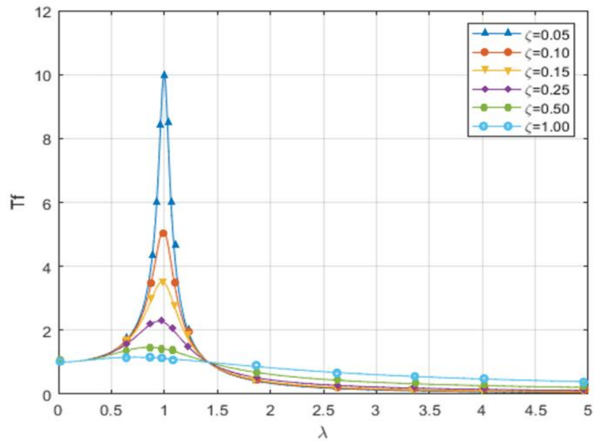

Figure 6. Transmission rate graph.

Analyzing **Figure 6**, the system has obvious vibration isolation effect only when the frequency $\lambda > \sqrt{2}$ [39]. However, when $\lambda > 4$, the representation curve of the transfer efficiency is essentially unchanged. Therefore, the choice of frequency is usually limited to the range of 2.5 to 4. On the other hand, from Equation (9), it is not difficult to conclude that the vibration isolation effect is better shown when the system has a lower intrinsic frequency and smaller damping. However, it is worth pointing out that the resistance should not be too low, otherwise significant vibration will occur when passing through the resonance region.

3.2. Intelligent control strategy for vibration isolation of drum washing machine

The analysis in Section 3.1 shows that the vibration control is executed through two aspects. The general control strategy is as follows:

On the one hand, when the washing machine is rotating at high speed with rated power, the excitation frequency of the washing machine is currently high. Combined with the content of the derivation in Section 3.1, the system has an obvious vibration isolation effect only when the excitation frequency is higher than $\sqrt{2}$ times of the intrinsic vibration frequency, and the higher the ratio of the excitation frequency of the washing machine to the intrinsic vibration frequency of the washing machine, the more obvious the vibration isolation effect is. To achieve effective vibration isolation, it's necessary to lower the intrinsic vibration frequency of the washing machine by reducing the support stiffness of the vibration isolation base. Therefore, a softer stiffness value is chosen for the design.

On the other hand, when the washing machine rotates at a low speed, to avoid the excitation frequency and the intrinsic vibration frequency of the washing machine, it is necessary to increase the intrinsic vibration frequency of the washing machine, i.e., to increase the support stiffness of the vibration-damping base, and to choose a stiffer stiffness value for the design.

Taking the Haier drum washing machine as an example, specific parameters are shown in **Table 1**, and the vibration damping base is designed with appropriate spring stiffness parameters and damping coefficients.

To ensure effective vibration damping when the washing machine rotates at high speed with rated power, the stiffness of the vibration damping base should be softer during this period. The design approach is as follows:

Table 1. Specific parameters of Haier washing machines.

Specific parameters of Haier washing machines	
Product Size	850 × 595 × 535 mm
Product weight	63 kg
Washing Capacity	5 kg
Constant power speed selection	700 rpm

Based on the specific parameters of the washing machine the required physical parameters can be organized as shown in **Table 2**.

Table 2. Physical parameters.

M	***m***	***e***	***ω***
63 kg	5 kg	0.25 m	73 rad/s

According to the analysis of the transfer rate curve in **Figure 5**, combined with the amplitude-frequency characteristics and phase-frequency characteristics curve, to achieve a better vibration damping effect, the design selects a larger frequency ratio as well as a smaller damping value, i.e., $\lambda = 3.5$, $\zeta = 0.2$.

$$T_f = \frac{P_T}{P_0} = \frac{\sqrt{1+(2\zeta\lambda)^2}}{\sqrt{(1-\lambda^2)^2+(2\zeta\lambda)^2}} = 0.15 \tag{10}$$

Equivalent to the addition of spring and damping vibration isolation after the transfer of the force to the foundation is only 0.15 times before the addition of the force, to achieve a very good vibration damping effect.

From this, the spring stiffness parameter and damping parameter can be deduced as:

$$k = {\omega_n}^2 M = \frac{\omega^2}{\lambda^2} M = \frac{27.4kN}{m} \tag{11}$$

$$c = 2\zeta M\omega_n = 2\zeta M\frac{\omega}{\lambda} = 0.526kN \times \frac{s}{m} \tag{12}$$

To ensure that the resonance frequency of the washing machine is avoided when the washing machine is spinning in forward and reverse start-stop low-speed rotation, based on the design advantage of controllable stiffness of the magnetorheological elastomer, the stiffness of the vibration-damping base support is increased to 4 times of the original value by changing the coil current. This can be realized in the engineering, research the current market of magnetorheological elastomer stiffness change can reach 8 times the initial value. After applying the excitation current, the stiffness and damping ratio of the magnetorheological elastomer are taken as follows:

$$k = 109.6\frac{kN}{m} \tag{13}$$

$$\zeta = \frac{c}{2M\omega_n} = 0.1 \tag{14}$$

Therefore, the stiffness control strategy of the magnetorheological elastomer is as follows, i.e., there is no need to apply the excitation current during the high-speed rotation, while the excitation current is added during the forward and reverse start-stop low-speed rotation to ensure a higher stiffness.

$$k_{semi-active} = \begin{cases} 4k_{design} & \omega \leq 240r/min \\ k_{design} & \omega > 240\ r/min \end{cases} \tag{15}$$

It can be found that the superior performance of the washing machine can be realized by the magnetorheological elastomer in the full frequency band range. Using MATLAB to alter stiffness to obtain the transmissibility curves for a vibration isolation base based on soft stiffness, compared to one based on hard stiffness. As shown in **Figure 7**, there exists a better application of the design theory of this project. The designed magnetorheological elastomer intelligent vibration damping base reduces the vibration transmitted to the floor by 85% when the washing machine rotates at high speed, and avoids its own structural resonance when the washing machine rotates at low speed for many times in forward and reverse start-stop, which ensures that the washing machine has a good vibration and noise control effect throughout the whole process of washing and dehydration, and solves the low-frequency resonance problem of the traditional vibration damping base of the washing machine.

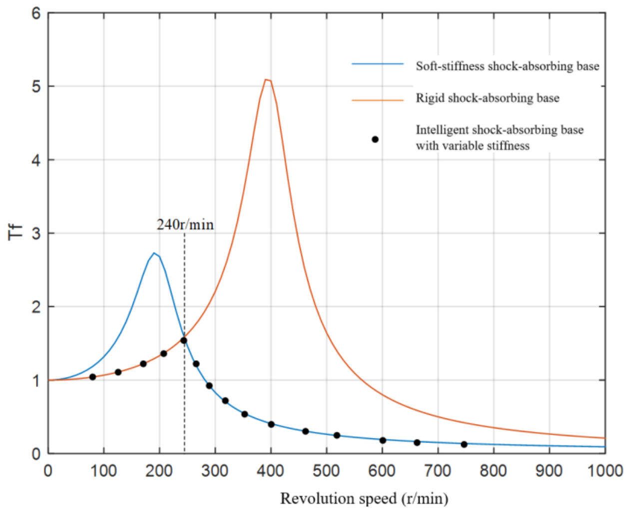

Figure 7. Vibration damping effect of variable stiffness based intelligent vibration damping base.

4. Magnetorheological elastomer design and preparation and kinetic experiments

4.1. Design and preparation of magnetorheological elastomers

To facilitate the realization of large stiffness changes, a softer silicone rubber is used as the matrix material, which is designed to have a modulus of elasticity of 0.6 MPa, and the magnetorheological elastomers are made by selecting spherical iron powders with diameters of 3 to 8 μm, which are proportioned according to a mass fraction of 50% to 80%. In order to achieve a larger range of stiffness variation, a value of 80% is taken in this paper. The stiffness k of the magnetorheological elastomer can be obtained from the following equation:

$$k = \frac{EA}{d} \tag{16}$$

where E is the elastic modulus of the magnetorheological elastomer, A is the cross-sectional area of the magnetorheological elastomer, and d is the thickness of the magnetorheological elastomer. In order to ensure that the damping element has a large amount of compression to improve the damping performance, the thickness of the magnetorheological elastomer is taken to be 60 mm, the stiffness that the elastomer can provide when no excitation current is applied is 27.4 kN/m, and a 4-angle support is used for the damping base of the washing machine. Bringing in Equation (16), the diameter of the magnetorheological elastomer is obtained as 30 mm.

The magnetorheological elastomer preparation process is shown in **Figure 8**. The preparation process is mainly divided into four steps, the first weighing the weight of silica gel, silicone oil, iron powder; the mass of the iron powder is 157.51 grams, and the raw materials are taken according to a volume ratio of 27% (Davis pointed out that at this volume ratio, the magnetorheological elastomer will have the best magneto-control performance), the second step of the silica gel, silicone oil, iron powder three stirring mixing, in the process of mixing add curing agent to accelerate the solidification of the silica gel; the third step of the mixture will be blended mixture layered filling the mold. Finally place the mixture into a mold with a diameter of 30 mm and apply a uniform high magnetic field, after curing for 12 h, the desired magnetorheological elastomer material can be obtained.

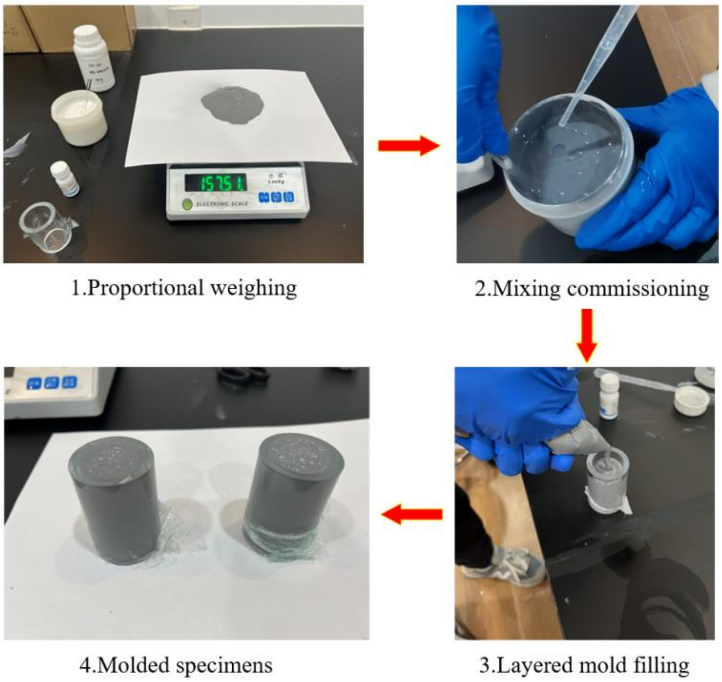

Figure 8. Flow of magnetorheological elastomer preparation.

4.2. Verification of vibration damping effect of washing machine base based on magnetorheological elastomer

The prepared magnetorheological elastomer was filled with the base of the washing machine to fabricate the smart vibration damping base of the washing machine as shown in **Figure 9**.

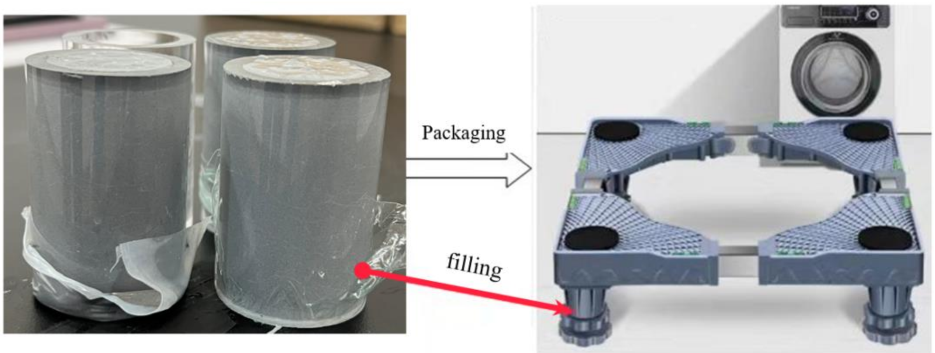

Figure 9. Intelligent vibration damping base for drum washing machines.

The magnetorheological elastomer stiffness variation realization device is shown in **Figure 10a,b**. In this device, a magnetic field is generated by passing an electric current through a coil, and the strength of the magnetic field is controlled by varying the magnitude of the current. The coil is wrapped around a magnetorheological elastomer, and controllable elastomer stiffness is achieved by controlling the strength of the magnetic field.

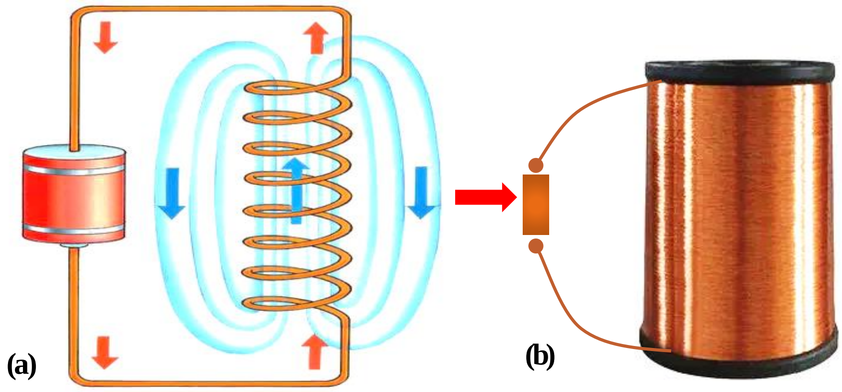

Figure 10. Physical device for variable stiffness realization: **(a)** schematic diagram of an electromagnetic coil; **(b)** magnetorheological elastomer with added coil.

The control algorithm of washing machine vibration reduction based on magnetorheological elastomer is shown in **Figure 11a,b**. Through experiments, when the magnetic field strength reaches 800 mT, the stiffness of the magnetorheological elastomer will be increased to 4 times of the initial value, which meets the demand of intelligent control in section 3.2. The detailed control algorithm is shown in **Figure 11b**. When rotating at a constant speed higher than 240 r/min, the strength of the magnetic field generated by the coil is 0, and at this time the magnetorheological elastomer is soft stiffness; when starting and stopping the rotation at a speed lower than 240 r/min, the strength of the magnetic field generated by the coil is 800 mT, and at this time the magnetorheological elastomer is hard stiffness.

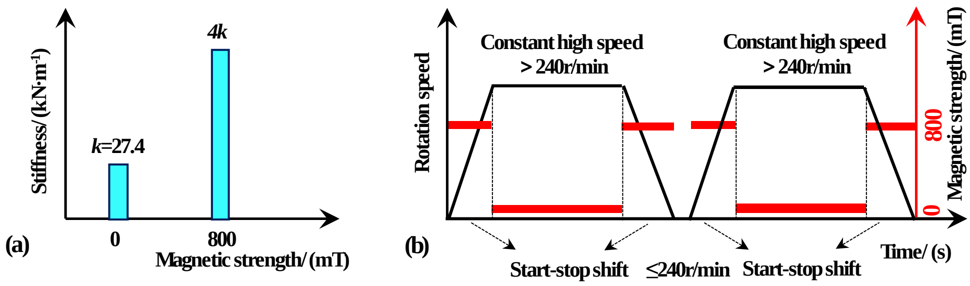

Figure 11. Damping control algorithm: **(a)** variation of magnetorheological elastomer stiffness under different magnetic fields; **(b)** magnitude of the applied magnetic field in different operating modes of the washing machine.

To verify the vibration damping effect of the intelligent vibration damping base, the dynamics test of the vibration damping base of the drum washing machine was carried out, as shown in **Figure 12**.

Figure 12. Dynamics test of intelligent vibration damping base of drum washing machine.

Comparing the vibration damping base of the washing machine filled with magnetorheological elastomer or not, the vibration response of the drum washing machine from the normal rated power operation to the cessation of operation is obtained by using the vibration acceleration sensor test as shown in **Figure 13a,b**. The results in **Figure 13b** show that there are significant resonance peaks in the vibration response of washing machines using traditional vibration damping bases. The vibration response of the washing machine is greatly reduced after using the intelligent vibration-damping base. The test results are basically consistent with the theoretical derivation in section 3.2, which proves the reliability of the designed intelligent vibration-damping base.

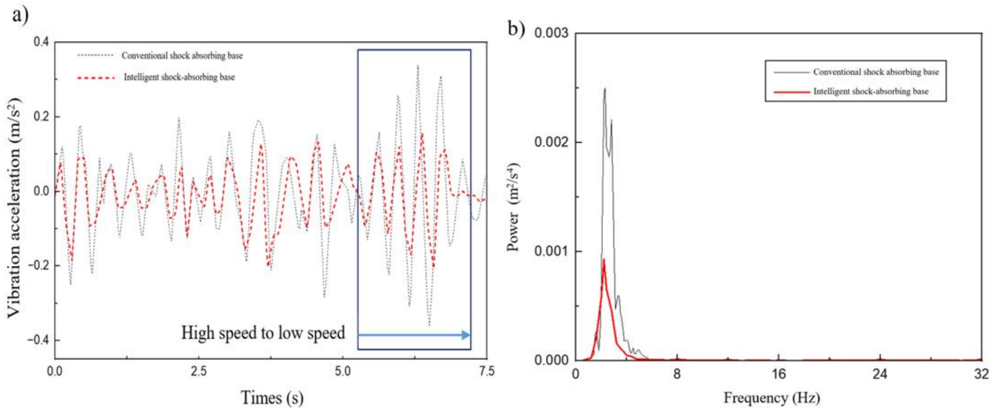

Figure 13. Damping effect of variable stiffness magnetorheological elastomer-based vibration damping base: **(a)** time course curve; **(b)** frequency distribution.

This paper develops a drum washing machine intelligent vibration damping base based on variable stiffness magnetorheological elastomer, the proposed vibration control algorithm while the overall cost increase is not substantial, to prevent resonance triggered by the frequency converter during washing machine motor operation., to achieve better performance across the entire frequency band of the washing machine, to address the issue of low-frequency resonance in traditional washing machine vibration damping bases. Although the intelligent control strategy has been discussed in the drum washing machine, the theoretical methods involved are not limited to drum washing machines but can also be promoted and applied to the design of vibration-damping bases for rail transportation and precision instruments, which holds significant theoretical value and practical implications for further development.

Traffic safety issues on freeways have always been popular topics [40,41]. The magnetorheological intelligent vibration reduction technology also has broad application prospects in vehicle road collaborative active safety control.

5. Conclusions

In this study, to address the problem of structural resonance in washing and spinning process of a washing machine, which leads to exacerbation of vibration noise and acceleration of damage to the internal structure, an intelligent vibration-damping base for a drum washing machine based on variable stiffness magnetorheological elastomers is developed according to the dynamics of mass-spring damped single-degree-of-freedom system. And the following conclusions are drawn through its theoretical and experimental studies.

(1) According to the dynamics of the mass-spring damped single-degree-of-freedom system, under the action of centrifugal inertia force generated by the eccentric mass, the equations of the system in the steady state response are deduced, and the relationship between amplitude, phase difference and frequency is obtained, and the typical amplitude-frequency characteristic curves and phase-frequency characteristic curves are plotted by Matlab, and the vibration reduction effect is better when $\lambda > 2.5$ and the damping ratio is small.

(2) According to the principle of vibration isolation of the foundation structure,

the force transferred from the system to the foundation is reduced, and the graph of transfer rate versus frequency is plotted, and it is concluded that λ is more suitable to be selected in the range of 2.5 to 4.

(3) Taking Haier drum washing machine as an example, the intelligent vibration-damping base design and vibration control scheme for washing machine based on variable stiffness magnetorheological elastomer is proposed, which reduces the force transmitted to the base by 85%, and achieves very significant vibration-damping effect, avoids the low-frequency resonance problem that exists in the traditional vibration-damping base for washing machine, and ensures good vibration and noise control in the whole process of washing and dewatering. This is very meaningful to reduce the vibration force transmitted to the foundation or floor slab and protect the equipment structure from vibration damage. This is very meaningful to reduce the vibration force transmitted to the foundation or floor slab and protect the equipment structure from vibration damage.

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