ORIGINAL ARTICLES

VIBRATION ANALYSIS AND DESIGN PROBLEMS OF THE VEHICLES MODIFIED WITH THE WHEELCHAIR TRANSPORTING APPARATUS

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Abstract: In order to extend the area of activity for wheelchair users, the vehicles modified with a wheelchair transporting apparatus (WTA) has been noticed recently. The WTA allows users to travel for long distance. However, this system has been described as uncomfortable because the wheelchair is rigidly secured on the vehicle floor and the vibration of the floor is directly transmitted to passenger. The objectives of the present study are to investigate the vibration in the WTA and to clarify the design problems.

First, in order to measure the vibration of the WTA, the driving experiment using an automobile was performed at 3 levels of 30, 50 and 70 km/h. The vibration in the front-back and vertical directions on the Passenger-Wheelchair-Floor system was measured by acceleration sensors. The measurement points were 5 points on the passenger's body, 3 points on the wheelchair, and 2 points on the floor. As a result, the input vibration of the floor between 1 and 10 Hz was found to generate resonance. In addition, the equipment used to secure the wheelchair was found to increase the acceleration of the floor vibration. Therefore, the input vibration between 1 and 10 Hz is revealed as a factor that causes discomfort in the WTA.

Next, as design problems, necessity of reducing acceleration between 1 and 10 Hz was pointed out. In order to solve this problem, a method to clarify the characteristics of shock-absorbing equipment was proposed.

Key Word: *Evaluation of vibration, Riding comfort, Wheelchair*

1. INTRODUCTION

According to recent provisional population estimates (May, 1998) performed by the Management and Coordination Agency of Japan, the population of senior citizens (65 years old or older) was over 20.28 million, accounting for 16.1% of the Japanese population. These figures reveal that Japan has become an aged society (the population of senior citizens is 14.0% of all or over). Furthermore, it has been projected that in 2020 senior citizens will account for over 25% of the Japanese population, in other words, one in every four Japanese persons will be over 65 years. Therefore, the creation of Japanese society in which senior citizens can live comfortably has become increasingly important.

In this aged society, the number of people who will have difficulty in walking and driving will come an increase. The inevitable reduction in physical and mental ability associated with aging will make travel inconvenient or, in some cases, impossible. At present, senior citizens with such mobility-handicaps are unable to go outside without difficulty, and eventually become bedridden. Therefore, the establishment of a system that allows senior citizens to maintain their mobility is one of the utmost importance.

Currently, wheelchairs are one of the most commonly used devices that aid the mobility of senior citizens. However, because the average distance that wheelchair users can travel is reported to be 500 meters, wheelchairs are not an adequate means of mobility for those who wish to travel outside the home. As the availability and condition of wheelchair facilities have not improved, for example, most roads are narrow and rough, using wheelchairs is a laborious work for senior citizens. This situation has increased interest in the recently developed the vehicles modified with a wheelchair transporting apparatus (WTA). The WTA shown in Figure 1, allows wheelchair users to travel for long distances and reduces the burden of caring persons to aid senior citizens with mobility-handicaps when traveling.

Although the design of the current WTA nearly satisfies the required level of functionality, the design does not satisfy comfort requirements. Future designs, however, must take comfort into consideration. Therefore, the present study focuses on the ability of the WTA to provide comfort for human. First, the causes of the insufficient comfort level of the current WTA is investigated. Next, the present study attempts to determine the design problems that must be solved in order to developed a comfortable WTA.

Figure 1: The vehicles modified with a wheelchair transporting apparatus

2. THE VEHICLES MODIFIED WITH THE WHEELCHAIR TRANSPORTING APPARATUS

2.1. Contents of the WTA

The WTA is comprised of all of the additional equipment required in order to convert a normal vehicle into a wheelchair-user car, such as a car hoist for the lift (Figure 2) and equipment for fastening a wheelchair (Figure 3) [1].

- i. Car hoists can be used to lift both persons and wheelchairs either inside or outside the vehicle.
- ii. Equipment for fastening a wheelchair in a car can be used to secure the wheelchair in the vehicle, including the equipment for holding the wheelchair's wheel by clips or straps.

In using the WTA, first, a person seated in a wheelchair is lifted into a vehicle by a car hoist. Secondly, the wheelchair is rigidly secured on the floor by equipment for fastening a wheelchair.

Currently, in Japan, some metropolitan bus lines employ buses equipped with the WTA. In addition, a mini-van equipped with the WTA has put into practice. The WTA is also becoming popular except in Japan. In the Kingdom of Sweden and the Kingdom of Norway, in order to facilitate boarding for wheelchair users, Ultra Low Floor Buses that have a floor height of 35 cm (generally 80 cm in Japan) are currently employed [2]. Moreover, an automobile that can be driven by a person seated in wheelchair is even more practical.

2.2. The WTA in classification

The WTA is installed in two of the four categories of assistive cars. These cars are classified according to physical ability of users, number of passengers, and form of utility [3]. The classification of assistive cars is shown in Figure 4.

- 1) Vehicles that a person can drive seated in a wheelchair.

Figure 2: Car hoist

Figure 3: Equipment for fastening a wheelchair

- 2) Vehicles with driving aids that are matched to the driver's impairment.
- 3) Vehicles that persons seated in wheelchairs and laid on stretchers can use for transport and travel.
- 4) Vehicles with transporting aids that move the seat in and out from the driver's side door.

The WTA is installed in 1) and 3), will likely become popular with the increase in the senior population. Because this system extends the area of activity, reduces the burden of caring persons to aid senior citizens with mobility-handicaps, and contributes to the mobility of senior citizens.

2.3. Problems of the WTA

Standardization of the WTA is proceeding. For example, security standards ISO/DIS 10542 [4] concerning equipment for fastening a wheelchair. Therefore, the functionality of the current WTA is adequately considered. However, future designs should consider the human factor, so that increased functionality, for example, comfort and ease of operation, will be important. Currently, comfort and the ability to minimize vibration fatigue are not adequately considered in the present design. In fact, the current WTA has been described as uncomfortable. In addition, it was verified that the WTA was uncomfortable on subjective evaluation in the previous experiment. The reason for this is

Figure 4: Assistive cars

the vibration of the vehicle floor is transmitted directly to the passenger without reduction. Furthermore, the reason of transmitting without reduction is considered that the current WTA uses fixing belts to secure the wheelchair to the floor.

In future, the demand for social activity of senior citizens will increase, and the use of the WTA for long-distance travel and for extended periods of time will increase too. In order to facilitate social life for senior citizens, the establishment of easy and comfortable means for transportation is necessary. Therefore, improving the comfort of the current WTA is essential.

3.VIBRATION ANALYSIS OF THE WTA BY VEHICLE WITH PERSONS SEATED IN WHEELCHAIRS

In order to investigate the source of discomfort, vibrations on the Passenger-Wheelchair-Floor system were analyzed under two conditions, with and without the equipment used to secure the wheelchair. The vibration data used in the analysis was acquired from an experiment for an automobile equipped with the WTA during driving conditions.

3.1. Experiment for vibration measurement

3.1.1. Definition of vibration measurement points

For the measurement of vibration, acceleration sensors were fastened on the floor of the automobile, the wheelchair, and passenger. Measurement points were representative points of sections of a model of the Passenger-Wheelchair-Floor system (Figure 5).

a) Measurement points on the passenger

In the present study, a model was used to represent the passenger in order to understand the overall vibration on the passenger. Therefore, the first criterion for modeling was simplicity in order to allow a simple determination of the level of vibration. The second criterion was mobility of the

Figure 5: Measurement points of vibration

joints. According to these two criteria, the model used in the p of five segments: head, upper torso, lower torso, thigh, and resent study was constructed. The model consisted shank. Each segment was divided by link points: vertebrae cervicales and trochanter major, which have multiple degrees of freedom, patella center and vertebrae lumbales at which bending in the sitting posture is almost performed. Then in order to determine the properties of each segment of model, such as segment mass and location of the center of mass, the method proposed by Ae [5] was employed. This report indicated that the properties could be determined by the ratio of each segment length to physical form. According to this report, each property of the model was determined using anthropometry to examine the ergonomics. As a panel, the 50th percentile male of Japanese young adults was adopted [6].

Vibration was measured at five points as representative ones on each segment of the passenger. As the representative points, the ones that were closest to the each segment center of mass on the sagittal plane were determined. Points of anthropometry and the results of anthropometric examination are shown in Figure 6 and Table 1.

b) Measurement points on the wheelchair and the floor

The measurement points on the wheelchair were determined as the points where the passenger touches the wheelchair. Three points were determined: Center of footrest (Footrest), Under trochanter major (Seat cushion), Rearward segment center of mass of lower torso (Seat back).

The measurement points on the floor are determined from the viewpoint of vibration entering wheelchair. Two points are determined: center of the contact between the front tire

Figure 6: Points of anthropometry

Table 1: Results of anthropometric examination

(a) Center of mass of human body			
	Segment length(mm)	Segment mass ratio(%)	Location of the center of mass(mm)
Head	130.4	82.1	107.1
Upper arm	291.5	52.9	154.2
Forearm	248.3	41.5	103.0
Hand	85.8	89.1	76.4
Upper torso	311.0	42.8	133.1
Lower torso	179.5	60.9	109.3
Thigh	373.8	47.5	177.6
Shank	413.0	40.6	167.7
Foot	251.5	59.5	149.6

(b) Center of mass of model		
	Segment length(mm)	Location of the center of mass(mm)
Head	130.4	107.1
Upper torso	311.0	100.5
Lower torso	179.5	109.3
Thigh	373.8	177.6
Shank	413.0	219.2

of the wheelchair and the floor (Front floor) and center of the contact between the rear tire and the floor (Rear floor).

c) Measurement method

From the results of the previous experiment, the vibration in the front-back and vertical directions was founded to be more dominant on Passenger-Wheelchair-Floor system for an automobile driving at a constant speed than in the right-left direction. Therefore, in the present study, vibration in the front-back and vertical directions was measured at each point.

Piezoelectric acceleration pick-up sensors were placed on each point in the front-back and vertical directions, and vibration data was recorded to a data recorder through a charge amplifier. In order to avoid contact resonance in the sensors fastened to the passenger, acceleration sensors were attached to square wooden boards of 4 cm in length.

3.1.2. Experimental condition

The vehicle used in the present experiment was an automobile equipped with the WTA (Figure 1), in which belts were used to secure the wheelchair.

The wheelchair was used a bi-manual rear-wheeled-driven wheelchair which currently comprises 70% of all wheelchairs used in Japan.

An asphalt road with few ruts was chosen for the present experiment because this is the most common condition under which the WTA is actually used.

Driving was performed 30, 50 and 70 km/h. The outline and condition under which the experiment was conducted are shown in Figure 7, Table 2.

Figure 7: Experimental outline

Table 2: Experimental condition

Item of measurement	Acceleration
Panel	23 years-old-male
Measurement points	Passenger [Head, Upper torso, Lower torso, Thigh, Shank (5 points)]
	Wheelchair [Footrest, Seat cushion, Seat back (3 points)]
	Floor of automobile [Front floor, Rear floor (2 points)]
Direction	Vertical and Front-back
Time	2 (min)
Speed	30, 50, 70 (km/h)
Equipment for fastening a wheelchair	With belts, Without belts

3.2. Analysis result and discussion

An FFT analyzer was used to analyze the obtained data. First, the power spectrum of each point was analyzed. Next, the frequency response functions for the input vibration at the Rear floor to the output vibration of each point at the passenger and wheelchair were analyzed.

3.2.1. Vibration of the vehicle floor

The power spectrum between the 0 and 20 Hz vibration of Front floor and Rear floor were analyzed (Figure 8), revealing that the power spectrum in the vertical direction characteristically increased at approximate 2 Hz regardless of the equipment used to secure the wheelchair. However, with the exception of approximate 2 Hz vibration, the power spectrum were white noise that was generally equal to between 0 and 20 Hz. A previous study indicated that the pitching motion of the automobile occurred clearly at 2 Hz [7]. Therefore, the increase at approximate 2 Hz vibration causes a pitching motion in the experimental automobile. In addition, the power spectrum in the front-back direction increased slightly at approximately 2 Hz and 14 Hz. The former vibration is believed to cause the pitching motion, whereas the latter is believed to cause primary bending and

Figure 8: Power spectrum of floor

twisting resonance of the automobile body structure due to the slight shocks caused by small ruts and slight increases and decreases in driving speed.

Secondly, the rms values of accelerations were calculated from the obtained power spectrum for each speed (Figure 9).

Consequently, the rms values of accelerations of the floor were found to depend on driving speed and the existence of the equipment for fastening a wheelchair. Therefore, vibration increased due to the equipment for fastening a wheelchair and due to the increase in driving speed. Between 50 and 70 km/h, there was no recognizable difference in vibration. This is most likely due to the good condition of road, which had no potholes or ruts.

In addition, the frequency response functions for the input vibration at the Rear floor to the output vibration at the Front floor were analyzed. The acceleration ratio, phase and coherence function are shown in Figure 10.

The coherence function is an index that expresses relationship between input vibration (Rear floor) and output vibration (Each Measurement Point), and can be used to evaluate the influence of non-linearity and time-lag of the

system as well as the effects of noise for a vibration measurement. Significance was evident from the high coherence between 1 and 14 Hz. In the same band, synchronism was revealed by the phase, which was almost 0 deg (Figure 10).

3.2.2. Vibration of the passenger and the wheelchair

As before, the power spectrum between 0 and 20 Hz vibration of each point was analyzed (Figure 11). The power spectrum in the front-back direction increased at

Figure 9: Acceleration of floor

Figure 10: Frequency response function

Figure 11: Power spectra for various segments of the passenger

Figure 12: Frequency response functions for segments of the passenger (Without belts, 50km/h)

approximately 2 Hz in all points regardless of the equipment used to secure the wheelchair. In addition, a gently peak was recorded between 10 and 14 Hz in the power spectrum in each point. Therefore, differences in the power spectrum between the floor and the passenger were revealed.

The frequency response functions for the input vibrations

at the Rear floor to the output vibrations at each point on the passenger and the wheelchair were analyzed. The acceleration ratios of each point are shown in Figure 12.

In Figure 12, various peaks between 1 and 10 Hz were recorded at every point in the acceleration ratios in both the vertical and front-back directions. These peaks express the

Figure 13: Comfort Evaluation Prediction System

increase in the output vibration for the given input vibration due to resonance. Figure 12 shows the resonance generated in the Passenger-Wheelchair-Floor system for the input vibration between 1 and 10 Hz. However, the slight coherence decrease in the front-back direction on passenger revealed the presence of noise.

4. DESIGN PROBLEMS OF THE WTA BY VEHICLE WITH PERSONS SEATED IN WHEELCHAIRS

Peaks in the acceleration ratio between 1 and 10 Hz at every segment of the passenger revealed the existence of resonance in the WTA. Therefore, the input vibration of the floor between 1 and 10 Hz was found to generate resonance. In addition, the equipment used to secure the wheelchair was found to increase the acceleration of the floor vibration that entered the Passenger-Wheelchair-Floor system.

A previous study indicated that human experience discomfort when subjected to vibration between 1 and 20 Hz, especially vibration between 4.5 and 9 Hz [8]. Therefore, an input vibration between 1 and 10 Hz is revealed as a factor that causes discomfort in the current WTA. In the design of the future WTA, the reduction of an input acceleration between 1 and 10 Hz and the suppression of resonance in passenger are necessary.

The installing of shock-absorbing equipment in Passenger-Wheelchair-Floor system appears to be one possible method of controlling such resonance. As a method of the installing, shock-absorbing equipment could be installed in the platform of the car hoist. This is convenient because such a method does not require the structure of currently used wheelchairs or equipment for fastening the wheelchair to be changed.

In order to improve the comfort, the future WTA should be designed only after the characteristics of the shock-absorbing equipment has been clarified. In addition, the characteristics should be determined after the variety of the relationship between human, artifacts and surroundings has been considered. Because the adoption of a design solution under average condition can not adequately satisfy various condition under which the system might be used, (human using the system, automobile used in conjunction with the system, wheelchair, transport environment). Therefore, on designing the future WTA, the Comfort Evaluation Prediction System (CEPS) is needed as means for clarifying appropriate design solutions. The CEPS can obtain appropriate design characteristics because initial parameters expressed the usage conditions are employed.

The devised CEPS is shown in Figure 13. The CEPS involves a process of estimating evaluation and a process of

obtaining feedback. The former process is performed using the Vibration Transmission Model (VTM) and the Vibration Evaluation Model (VEM), the latter process involves changing the characteristics of the shock-absorbing equipment. The CEPS can clarify the appropriate characteristics of the shock-absorbing equipment for a given objective evaluation. The VTM is a mass-damper model that can estimate transmitted vibration at every segment of the passenger from an input vibration, including characteristics of the human, the wheelchair and the shock-absorbing equipment. The VEM can estimate evaluation factors and total evaluation from transmitted vibration at every segment of the passenger.

5. CONCLUSION

The present study investigated the possibility of enhancing the comfort of the current WTA via examination of the vibration induced in the system. In the examination, the power spectrum of the floor vibration was found to be white noise between 1 and 20 Hz without 2 Hz. The equipment used to secure the wheelchair contributed to an increase in the vibration. Resonance projected in the passenger was recorded between 1 and 10 Hz. Therefore, the input vibration between 1 and 10 Hz are revealed as a factor that causes discomfort in the current WTA. In the design of the future WTA, the reduction of input acceleration between 1 and 10 Hz and attempting to the suppression of resonance in the passenger are necessary. As a method of reducing the resonance in the passenger, the installing of shock-absorbing equipment in the Passenger-Wheelchair-Floor system was proposed. When designing, the characteristics of shock-absorbing equipment to be used in the system should be clarified after the variety of the relationship between human, artifacts and surroundings is considered. Therefore, the CEPS was proposed as a means to clarify the appropriate characteristics.

The knowledge obtained in the present study for the state of vibration, especially the vibration on the passenger, is useful for the construction of the VTM within the CEPS. In future studies, the authors will apply the design gained in the present study to improve the comfort of the current WTA.

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