Springer

KSME

Journal of Mechanical Science and Technology 24 (2010) 223~226
www.springerlink.com/content/1738-494x
DOI 10.1007/s12206-009-1132-7

# Vibration transmissibility reduction module with flexure mechanism for personal tools †

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(Manuscript Received May 1, 2009; Revised September 29, 2009; Accepted October 16, 2009)

**Abstract**

In many mechanical operations, vibrations from personal tools may cause serious injuries to the human body. This is particularly true in the case of vibrations that are constantly and repeatedly transferred to humans. In fact, a serious physical problem, Raynaud's phenomenon, may occur. In this paper, we propose a vibration transmissibility reduction module with a flexure mechanism for personal tools. First, a target personal tool, that is, a grass cutter is selected, and the level of vibration transmissibility to the hand is measured. Subsequently, we develop a concept design of the module with stiffness to reduce the vibration transmissibility by more than 20%. The vibration transmissibility is measured by an accelerometer. In addition, the vibration reduction is enhanced when the gap between the inner and outer bodies is filled with silicone gel. Finally, this is verified experimentally.

*Keywords*: Tool engineering; Vibration damping; Flexure; Silicon gel

## 1. Introduction

"Personal tools" refer to tools and instruments handled by humans. Today, with the increasing mechanization of work, requirements, and industrial applications, many types and uses of personal tools are available. However, personal tools suffer from the problem of vibration. Vibrations not only weaken their performance and reliability, but also harm the worker. For instance, the vibrations may cause Raynaud's phenomenon, which is a kind of obstruction in blood circulation [1].

Some devices have been developed and patented to isolate the vibration of power machines [2, 3]. However, the manner in which these machines reduce the vibration has not been systematically described. Furthermore, their mechanisms have many components and their fabrication is complicated. Due to the complex mechanisms, it is difficult to model the friction and stiffness in the contacts or in the fastenings used in the parts. Moreover, they cannot be applied to general applications as a simple module.

In this paper, we propose a vibration reduction module, model the vibration reduction, and finally perform an experiment to evaluate its performance. The design of the proposed device is simple but effective, and it can be applied to various personal tools. We select a target tool, a grass cutter, it is widely used and has significant vibration levels, actuated by an internal combustion engine (see Fig. 1). The engine causes significant vibrations that are transferred to a worker's body through the shaft of the tool. In this study, we focus on reducing the vibration of the shaft gripped by the worker's hand.

## 2. Design

### 2.1 Concept design

The proposed module is considered a vibration isolator on a rigid base [4]. The vibrating mass rests on a flexible mechanism, and the system can be ideally modeled, as shown in Fig. 2.


Fig. 1. Grass cutter.

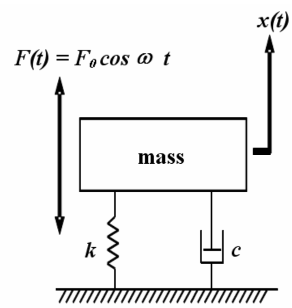


Fig. 2. Ideal model of a one-degree-freedom (1 DOF) spring-damper system.

† This paper was presented at the ICMDT 2009, Jeju, Korea, June 2009. This paper was recommended for publication in revised form by Guest Editors Sung-Lim Ko, Keiichi Watanuki.

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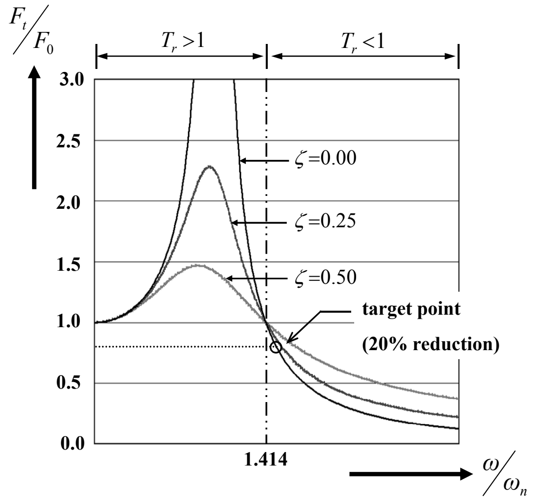



Fig. 3. $\omega$ versus transmissibility ($T_r$) and the target point.

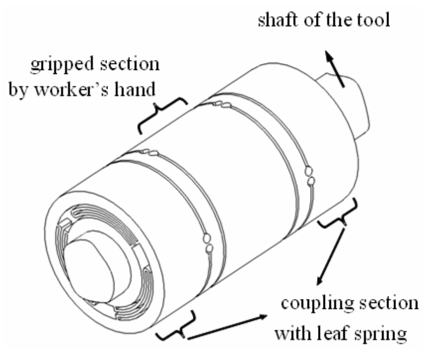



Fig. 4. Conceptual design of the proposed module.

Here, the force transmissibility and transmission ratio are calculated using Eq. (1), where $F_t$ is the force transmitted through the spring and damping. In this paper, we focus on modules composed of only flexural springs without dampers.

In Eq. (1), $T_r$ denotes the transmission ratio, $\omega$ is the excitation frequency caused by the tool, and $\omega_n$ is the natural frequency of the system. The required parameter, stiffness $k$, is calculated from $\omega_n$.

$$T_r = \frac{F_t}{F_0} = \left\{ \frac{1 + \left(2\zeta \frac{\omega}{\omega_n}\right)^2}{\left[1 - \left(\frac{\omega}{\omega_n}\right)^2\right]^2 + \left(2\zeta \frac{\omega}{\omega_n}\right)^2} \right\}^{1/2} \tag{1}$$

We target a reduction ratio of 20% for the force transmissibility. This is demonstrated in the graph of $\omega$ versus transmissibility ($T_r$) in Fig. 3. The force transmissibility decreases when the excitation frequency ($\omega$) becomes greater than the natural frequency of the system ($\omega_n$) by more than 1.414. Accordingly, we designed the stiffness of the module.

To reduce the force transmissibility, we propose the module shown in Fig. 4. This module is implemented with three flexure leaf springs. Each section is tri-symmetrical, and the overall design is symmetric. The inner cylinder is mounted on the tool's shaft, and the outer cylinder connected by a leaf spring is gripped by the worker's hand. When the shaft vibrates, the module reduces the vibration transmissibility through the elastic deformation of leaf springs, as shown in Fig. 5. Moreover, the module has five degrees-of-freedom (5 DOFs) when two sets of notches are hinged.

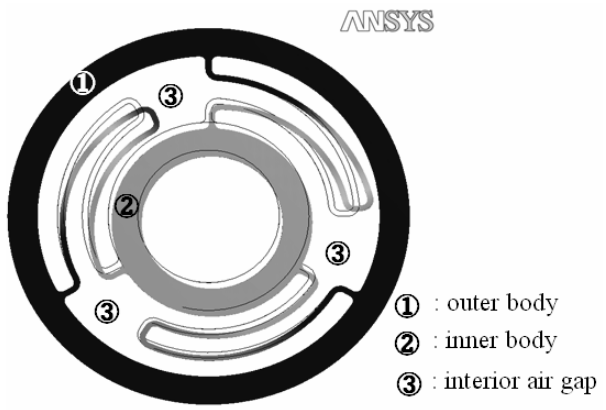



Fig. 5. Elastic deformation simulation results of the module.

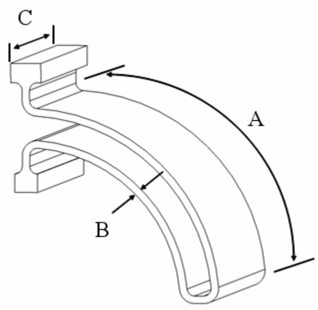



Fig. 6. Main design factors of the proposed flexure leaf spring.

### 2.2 Optimal design

To design a vibratory-force-transmissibility reduction module with a flexure mechanism, many design factors should be considered. In this study, we consider the maximum stress caused by vibrations and the natural frequency of the module, which has an effect on durability and reliability.

To achieve design optimization to enhance the performance of the module, the main design factors shown in Fig. 6 are categorized into control factors, as listed in Table 1. All the control factors are the design parameters that form the leaf spring. As the performance of the module is affected by the leaf spring level as mentioned above, the proposed module is configured with three leaf springs having the same shape.

The material of the module selected is duralumin because of its light-weight and high stiffness. Table 2 lists the evaluation criteria according to the control factor, noise factor, and change at each level. The table of the orthogonal array is organized based on the basis of Table 1. A three-dimensional finite element analysis (FEA) for conducting evaluations according to each factor and level was conducted.

Table 1. Factors and levels.

| Sort | | Factor | Level 1 | Level 2 | Level 3 | Level 4 |
|---|---|---|---|---|---|---|
| Control factor | A | Length of leaf spring [mm] | 31.0 | 32.4 | 33.8 | 35.2 |
| | B | Thickness of leaf spring [mm] | 0.8 | 1.0 | 1.2 | 1.4 |
| | C | Height of leaf spring [mm] | 10 | 15 | 20 | 25 |
| | D | Radius of fillet [mm] | 0.5 | 1.0 | 1.5 | 2.0 |
| Noise factor | P | Fabrication error in leaf spring thickness | good | bad | good : ideal case bad : actual case | |
| | Q | Assembly error between flexure mechanism and tool shaft | good | bad | | |

Table 2. Evaluation criteria.

| No. | Evaluated characteristics | Type |
|---|---|---|
| 1 | Force transmissibility reduction ratio | larger-the-better |
| 2 | Maximum stress | small-the-better |
| 3 | 1st resonance frequency | nominal-the-better |

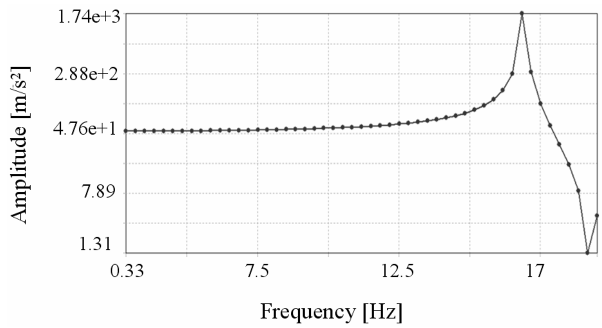



Fig. 7. Simulation result of frequency response.

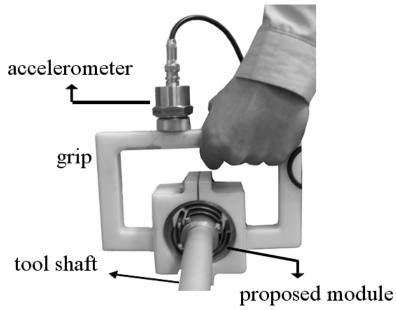
The signal to noise ratio (S/N ratio) can be obtained by using the result of each analysis and the number of experiments. As a result, the optimal design was determined.

Fig. 7 shows the simulation results of the frequency response. The frequency at the maximum amplitude is 15.7 Hz. The module's shaft and cutter has a mass of 6 kg; thus, the stiffness of the proposed module is 126 kN/m. Considering that the tool's average working frequency is 20 Hz (=1200 rpm), the module reduces the force transmissibility from the tool shaft to the worker's grip by 21.5%. Other simulation results on the maximum stress also satisfy the conditions of the yield strength of the material. To verify the simulation results, we fabricated the module and conducted experiments on the performance.

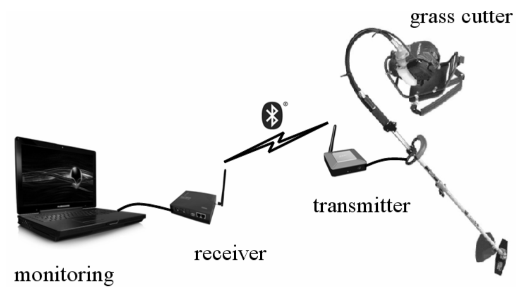
## 3. Experimental setup

### *3.1 Performance test of the module*

The force transmissibility reduction module was fabricated by wire electro-discharge machining. The fabricated part was mounted on the shaft of a grass cutter tool. The experimental setup is shown in Fig. 8. The characteristics of this module, such as force transmissibility reduction, were measured using a wireless ANYLOGGER$^{TM}$ accelerometer with a measurement accuracy of 0.1% and 1 kHz real-time sampling rate.




(a) Accelerometer setup with the module and tool




(b) Schematic of data acquisition

Fig. 8. Experiment setup.

This wireless instrument works by Bluetooth communication between the transmitter mounted on the tool shaft with the proposed module and the data acquisition receiver connected to a monitoring PC. As shown in Fig. 8(a), the transmitter is mounted on a shaft grip that is also gripped by the worker's hand. Real time acquired data are displayed as a graph of time versus acceleration. In this manner, we can measure the vibration transmissibility reduction ratio.

Fig. 9 shows the result of the experiments. As the accelerometer records the data as real time, we sampled them directly for analysis. The results indicate that the amplitude of vibration transmissibility decreases from 11 G without the module to 7 G with the module, which is a decrease of more than 20%. The experimental results show that the error compared with the simulation result is within 5%.

### *3.2 Applying damping to design*

The proposed module was fabricated without using damping material. Hence, we applied a viscoelasticity gel to achieve greater force transmissibility reduction. In this case, the stiffness of the module should be larger than the previous.

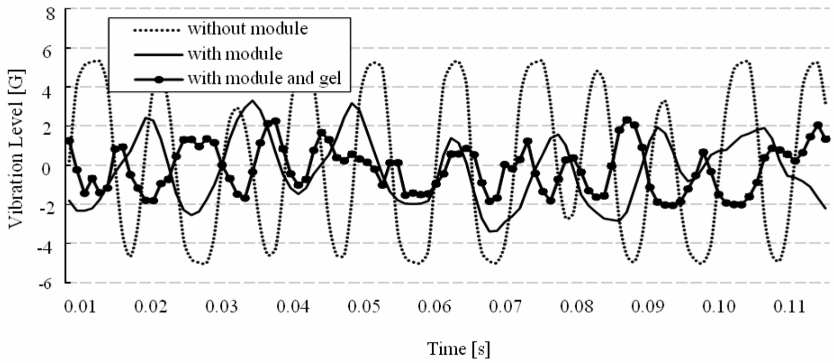



Fig. 9. Experimental result of the vibration transmissibility reduction by the proposed module.

The large internal damping of the viscoelastic material can compensate. Furthermore, it can help reduce the force transmissibility and prevent the unnecessary deflection of the leaf spring by the shaft weight.

We filled the interior gap with a commercial viscoelastic silicone gel with a dynamic viscosity 430 cp [5]. The selected gel was considered having not only minimum elasticity but also maximum viscosity.

The results of the experiment, which are given in Fig. 9, show that the gel-filled module reduces the force transmissibility by more than 5% compared with the result of the module without the gel.

## 4. Conclusions

This paper describes the design, fabrication, and experimental results of the vibration transmissibility reduction module. The module implemented by three symmetric flexural leaf springs reduces the vibration transmissibility by more than 20%. Furthermore, an additional experiment was conducted by filling the interior with viscoelastic silicone gel to achieve greater reduction in force transmissibility.

Compared with many other vibration reduction mechanisms, our proposed module provides structural simplicity and generality. In the case of the proposed module, there are no restrictions on the working conditions such as magnetic or electric fields. Moreover, due to the ease of implementation using a flexure mechanism and the lack of need for control, this module can be applied not only to various personal tools but also to industrial fields having problems with vibration.

## Acknowledgment

This research was financially supported by Korea Industrial Technology Foundation (KOTEF) through the Human Resource Training Project for Strategic Technology and the project of Strategic Technology Development.

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