Vibration Analysis and Control of the Suspension System of the Drum Washing Machine by Applying SMA

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Abstract. The suspension system of the drum washing machine is the object of study. To reduce the vibration of drum washing machines during high-speed dehydration, a shape memory alloy is proposed to be used to make suspension spring. The spring stiffness can be controlled according to the characteristic that the elastic modulus of SMA varies with temperature to achieve damping effect. The mathematical model and multi-body dynamics simulation model are established for the suspension system of the drum washing machine, the vibration generation mechanism of the drum washing machine and the SMA active vibration control principle are analyzed, and the vibration control effect of the SMA suspension spring is studied for different speed simulations. The results show that the SMA variable stiffness suspension spring has a significant vibration control effect compared with the spring of general material.

1. Introduction
In recent years, drum washing machines have taken up a large market share due to their advantages such as high washing efficiency, water saving, and low abrasion on clothes. At present, drum washing machines on the market are increasingly pursuing large capacity and low noise to meet the needs of consumers. In the process of high-speed dehydration, the uneven distribution of clothes leads to an eccentric load, resulting in dehydration vibration, which not only brings noise pollution but also affects the service life of the drum washing machine. Therefore, the high-speed vibration control method of drum washing machines has become a hot topic of current research.

Chen [1] et al. proposed a strategy to reduce the system vibration by current-controlled damper damping; Liu [2] et al. achieved a great control effect of dehydration vibration by optimizing the analysis of the suspension system composition and motor speed control method; Gu [3] et al. optimized the simulating elastic footing to achieve the vibration control effect; Liu [4] et al. applied fuzzy control to dehydration vibration control of drum washing machines; Hou [5] et al. conducted simulation experiments by establishing differential equations of the suspension system and multi-body dynamics model to continuously optimize the spring stiffness coefficient and damper damping coefficient to achieve the best vibration control effect. Guo [6] et al. evaluated and optimized the suspension system parameters of drum washing machines by using Adams to improve the dynamic characteristics of the suspension system.

SMA has been widely used in the field of structural vibration control recently. Ren [7] et al. proposed that the addition of SMA material in friction series composite dampers can effectively control the vibration of eccentric structures; Naeem [8] et al. studied the vibration control performance of SMA dampers by using numerical simulation; Huang [9] et al. improved the nodal energy
dissipation performance by using SMA material to reduce the residual deformation of wood structures; Mani [10] et al. studied an SMA-based dynamic absorber and used a single-chip microcomputer to change the SMA spring current to achieve dynamic variable vibration control effect.

According to the available literature, the application of SMA on the suspension system of drum washing machines is still rare. In this paper, SMA is applied to the suspension spring to study the vibration control effect of such a suspension system by using the temperature-dependent property of SMA elastic modulus.

2. Working Principle

2.1 Suspension System

The suspension system of the household drum washing machine consists of an outer cylinder, an inner cylinder, springs, damping, and counterweight blocks [11]. Eccentricity occurs in the use of drum washing machine, and the centrifugal force caused by eccentricity is an important cause of vibration. When the cylinder is displaced by vibration, the spring and damper convert part of the kinetic energy of the system into potential energy, which attenuates the vibration.

2.2 SMA

Thanks to the super elasticity (SE) and shape memory effect (SME), Shape Memory Alloy (SMA) has been greatly developed in recent years for applications in mechanical engineering, civil engineering, aerospace, and other fields. SMA has thermodynamic properties that can adjust the stiffness and damping characteristics according to the change of temperature. The high cycle fatigue characteristics can guarantee the service life of SMA springs, which is important in semi-active control.

Ni-Ti SMA is relatively mature due to its early development, and its properties such as super elasticity and shape memory effect are more stable compared with copper-based SMA and iron-based SMA. At the same time, Ni-Ti SMA has also made a great breakthrough in material form, which can be made into various forms such as wire, rods, and plates. This paper takes Ni-Ti SMA as the research object.

When the drum washing machine vibrates violently, the main control chip will issue control instructions to change the SMA spring current, and then change the SMA working temperature. As the temperature rises, the SMA stiffness coefficient increases, thus providing a good vibration control effect.

3. Modeling of the Suspension System

3.1 Mathematical Model

The suspension system of the drum washing machine can be abstracted as a mass-spring-damping system, so the mathematical theory of the system's vibration can be derived by establishing the system differential equations. To facilitate the calculation, the following assumptions are made for the suspension system: Ignoring the mass of the damper and the spring, both are regarded as ideal components, and the connection points on the box and the inner cylinder are fixed; the inner and outer cylinders are regarded as rigid bodies, ignoring deformation, and they are coaxial; the clothing eccentric mass is simplified to a particle of constant mass, and fixed on the wall of the inner drum; the suspension system performs the plane motion, ignoring the rotation and movement along the direction of the drum axis. According to the simplification and assumptions, the mechanical model of the suspension system is established, as shown in Figure 1.
Figure 1. Mechanical Model of Suspension System of Drum Washing Machine

\( m_1 \) is the mass of the inner cylinder, \( m_2 \) is the mass of the outer cylinder, \( m_3 \) is the counterweight mass, \( m_0 \) is the clothing eccentric mass, \( L_0 \) and \( n_0 \) are the initial lengths of the suspension springs and the dampers in static balance, \( \varphi_1 \) and \( \varphi_2 \) are the angles between the suspension springs and the vertical direction in the balance, \( \omega \) is the rotational speed of the drum, 1, 2, 5, 6 represent the four suspension springs above, 3, 4, 7, 8 represent the two dampers respectively below.

The system dynamics equation is established according to the Lagrange equation as follows,

\[
\frac{d}{dt}\left(\frac{\partial T}{\partial \dot{q}_j}\right) - \frac{\partial T}{\partial q_j} + \frac{\partial P}{\partial \dot{q}_j} + \frac{\partial L}{\partial q_j} = Q_j(t) (j = 1, 2, ..., N) \tag{1}
\]

In the equation, \( T \) is the kinetic energy of the system, \( P \) is the potential energy of the system, and \( L \) is the energy dissipation function of the system, \( q_j \) is the generalized coordinate, \( \dot{q}_j \) is the generalized velocity, \( Q_j(t) \) is the generalized excitation force.

### 3.1.1 Kinetic Energy of System

\[
T = \frac{1}{2} m_1 |v_{c1}|^2 + \frac{1}{2} I_1 (\dot{\theta} + \omega)^2 + \frac{1}{2} m_2 |v_{c2}|^2 + \frac{1}{2} I_2 \dot{\theta}^2 + \frac{1}{2} m_0 |v_{e0}|^2 + \frac{1}{2} m_3 |v_{e3}|^2 + \frac{1}{2} I_1 \omega^2 + \frac{1}{2} J_1 \alpha_1^2 + \frac{1}{2} J_2 \alpha_2^2 \tag{2}
\]

In the equation, \( v_{c1} \) is the centroid velocity of the inner and outer cylinders, \( \dot{\theta} \) is the angular velocity of outer cylinder rotation around the drum axis, \( v_{e0} \) is the centroid velocity of the eccentric mass of the clothing, \( v_{e3} \) is the centroid of the upper counterweight, \( I_1, I_2 \) and \( I_3 \) are respectively the moment of inertia of the inner cylinder, outer cylinder, and upper counterweight, \( J_1, J_2 \) are respectively the moment of inertia of the system rotating around vertical direction and horizontal direction, \( \alpha_1 \) and \( \alpha_2 \) are respectively the angular velocity of the system around vertical direction and horizontal direction.
3.1.2 Potential Energy of System

\[ P = \frac{1}{2}k[(x_0 + x_1)^2 + (x_0 - x_2)^2 + (x_0 + x_3)^2 + (x_0 - x_4)^2] + (m_1 + m_2 + m_0)g\Delta h + m_1g\Delta h_i \]  

(3)

In the equation, \( x_1, x_2, x_3, x_4 \) represents the change in length of the suspension spring respectively, \( k \) is the stiffness of the spring, \( g \) is the acceleration of gravity, \( \Delta h \) is the change in height of the centroid along the direction of gravity when the inner cylinder, outer cylinder, and clothing eccentric mass are considered as a whole, \( \Delta h_i \) is the change in height of the upper counterweight centroid along the direction of gravity.

3.1.3 System Energy Dissipation Function

Assuming the suspension system damping is viscous damping, the damping force \( f = -c\dot{x} \), then the energy dissipation function \( L \) is the work done by the force in the direction of the damping displacement \( x_1, x_4, x_7, x_8 \).

\[ L = \frac{1}{2}c[(\dot{x}_1)^2 + (\dot{x}_4)^2 + (\dot{x}_7)^2 + (\dot{x}_8)^2] \]  

(4)

In the equation, \( c \) is the damping coefficient, \( \dot{x}_1, \dot{x}_4, \dot{x}_7, \dot{x}_8 \) are the damper velocity respectively.

3.2 Multi-body Dynamic Model

The dynamics simulation is performed in Adams, for easy calculation, the displacement of the box and the effect of deformation are not considered; the motor shaft directly drives the rotation of the inner cylinder; simplify some parts of the model, such as small masses of connectors and control panels; the constraints in the model are considered as ideal constraints. The multi-body dynamics model of the drum washing machine established according to the assumptions is shown in Figure 2.

![Figure 2. 3D Model of the Drum Washing Machine](image)

The drum washing machine studied in this paper comes from a well-known Chinese manufacturer, and the main component parameters are shown in the table below.
Table 1. Component Parameters of Drum Washing Machine

| Component          | Mass (kg) | Moment of Inertia (kg·mm²) |
|--------------------|-----------|----------------------------|
| Outer Cylinder     | 25.0      | 1.04×10⁶                   |
| Inner Cylinder     | 10.0      | 3.24×10⁵                   |
| Counterweight      | 14.0      | 1.89×10⁴                   |
| Motor Shaft        | 4.0       | 2.29×10⁴                   |
| Stiffness of       |           | 5.0                        |
| Suspension Spring  |           | (N/mm)                     |
| Damping of Spring  |           | 0.15                       |
| Damper (N·s/mm)    |           |                            |

4 Vibration Control Strategy by applying SMA

Based on the thermodynamic properties of SMA, when the SMA suspension spring is heated above the end temperature of austenite by current, the elastic modulus of SMA can reach 2-3 times of that of low temperature martensite status, and its stiffness will be significantly increased. Therefore, SMA is made into a certain form of spring and the stiffness coefficient can be changed by changing the incoming current of the SMA suspension spring, and the control process is shown in Figure 3. The elastic modulus-temperature curve of a certain Ni-Ti SMA material studied in this paper is shown in Figure 4[12].

5. Simulation Experiment and Results Analysis

The rotation speed of the drum washing machine is usually divided into several gears, and the common three gears of 400 r/min, 800 r/min and 1000 r/min are used as examples. In the process of
dehydration, the SMA spring is gradually heated by the current to change stiffness. Presuming that the stiffness coefficient of the SMA spring ranges from 5 N/mm to 13 N/mm and setting the eccentric clothing with masses of 1 kg, 2 kg, and 5 kg in Adams, the vibration of the outer cylinder is simulated as shown in Table 2.

Table 2. Experimental Results of Dynamics Simulation

| Rotational Speed (r/min) | Mass of Clothing | Fixed Stiffness Spring | SMA Variable Stiffness Spring |
|-------------------------|------------------|------------------------|-------------------------------|
|                         |                  | X1 (mm)  | Y1 (mm) | K1 (N/mm) | X2 (mm) | Y2 (mm) | K2 (N/mm) |
| 400                     | 1kg              | 15.59    | 38.32   | 5         | 8.4     | 18.33   | 7         |
| 800                     | 1kg              | 16.81    | 38.61   | 5         | 8.82    | 21.87   | 6.75      |
| 1000                    | 1kg              | 17.17    | 38.75   | 5         | 10.32   | 19.38   | 8.25      |
| 400                     | 2kg              | 24.95    | 44.01   | 5         | 18.71   | 24      | 9.5       |
| 800                     | 2kg              | 23.57    | 45.17   | 5         | 13.7    | 30.73   | 8.5       |
| 1000                    | 2kg              | 20.9     | 43.38   | 5         | 13.06   | 26.97   | 8.25      |
| 400                     | 5kg              | 53.09    | 83.69   | 5         | 44.39   | 44.78   | 11.5      |
| 800                     | 5kg              | 46.08    | 63.98   | 5         | 32.5    | 52.17   | 9.25      |
| 1000                    | 5kg              | 40.27    | 65.99   | 5         | 29.39   | 50.72   | 10        |

The experimental data are processed by MATLAB as shown in Figures 5-10.

Figure 5. Relationship between Horizontal Amplitude and Rotation Speed, Eccentric Clothing Mass under Fixed Stiffness Spring(left) and SMA Variable Stiffness Spring(right)

Figure 6. Relationship between Vertical Amplitude and Rotation Speed, Eccentric Clothing Mass under Fixed Stiffness Spring(left) and SMA Variable Stiffness Spring(right)
Figure 7. Comparison Chart of Vibration Reduction Effect at 1kg Eccentric Clothing

Figure 8. Comparison Chart of Vibration Reduction Effect at 2kg Eccentric Clothing

Figure 9. Comparison Chart of Vibration Reduction Effect at 5kg Eccentric Clothing
Figure 10. Relationship between SMA Spring Stiffness, Speed and Mass of Eccentric Clothing at Minimum Amplitude

Analyzing the simulation experiment results, from Figure 5 and Figure 6, it can be seen that the horizontal and vertical amplitudes of each mass are reduced to varying degrees after using SMA variable stiffness suspension spring at different speeds; it is found from Figure 5 that the vibration reduction effect in the horizontal direction has no obvious relationship with the rotational speed, and the vibration reduction amplitude increases with the increase of the mass of eccentric clothing; from Figure 6, the damping effect in the vertical direction decreases with the increase of rotational speed, and the it is obvious when the eccentric clothing is heavy; according to the comparison in Figures 7 – 9, when the mass is small, the vibration amplitude at each rotational speed is basically the same, the greater the mass of eccentric clothing, the more intense the vibration at low speed, but the vibration reduction effect is better; it can be seen from Figure 10 that the optimal stiffness of the suspension spring is related to the rotation speed and the mass of eccentric clothing. By the theoretical derivation and experimental results, the current can be directly changed when the speed and the eccentric mass of the clothing change, and the stiffness coefficient of the SMA suspension spring can be adjusted, to realize the active vibration control of the suspension system.

6. Conclusion
In this paper, the suspension system of the drum washing machine is taken as the object of study. To address the problem of the excessive amplitude of the drum washing machine in the process of dehydration, the mathematical model and multi-body dynamics model for the system have been established. The influence of rotational speed and eccentric clothing mass on the vibration of the drum washing machine is studied, and the use of SMA elastic modulus with temperature-dependent property to make suspension spring is proposed. The results show that when the SMA suspension spring is heated to increase its stiffness, both horizontal and vertical amplitudes are reduced; the vibration control effect of the SMA variable stiffness spring is obvious when the mass of eccentric clothes is larger, but the amplitude is still higher than the amplitude produced by a small mass of eccentric clothes; the larger the rotational speed, the greater the amplitude in the vertical direction. The vibration control effect of the SMA variable stiffness spring in the vertical direction is not obvious, and the vibration in the horizontal direction is less affected by the rotational speed.
References

[1] Chen Haiwei and Zhang Qiuju. Analysis and Control of Transient Dehydration Vibration of Drum Washing Machine [J]. Journal of Vibration and Shock, 2013, 32 (15):47-53.

[2] Liu Zhu, Chen Haiwei and Wang Zhongcheng. Research on Vibration Characteristics of a New Drum Washing Machine with Inverted Pendulum Suspension Structure [J]. Light Industry Machinery, 2018, 36 (03):30-35.

[3] Gu Wei, Sun Beibei and Zhang Jianrun. Analysis of Body Shift Characteristics of Drum Washing Machine [J]. Journal of Vibration, Measurement & Diagnosis, 2013, 33 (S1):180-183+229-230.

[4] Liu Jiafeng and Ji Weixi. Development of Vibration Control Technology for Drum Washing Machine [J]. Mechanical Engineer, 2013(04):41-43.

[5] Hou Kaize, Dai Longxiang, Jiang Zou, Li Bin, He Jiakuan and Luo Liangchen. Analysis and Control of Dehydration Vibration of High-speed Drum Washing Machine [J]. Environmental Technology, 2019, 37 (05):105-111.

[6] Guo Yuanhu and Liu Lei. Parameter Optimization of Suspension System of Drum Washing Machine Based on ADAMS [J]. Mechanical Engineer, 2017(02):60-62.

[7] Ren Wenjie, Yao Huizhe, Ma Zhicheng and Song Wali. Research on Shape Memory Alloy-Friction Tandem Composite Dampers for Vibration Control of Eccentric Structures [J]. Journal of Vibration and Shock, 2015, 34 (08):112-116.

[8] Naeem, A., Eldin, M.N., Kim, J. et al. Seismic performance evaluation of a structure retrofitted using steel slit dampers with shape memory alloy bars. Int J Steel Struct 17, 1627–1638 (2017).

[9] Huang H, Chang W S. Seismic resilience timber connection—adoption of shape memory alloy tubes as dowels[J]. Structural Control and Health Monitoring, 2017, 24(10): e1980.

[10] Mani Y, Senthilkumar M. Shape memory alloy-based adaptive-passive dynamic vibration absorber for vibration control in piping applications. Journal of Vibration and Control. 2015;21(9):1838-1847.

[11] Wang Hao and Liu Lei. Dynamics Modeling and Experiments of Suspension System of Drum Washing Machine [J]. China Mechanical Engineering, 2017, 28 (11):1305-1311.

[12] WANG Mingyi. Research on Structural Stiffness Control Based on Shape Memory Alloy [D]. Nanjing University of Aeronautics and Astronautics,2014.