Vibration analysis and experimental research on metal rubber vibration isolation of vehicle steering wheel

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Abstract. The requirement for the steering wheel of a vehicle is to have a certain sense of vibration, because the intense sense of vibration will make driver fatigue. Therefore, it is very necessary to study the vibration isolation of the steering wheel. Aiming at the problem of the vibration of the a certain type of tractor’s steering wheel, theoretical and experimental studies have been made, the experiment use vibration isolation pad made of Metal Rubber material, the results show that the vibration amplitude is obviously reduced. This paper proposes a novel thought to solve the vibration isolation of the system under sinusoidal and random excitation.

1. Introduction
Vehicle vibration and noise are important indicators for evaluating vehicle comfort. The external and internal force directly or indirectly affect the vehicle body such as road surface excitation, engine excitation, wheel imbalance dynamic force, dynamic imbalance force of the transmission system, and dynamic force generated by relative motion of other components, thereby causing the vehicle body to vibrate[1]. The steering wheel is the part directly touched by the driver. The level of the vibration sense directly affects the comfort of the driver[2]. However, there is no suitable vibration isolation device to solve the vibration problem for the steering wheel, as shown in figure 1. Qiao adjusted the modal frequencies of the steering wheel and the exhaust system[3], the problem that steering wheel shake at idle is solved, hence improving product quality. Fernholz optimized pulley design to improve the NVH performance of power steering pumps[4]. However, the above methods achieve vibration reduction through changing the structural parameters of the vehicle, and affect the performance and service life of the vehicle. This paper proposes a method for using the damping cushion made of metal rubber porous material to attenuate excessive vibration amplitude of steering wheel when the engine rotates at a high speed.

2. Hysteretic Characteristics of Metal Rubber Isolator
The method of vibration reduction proposed in this paper is install four metal rubber vibration isolator between the steering wheel and the diverter. The structure is shown in figure 2.
Metal rubber vibration isolator is composed of upper and lower parts, as shown in figure 3, which are the metal rubber vibration damping flat pad (left) and the metal rubber vibration damping step pad (right).

Through the static test, the compression and corresponding elastic force of metal rubber isolation damping pads are measured. The metal rubber isolation damping pads shows the hysteresis characteristics which is caused by the inner dry friction between adjacent metal wires in metal rubber material. The specific manufacturing technology of this kind of material is controlled to confirm its damping performance. Its hysteresis loop is shown in figure 4, in which the loading and unloading curves are expressed as $F_1(x)$ and $F_2(x)$, respectively. It can be seen from the figure that with the increase of the deformation of metal rubber elements, it becomes stiffer caused by the eventual increase of numbers of contact pairs inside the wires. The non-coincidence between the loading and the unloading curves is caused by the inner friction in the elements, so its elastic force, $F_k$, and damping force, $F_f$, can be expressed as follows:

\[
\begin{align*}
F_k &= \frac{1}{2}[F_1(x)+F_2(x)] \\
F_f &= \frac{1}{2}[F_1(x)-F_2(x)]
\end{align*}
\]  

(2.1)

With consideration of the accuracy and efficiency of curve fitting, the loading and unloading lines of metal rubber in figure 4 are fitted as the following polynomials:
The stiffness, $k(x)$, and damping ratio, $c$, can be calculated by equations (1.3) and (1.4), respectively:

$$
k(x) = \frac{dF_k(x)}{dx} = 2974.95x^2 - 1057.72x + 122.141$$

$$c = \frac{\int_{\text{hysteresis}} [F_1(x) - F_2(x)]dx}{\int_{\text{resilience}} [F_1(x) + F_2(x)]dx} = 0.68$$

The overall hysteresis characteristics of the metal rubber isolator can also be obtained from the test data. From the experimental data, the overall equivalent stiffness of metal rubber isolator can be calculated.

### 3. Steering Vibration Response Under Sinusoidal Excitation

The dynamical model of steering wheel is shown in equation (2.1):

$$m\ddot{X} + c\dot{X} + kX = F$$

where $m$ is the equivalent mass of steering wheel, $c$ is the damping ratio of system, $k$ is the stiffness of metal rubber isolator, and $F$ is the sinusoidal excitation. In this study, $m=2.5$kg, $c=0.68$, $k=540.4$N/m.

In order to study the vibration isolation performance of metal rubber isolator in practical applications, a dynamic test is carried out according to specific parameters in the dynamical model. The results of the isolation system under sine sweep are shown in figure 5. The resonance frequency $f_0=75$Hz, and resonance transmissibility, $\eta_0 = 3.5$, defined as $\eta = a_{\text{output}} \cdot a_{\text{input}}^{-1}$, where $a_{\text{output}}$ and $a_{\text{input}}$ are output and input of acceleration values, respectively.
According to the literature [5], this type of tractor steering wheel has the most obvious vibration when the engine speed range is from 1300r/min to 1590r/min. The corresponding excitation frequency is ranged from 32.5Hz to 40.5Hz, resulting the resonance of the steering wheel. According to figure 5, the transmissibility of the system with metal rubber isolator under this frequency range is 1.0864~1.1505. Compared with this, the transmissibility in reference [5] is 2.2~2.4. The relative change of transmissibility before and after using metal rubber isolator is more than 50%. So it can be concluded that the application of metal rubber isolator into the steering wheel system is effective.

4. Random vibration
In the previous step, the steering wheel vibration amplitude meets the requirements under sinusoidal excitation. However, the incentives are all random excitations during the actual driving of the vehicle. Presently, the random vibration test can be easily applied to product performance tests.

Miles proposed a solution to the acceleration response under random vibration[6]. The Miles formula, which approximates the random vibration load to an equivalent static load, is established for a single degree of freedom system:

\[ a = 3.1 \left( \frac{\pi A f_0 \eta_0}{2} \right)^{1/2} \]  

(4.1)

where \( a \) is the random vibration acceleration peak, \( A \) is the power spectral density, \( \eta_0 \) is the resonance transmissibility, \( f_0 \) is the resonance frequency. In this study, \( a=2.5g \), \( A=0.001684g^2/Hz \), \( f_0=75Hz \), and \( \eta_0=3.5 \).

The random vibration test is carried out and the results is shown in figure 6, in which the orange line is the target spectrum, the blue line is the input spectrum, the red line is the output spectrum. By analyzing the figure, the resonance transmissibility is 6.89 at resonant frequency 75 Hz under random vibration conditions.

5. Conclusions
In this paper, the metal rubber elements with dry friction hysteresis characteristics are applied in between the steering wheel and diverter. Its damping characteristics are analyzed and its vibration isolation performance are studied experimentally. The metal rubber element shows large damping capacity and it reduces the vibration amplitude of isolated system effectively, especially when the engine is rotating at a high speed. The practical application of metal rubber material is beneficial to the vibration isolation of the system under sinusoidal and random excitation.
Figure 6. Vibration response under random excitation.

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