Journal of Physics: Conference Series

PAPER • OPEN ACCESS

# Design and Experimental Verification of Vibration Suppression Device on the Lift of Wheelchair-accessible Vehicles

To cite this article: Yasuyoshi Hatano and Masaki Takahashi 2016 *J. Phys.: Conf. Ser.* **744** 012221

# Design and Experimental Verification of Vibration Suppression Device on the Lift of Wheelchair-accessible Vehicles

**Yasuyoshi Hatano**※1**, Masaki Takahashi**※2

※1School of science for Open and Environmental Systems, Keio University
3-14-1 Hiyoshi, Kohoku-ku, Yokohama 223-8522, Japan
YasuyoshiHatano@keio.jp

※2Department of System Design Engineering, Keio University
3-14-1 Hiyoshi, Kohoku-ku, Yokohama 223-8522, Japan
takahashi@sd.keio.ac.jp

**Abstract**. In recent years, the number of wheelchair-accessible vehicles has increased with the aging of the population. Such vehicles are effective in reducing the burden on caregivers because the wheelchair user does not have to move from his/her wheelchair to a seat of the vehicle. Wheelchair-accessible vehicles are expected to be widely used in the future. However, wheelchair users have reported poor ride comfort. It is thus necessary to suppress the vibration of the vehicle considering the wheelchair user. We designed a passive damping device on the lift of wheelchair-accessible vehicles to improve the ride comfort for wheelchair users. The vibration due to road disturbances reaches the wheelchair user's body through the vehicle and wheelchair. Our control device decreases the acceleration of the torso and improves the ride comfort by ensuring that the frequency of the vibration reaching the wheelchair user differs from the resonance frequency band of the acceleration of the torso, which is the body part that feels the most discomfort. The effectiveness of the control device is verified experimentally.

## 1. Introduction

Japan's population has aged in recent years. There are approximately 30 million people who are older than 65 years in Japan, accounting for about 24.1 percent of the total population [1]. Older people tend to have difficulty in walking because of disabilities associated with exercise functions and cognitive functions due to aging. The person who has difficulty walking might use a wheelchair, and the number of wheelchair users is expected to increase with an increase in the number of older people in the future. The wheelchair is most commonly used as an assistive device for moving a handicapped person. However, the range of motion of a wheelchair user is limited by the excessive effort required to navigate obstacles of the road surface. Welfare vehicles have thus been developed for the long-range transport of handicapped people, including wheelchair users.

A welfare vehicle is easy for a physically disabled person to use. There are different types of welfare vehicles. As one type of welfare vehicle, the wheelchair-accessible vehicle provides high convenience because the wheelchair user does not have to move from his/her wheelchair to a seat of the vehicle. In addition, it reduces the burden on the caregiver. It is hoped that wheelchair-accessible vehicles will be used widely in the future [2]. However, it has been reported that wheelchair users find wheelchair-accessible vehicles to have poor ride comfort [3][4][5]. An investigation into the ride comfort of this vehicle revealed that approximately 50% of wheelchair users were dissatisfied with the vibration of the wheelchair [3]. The present study investigates the wheelchair-accessible vehicle shown in Fig. 1 [6].

A previous study revealed that the discomfort felt by a wheelchair user is caused by the vertical acceleration of the torso of the user. The resonance frequency band of the vertical acceleration of the torso is 4 to 6 Hz, while that of the wheelchair is 2 to 6 Hz [7]. The resonance frequency band of the vertical acceleration of the torso thus matches that of the wheelchair, and it is therefore necessary to suppress the vibration of the vehicle considering the vibration characteristic of the wheelchair.

One technique of reducing such vibration is to provide suspension between the tires and bodies of vehicle. The suspension is designed according to the size and performance of the vehicle. For example, the spring and damper of a suspension system are adjusted to reduce vibration at a specific frequency [8]. However, the suspension functions to support the load, stabilize the operation, and reduce the noise in addition to providing ride comfort. The suspension thus cannot be designed with consideration of only the ride comfort. It is thus necessary to improve the ride comfort of the wheelchair user employing a method that is not based on suspension.

## 2. Vibration control device

The present study proposes a vibration suppression device on the lift of wheelchair-accessible vehicles so as to improve the ride comfort of the wheelchair user. The vibration suppression device is summarized in Fig. 2.

The vibration control device is a passive damping device comprising springs and rubber. The vibration control device has low cost and is compact. We design the springs and rubber of this control device in the present study. The aim is to show the usefulness of the vibration control device.


Fig. 1 Wheelchair-accessible vehicle

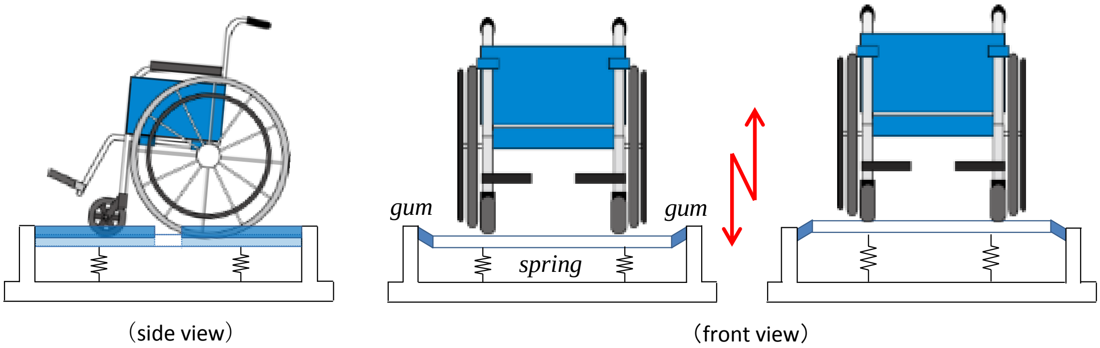



Fig. 2 Vibration control device

## 3. Design of the vibration control device

### 3.1. Modeling of the wheelchair-accessible vehicle

The wheelchair-accessible vehicle model used in this study is shown in Fig. 3. The model is expressed as 10 rigid bodies, namely the front and rear wheels of the vehicle, the vehicle floor, the vibration suppression device, the wheelchair, and the head, torso, waist, thigh and leg of the human body.

The model parameters are given in Table 1 and are set in reference to CarSim and a previous study [4]. The model parameters $k_{1f}$ , $k_{1r}$ , $c_{1f}$ , and $c_{1r}$ are spring constants and damping coefficients of the suspension. The model parameters $K$ and $C$ are the spring constant and damping coefficient of the control device. The joints of parts of the human user are expressed by a rotary spring and rotary damper.

The person's waist and thigh and the point of contact of the torso and waist are connected to the wheelchair with a spring and damper. The foot and the footrest of wheelchair are fixed. The front and rear wheels of the wheelchair model are expressed with a spring and damper and are joined to the floor of the vehicle.

The generalization coordinate $\boldsymbol{q}$ of the wheelchair-accessible vehicle model is defined as

$$\boldsymbol{q} = [z_v \quad z_{wc} \quad \theta_v \quad \theta_{wc} \quad z_f \quad z_r \quad \cdots \theta_9 \quad q \quad \theta_1 \quad \theta_2 \quad \theta_3 \quad \theta_4 \quad \theta_5]^T , \tag{1}$$

where $z_v$ , $z_d$ $z_f$ , $z_r$ , and $q$ respectively denote the vertical displacements of the vehicle floor, the front wheel, the rear wheel, and the footrest of the wheelchair and $\theta_v$ , $\theta_d$ , $\theta_9$ , $\theta_1$ , $\theta_2$ , $\theta_3$ , $\theta_4$ , and $\theta_5$ respectively denote the pitch displacements of the vehicle floor, wheelchair, leg, thigh, waist, torso, and head.

The Lagrange equation is

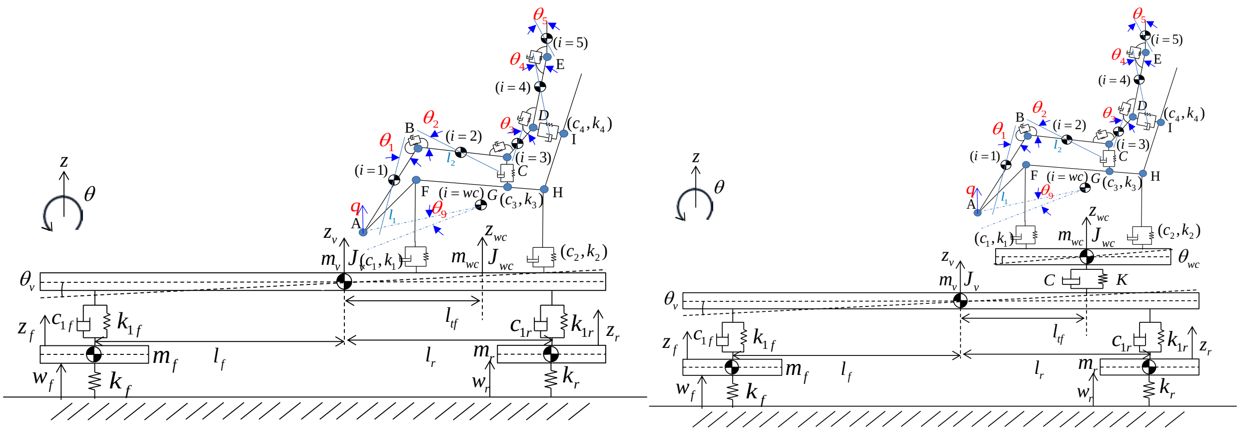
$$L = T - U ,$$
$$\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{q}}\right) - \left(\frac{\partial L}{\partial q}\right) = F , \tag{2}$$

where $F$ is a general force that is the force of vibration input to the vehicle by the road surface in this study.

The equation of motion is

$$\boldsymbol{M}\ddot{\boldsymbol{q}} + \boldsymbol{C}\dot{\boldsymbol{q}} + \boldsymbol{K}\boldsymbol{q} = \boldsymbol{F} , \tag{3}$$

where $\boldsymbol{M}$ , $\boldsymbol{C}$ , and $\boldsymbol{K}$ are $13 \times 13$ matrices.



(a) without the control device (b) with the control device

Fig. 3 Half model of the wheelchair-accessible vehicle

Journal of Physics: Conference Series **744** (2016) 012221 doi:10.1088/1742-6596/744/1/012221

Table 1 Parameters of the wheelchair-accessible vehicle model

| Parameter | Symbol | Unit | Value |
|---|---|---|---|
| Mass of vehicle floor | $m_v$ | kg | 1100 |
| Pitch moment of inertia of sprung mass | $I_v$ | $kgm^2$ | 2975 |
| Distance between the front tire center and center of the gravity | $l_f$ | m | 1.35 |
| Distance between the rear tire center and center of the gravity | $l_r$ | m | 1.225 |
| Suspension (front spring) | $k_{1f}$ | N/m | $6.2\times10^4$ |
| Suspension (rear spring) | $k_{1r}$ | N/m | $6.2\times10^4$ |
| Suspension (front damping) | $c_{1f}$ | Ns/m | 14700 |
| Suspension (rear damping) | $c_{1r}$ | Ns/m | 14700 |
| Mass of front tire | $m_f$ | kg | 50 |
| Mass of rear tire | $m_r$ | kg | 50 |
| Front tire of spring | $k_f$ | N/m | $260\times10^3$ |
| Rear tire of spring | $k_r$ | N/m | $260\times10^3$ |
| Distance between the front vibration device and center of the gravity | $l_{tf}$ | m | 1.0 |
| Distance between the rear vibration device and center of the gravity | $l_{tr}$ | m | 1.4 |
| Vibration control device (spring) | $K$ | N/m | - |
| Vibration control device (damping) | $C$ | Ns/m | - |

| | Leg ( $i=1$ ) | Thigh ( $i=2$ ) | Waist ( $i=3$ ) | Body ( $i=4$ ) | Head ( $i=5$ ) |
|---|---|---|---|---|---|
| Mass, $m_i$ [kg] | 8.00 | 14.2 | 12.1 | 25.8 | 4.50 |
| Moment of inertia $I_i$ [ Nm / rad ] | 0.184 | 0.154 | 0.070 | 0.316 | 0.017 |
| Length $l_i$ [m] | 0.458 | 0.419 | 0.191 | 0.282 | 0.315 |
| Center of gravity $l_{ia}$ [m] | 0.215 | 0.220 | 0.075 | 0.191 | 0.168 |
| Angle $w_i$ [rad] | 1.08 | 6.06 | 1.42 | 1.46 | 1.50 |
| Damper $c_i$ [ Nms / rad ] | $1.81\times10^4$ | $3.11\times10^3$ | $3.89\times10^3$ | 6.61 | - |
| Spring $k_i$ [ Nm / rad ] | $2.85.\times10^4$ | $9.23\times10^4$ | $4.03\times10^4$ | $1.97\times10^4$ | - |

| Parameter Unit | Value |
|---|---|
| Mass of wheelchair, $m_{wc}$ [kg] | 18.4 |
| Moment of inertia of Wheelchair $I_{wc}$ [ $Ns^2$ / m ] | 8.074 |

| | Knee ( $i=b$ ) | Trochanter major ( $i=c$ ) | Lumber ( $i=d$ ) | Cervical vertebra( $i=e$ ) |
|---|---|---|---|---|
| Rotational spring constant $K_i$ [ Nm / rad ] | 9.10 | 6.69 | 46.9 | 1.20 |
| Rotational damping constant $C_i$ [ Nms / rad ] | $5.22\times10^{-2}$ | $3.84\times10^{-2}$ | $2.67\times10^{-1}$ | $6.84\times10^{-3}$ |

The equation of motion is expressed as

$$\ddot{\boldsymbol{q}} = \boldsymbol{M}^{-1}\left(-\boldsymbol{C}\dot{\boldsymbol{q}} - \boldsymbol{K}\boldsymbol{q} + \boldsymbol{Y}w_f + \boldsymbol{Z}w_r\right),$$
$$\boldsymbol{Y} = \begin{bmatrix}0 & \cdots & k_f & 0 & 0 & \cdots & 0\end{bmatrix}^T, \boldsymbol{Z} = \begin{bmatrix}0 & \cdots & 0 & k_r & 0 & \cdots & 0\end{bmatrix}^T, \quad (4)$$

where $w_f$ and $w_r$ denote the vibration input to a tire by the road.

The equation of state is thus expressed as

$$\dot{\boldsymbol{X}} = \begin{bmatrix}\boldsymbol{0} & \boldsymbol{I} \\ -\boldsymbol{M}^{-1}\boldsymbol{K} & -\boldsymbol{M}^{-1}\boldsymbol{C}\end{bmatrix}\boldsymbol{X} + \boldsymbol{B}w_f + \boldsymbol{E}w_r,$$
$$\boldsymbol{X} = \begin{bmatrix}\boldsymbol{q} \\ \dot{\boldsymbol{q}}\end{bmatrix}, \boldsymbol{B} = \begin{bmatrix}\boldsymbol{0} \\ \boldsymbol{M}^{-1}\boldsymbol{Y}\end{bmatrix}, \boldsymbol{E} = \begin{bmatrix}\boldsymbol{0} \\ \boldsymbol{M}^{-1}\boldsymbol{Z}\end{bmatrix}. \quad (5)$$

### *3.2. Design of the vibration control device*

#### *3.2.1. Procedure of the design*

The vibration characteristic of the vibration control device is determined by simulation. We confirmed the vibration of the wheelchair user when vibration from the road surface was input to the model of the wheelchair-accessible vehicle in the simulation. The vibration is provided by a class C equivalency of the road surface defined in ISO standards [9]. Simulation is carried out at a sampling interval of 1 ms. It is assumed in the simulation that the vehicle runs at a constant speed of 40 km/h for 10 seconds.

The procedure for designing the vibration control device is as follows.

1. Input the vibration of the road surface to the model of the wheelchair-accessible vehicle.
2. Calculate the root mean square (RMS) of the acceleration of the torso in the wheelchair-accessible vehicle.
3. Choose the vibration characteristic of the vibration control device when the vertical acceleration of the torso is lowest.

The parameters of the wheelchair and human body in the vehicle given in Table 1 are then used as the nominal model.

#### *3.2.2. Conditions of the design*

The spring constant $K$ and damping constant $C$ of the vibration control device are calculated from the composition of the spring and rubber. The spring constant $k_{gum}$ and damping constant $c_{gum}$ of rubber are defined from dimensions of the rubber as

$$k_{gum} = \frac{Glh}{w}, \quad (6)$$

$$c_{gum} = 2\zeta_{gum}\sqrt{mk_{gum}}, \quad (7)$$

where $w$, $G$, $l$, $h$, and $\zeta_{gum}$ are the width of the rubber, modulus of the transverse elasticity of the rubber, length of adhesion of the rubber, height of adhesion of the rubber, and damping ratio of the rubber. $m$ expresses the load added to the rubber because of the weight of the person and the mass of the vibration control device ( $m_d$ ). In addition, the spring constant $K$ and damping constant $C$ of the vibration control device are defined as

$$K = k_{gum} + k_{sp}, \quad (8)$$

$$C = c_{gum}, \quad (9)$$

where $k_{sp}$ is the spring constant of the spring of the vibration control device.

The limitations of the vibration control device determined by the dimensions of the lift of the wheelchair–accessible vehicle are given in Table 2. The rubber is then warped by the mass on the vibration control device. Such a phenomenon is expressed as

$$\delta = \frac{Mg}{K} . \tag{10}$$

It is necessary to limit the spring constant of the device so that the rubber does not undergo plastic deformation by distortion.

The limitations of the spring constant and damping constant of the device are therefore expressed as

$$K \geq \frac{M_{\max} g}{\delta_{\text{limit}}(w)} = \frac{M_{\max} g}{\sqrt{\left( w \cdot r_{rate} / r_{safe} \right)^2 - w^2}} , \tag{11}$$

$$C \leq 2\zeta_{gum} \sqrt{mK} , \tag{12}$$

where $r_{rate}$, $r_{safe}$, and $M_{\max}$ are respectively the growth rate, factor of safety, and maximum assumed mass. These expressions therefore guarantee a condition that the rubber does not undergo plastic deformation even if there is a maximum mass $M_{\max}$ loading the device.

Under the conditions $w = 0.03$, $M_{\max} = 103$, $r_{rate} = 2$, and $r_{safe} = 1.2$, the limitations of the spring constant and damping constant can be expressed as

$$K \geq 22000 , \tag{13}$$

$$C \leq 789.3 . \tag{14}$$

In this case, $m$ in expression (12) is 93 kg; this is the total mass of the person and wheelchair of the nominal model and the mass of the device.

*3.2.3. Design of the device*

The RMS of vertical acceleration of the torso is calculated by simulation. The relationship between the RMS of vertical acceleration of the torso and the vibration characteristic of the device is shown in Fig. 4. In the figure, the horizontal axis gives the spring constant $K$ and the vertical axis the damping constant $C$.

The vibration characteristics of the device are set as $K = 22000$ and $C = 600$ so that the RMS of vertical acceleration of the torso is lowest within the limitations of the device.

Dimensions of the rubber and the size of the spring that match the vibration characteristic are given in Table 3.

Table 2 Constraint ranges

| Parameter | Symbol | Unit | Constraints range |
|---|---|---|---|
| Width of gum | $w$ | m | $w \leq 0.03$ |
| Height of gum | $h$ | m | $0.005 \leq h \leq 0.010$ |
| Adhesion length of gum | $l$ | m | $h \leq 3.64$ |
| Maximum growth rate of gum | $r$ | m | $r = wr_{rate} / r_{safe}$ |
| Maximum strain amount of gum | $\delta_{\text{limit}}$ | m | $\delta_{\text{limit}} = \sqrt{\left( wr_{rate} / r_{safe} \right)^2 - w^2}$ |

$r_{rate}$ : Growth rate
$r_{safe}$ : Safety factor

IOP Publishing
doi:10.1088/1742-6596/744/1/012221

Table 3 Parameters of the vibration control device

| | Symbol | |
|---|---|---|
| Width of gum [m] | $w$ | 0.03 |
| Height of gum [m] | $h$ | 0.006 |
| Adhesion length of gum [m] | $l$ | 3.41 |
| Spring [N/m] | $k_{sp}$ | 13827 |

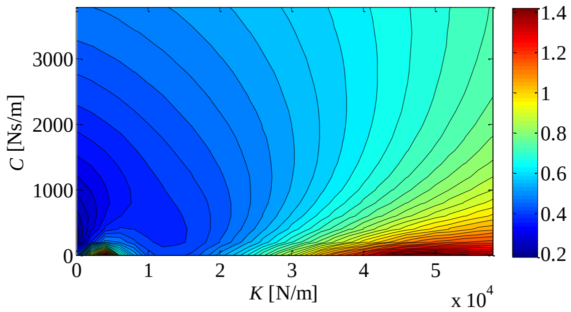



Fig. 4 RMS of the vertical acceleration of the torso

## 4. Analysis and inspection

### *4.1. Results of analysis*

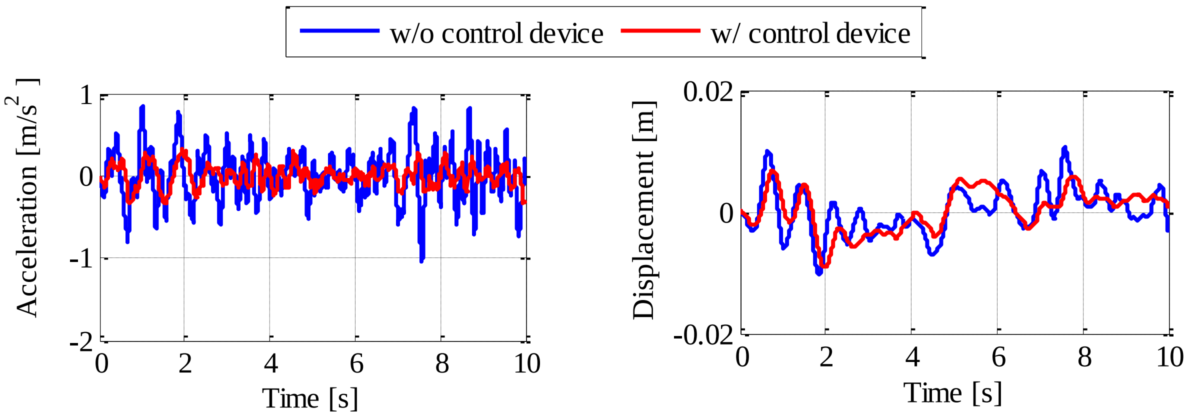
This section presents results obtained for the performance of the device designed in the previous section.

The difference in the vibration behavior of the wheelchair user with the device and without the device is derived by simulation analysis. The analysis condition is that the vehicle travel across a road surface of class C at 40 km/h, in the same way as in the design of the control device.

The simulated vertical acceleration and displacement of the torso are shown in Fig. 5. The figure confirms that the control device reduces the vertical acceleration of the torso. Moreover, the vertical displacement is not worse when using the control device.

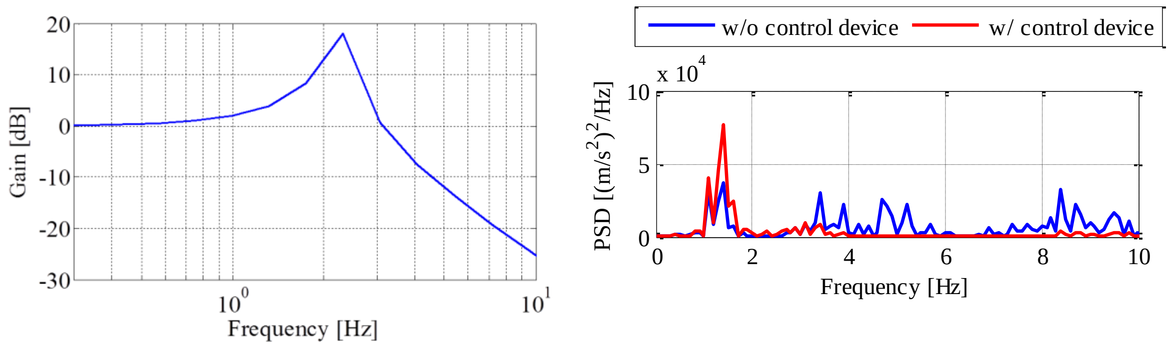
The vibration characteristic of the device is shown in Fig. 6. The device reduces vibration in the frequency range of 4 to 6 Hz as designed.

The power spectral density (PSD) of the vertical acceleration of the installation surface of the wheelchair is shown in Fig. 6. It is seen in the figure that the acceleration and displacement of the installation surface of the wheelchair are reduced because of the reduction of vibration in the frequency range of 4 to 6 Hz by the control device.



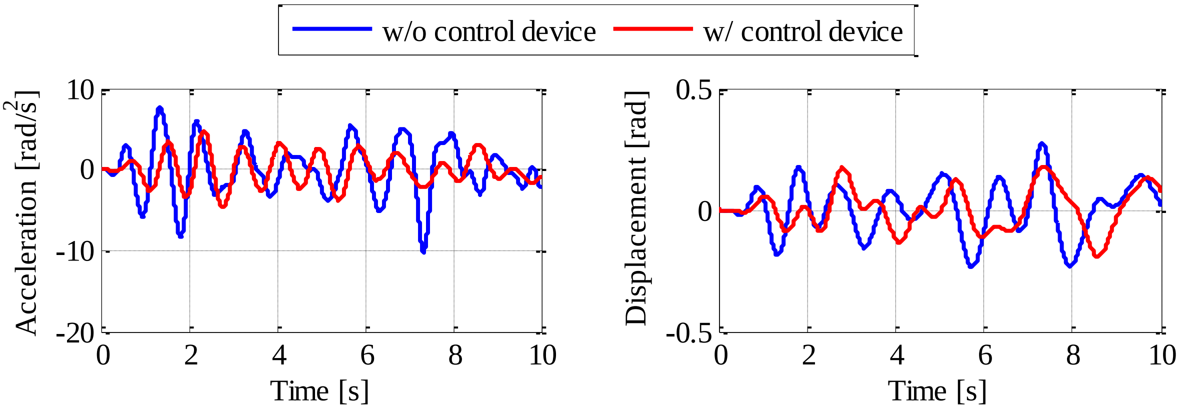

(a) acceleration (b) displacement

Fig. 5 Vertical vibration behavior of the torso




(a) vibration characteristic of device (b) PSD of installation surface of wheelchair

Fig. 6 Performance of the control device



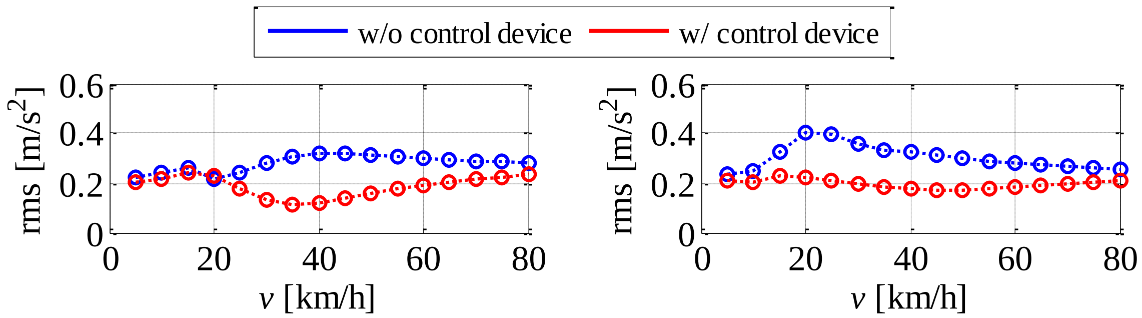

(a) acceleration (b) displacement

Fig. 7 Pitch behaviors of the user's head

In addition, pitch acceleration, and pitch displacement of the user's head are shown in Fig. 7. This quantity is also reduced by the control device.

### 4.2. *Verification of robustness*

Further simulation is carried out using model parameters for a large male subject [4] and small female subject [4]. The relationship between the RMS of vertical acceleration of the torso of the large male and the speed of the vehicle is shown in Fig. 8, while that between the RMS of vertical acceleration of the torso of the small female and the speed of the vehicle is shown in Fig. 8. We confirm that the control device performs well for both human models.




(a) Male (b) Female

Fig. 8 Relationships between the velocity and acceleration of the torso

## 5. Experiment using a traveling wheelchair-accessible vehicle

### *5.1. Purpose and method of the experiment*

We constructed the vibration control device designed in the previous section. The vibration control device is shown in Fig. 9. The control device uses six coil springs[10] with a combined spring factor of 22,932 N/m. Chloroprene rubber was used in the device.

We measured the acceleration of a person and a wheelchair in an experiment using the vibration control device. In the experiment, the wheelchair-accessible vehicle travelled at a constant speed along a straight road, and acceleration meters were attached to the person and wheelchair. We measured acceleration with and without the vibration control device.

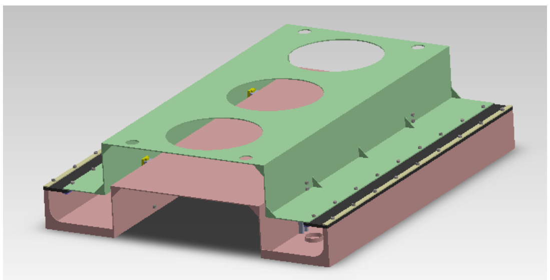
### *5.2. Conditions of the experiment*

The experiment conditions are shown below. In the experiment, the wheelchair-accessible vehicle travelled at 20 km/h for 10 seconds along a private road of a university. Then, the wheelchair-accessible vehicle was used the SERENA of Nissan. Wherein the running speed, which were designed with 40 km/h in the analysis, set 20 km/h in the experiment because the speed limit is 20 km/h in experimental environment.

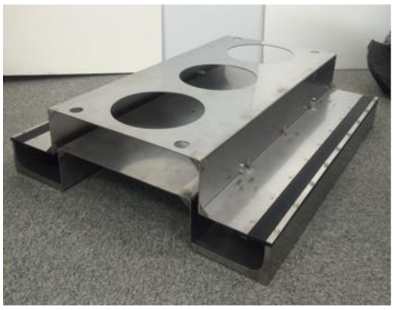
The acceleration meters were set at the user's head and torso, the wheelchair, the front wheel of the wheelchair, the rear wheel of the wheelchair and under the wheelchair. We examined it on such an experiment condition and measured the acceleration for three people; photographs of the experiment are shown in Fig. 10. The heights and weights of the subjects are given in Table 4.

Table 4 Characteristics of subjects participating in the experiment

| | Sex | Weight [kg] | Height [cm] | Classification |
|---|---|---|---|---|
| Subject 1 | female | 44 | 155 | small |
| Subject 2 | male | 55 | 170 | normal |
| Subject 3 | male | 65 | 178 | large |



(a) Computer-aided design of the vibration control device



(b) Real equipment

Fig. 9 Computer-aided design and actual equipment of the vibration control device

Fig. 10 Conditions of the experiment

### *5.3. Results and considerations of the experiment*

#### *5.3.1. Results*

Figures 11–13 present time histories of the acceleration and transmissibility of vibration from the vehicle floor for three people (subjects 1, 2, and 3 in the experiment).

When the weight was normal or light, we find that the acceleration of the torso was amplified by the control device. Meanwhile, the acceleration of the torso of a heavy person was reduced by the control device.

In Fig. 11–Fig. 13, each case has a specific frequency of high vibration transmissibility; i.e., 4, 5, or 3.5 Hz. This tendency was found in all results.

#### *5.3.2. Considerations*

The previous section confirmed that the acceleration of the torso was amplified in the case of a light person or person of normal weight. The relationship between the loading mass of the control device and the distortion of the control device is presented in Table 6.

Table 6 shows that, when the loading mass is light, the control device has a desired spring constant. However, when the loading mass is heavy, the spring constant is larger than that desired.

It is thought that we have exceeded the linear domain of the spring and rubber by the loading mass. The relationship between the spring constant and resonant frequency $\omega_0$ is then defined as

$$\omega_0 = \sqrt{K/m}\,. \tag{15}$$

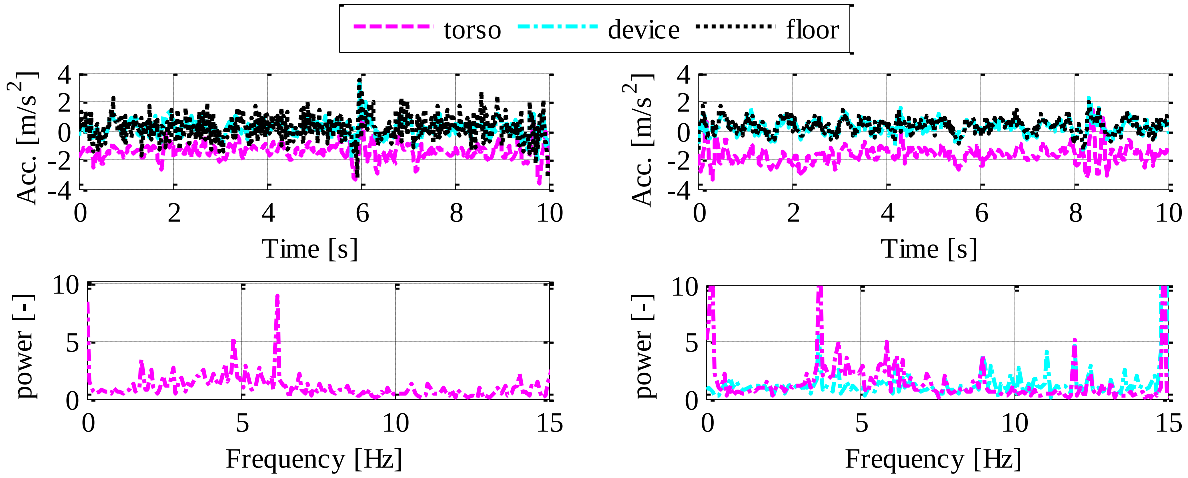
It is thought that the resonance frequency increases with the spring constant. According to expression (15), for a light person, a person of normal weight, and a heavy person, the resonance frequency of the control device is 4.4, 4.25, and 3.95 Hz respectively. In the case of a light person or person of normal weight, the resonance frequency of the control device matches the resonance frequency of the acceleration of the torso. Meanwhile, for a heavy person, the resonance frequency of the control device does not match the resonance frequency of the acceleration of the torso. It was therefore possible to reduce the acceleration of the torso of the wheelchair user using the control device in the case of a heavy person. It is thus necessary to design the control device again to obtain a desired spring constant.

Table 5 RMS of acceleration of the torso in the experiment

| | the first experiment | | the second experiment | |
|---|---|---|---|---|
| | w/o device | w/ device | w/o device | w/ device |
| Subject 1 | 1.51 (Fig. 11) | 1.77 (Fig. 11) | 2.35 | 3.96 |
| Subject 2 | 0.71 | 1.11 | 0.64 (Fig. 12) | 1.06 (Fig. 12) |
| Subject 3 | 1.22 (Fig. 13) | 0.73 (Fig. 13) | 1.29 | 0.71 |

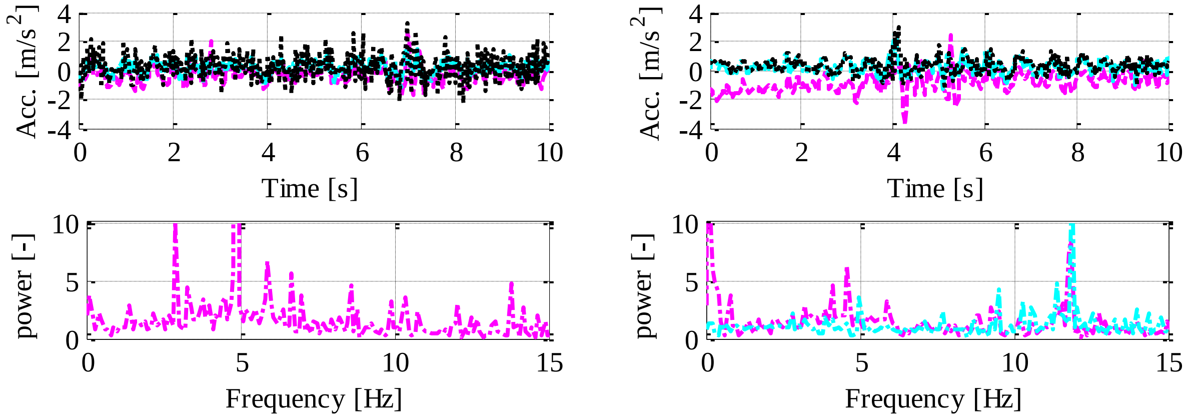
Table 6 Relation of the loading mass and the distortion of the control device

| Loading mass [kg] | Distortion [mm] | Spring constant [N/m] |
|---|---|---|
| 10 | 4 | 24500 |
| 60 | 13 | 45230 |
| 70 | 15 | 50306 |



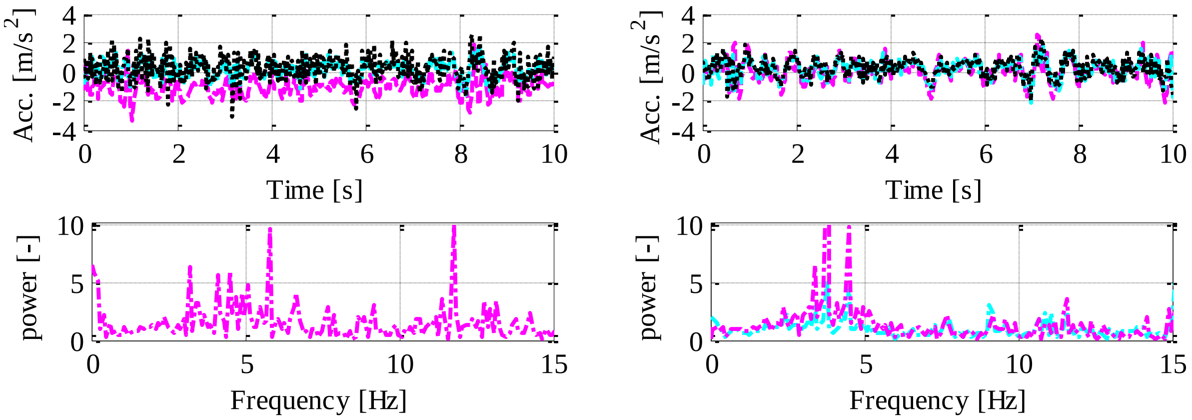

(a) without the control device (b) with the control device

Fig. 11 Time history and transmissibility of vibration from the vehicle floor (subject 2)




(a) without the control device (b) with the control device

Fig. 12 Time history and transmissibility of vibration from the vehicle floor (subject 4)




(a) without the control device (b) with the control device

Fig. 13 Time history and transmissibility of vibration from the vehicle floor (subject 6)

## 6. Conclusion

This study presented a vibration suppression device on the lift of wheelchair-accessible vehicles. The proposed device attempts to improve the ride comfort for wheelchair users by reducing vibration in the resonance frequency band. Analysis revealed that the proposed device suppressed the vertical acceleration of the torso of the wheelchair user.

In addition, we produced the designed vibration control device and experimentally demonstrated its potential in reducing the acceleration of the torso of the wheelchair user. In the experiment, we confirmed that the acceleration of the torso of a heavy person was reduced by the control device. However, it is necessary to design the control device again to obtain a desired spring constant. And it is necessary to experiment with more running speed and more subjects.

Therefore, we would like to further experimentally again and verify the usefulness of the proposed device.

**Acknowledgements**

This work was supported by JKA (27-160) and its promotion funds from Auto Race.

**References**

[1] Ministry of internal affairs andcommunications, “Population of the elderly person”, http://www.stat.go.jp/data/topics/topi631.htm (as of Jun.2014).

[2] Japan Automobile Industry Association (JAMA) , “Market trend of the welfare vehicle of the 2013”, http://release.jama.or.jp/sys/news/detail.pl?item_id=1654 (as of Jun.2014).

[3] Kentaro S., Emiko K., Takashi K., “A study on safely and comfortableness about utilization of the wheelchair transportation behicle”, The Journal of Hapan Academy of Health Sciences, Vol.10, (2007), pp.23-33.

[4] Yoshiyuki M., Kohei K., and Ryo S., “Vibration Simulation Model of Passenger-Wheelchair System in Wheelchair-Accessible Vehicle”, Journal of Mechanical Design, Vol.125, (2003), pp.779-785.

[5] Ministry of Land, Infrastructure, Transport and Tourism (MLIT) , “About the fixed method of the crew of the wheelchair and the wheelchair”, http://www.ntsel.go.jp/forum/16files/16-09p.pdf(as of July 2014).

[6] SUZUKI MOTOR CORPORATION, “Welfare vehicle of SUZUKI, wagon R wheelchair -acce ssible vehicle”, http://www.suzuki.co.jp/release/a/2002/0115/index.html (as of Jun.2014).

[7] Matsuoka Yoshiyuki, “Experimental Vibration Model Analysis of the Wheelchair Transporting Apparatus : Design Support Methods for Riding Comfort of Vehicles for Wheelchair Users (1) ”, Japanese Society for the Science of Design, Vol. 47, No. 1 (2000), pp.43-48.

[8] Liu, C., Gazis, D. C. and Kennedy, T. W.: “Human judgment and analytical derivation of ride quality, journal of Transportation Science, Vol. 33, No. 3 (1999), pp.290-297.

[9] ISO-2631: Guide for the Evaluation of Human Exposure to Whole body Vibration”, International Organization for Standardization, (1985).

[10] MiSUMi-VONA , “Coil spring for more than flexibility| MISUMI”, http://jp.misumi-ec.com/vona2/detail/110302605430/? (as of Nov.2015).