Multi-body Dynamics Modelling of Seated Human Body under Exposure to Whole-Body Vibration

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Abstract: In vehicle systems occupational drivers might expose themselves to vibration for a long time. This may cause illness of the spine such as chronic lumbago or low back pain. Therefore, it is necessary to evaluate the influence of vibration to the spinal column and to make up appropriate guidelines or counter plans. In ISO2631-1 or ISO2631-5 assessment of vibration effects to human in the view of adverse-health effect was already presented. However, it is necessary to carry out further research to understand the effect of vibration to human body to examine their validity and to prepare for the future revision. This paper shows the detail measurement of human response to vibration, and the modelling of the seated human body for the assessment of the vibration risk. The vibration transmissibilities from the seat surface to the spinal column and to the head are measured during the exposure to vertical excitation. The modal parameters of seated subject are extracted in order to understand the dominant natural modes. For the evaluation of adverse-health effect the multi-body modelling of the spinal column is introduced. A simplified model having 10 DOFs is constructed so that the transmissibilities of the model fit to those of experiment. The transient response analysis is illustrated when a half-sine input is applied. The relative displacements of vertebrae are evaluated, which can be a basis for the assessment of vibration risk. It is suggested that the multi-body dynamic model is used to evaluate the vibration effect to the spinal column for seated subjects.

Key words: Bio-dynamic response, Whole-body vibration, Modelling, Spinal column

Introduction

In vehicle designs it is necessary to assess the effect of vibration to the drivers or passengers from the viewpoint of health. Occupational drivers of industrial vehicles such as power shovels, bulldozers or tractors may suffer from chronic lumbago or low back pain after some period of engagement. Therefore the exposure limit of whole body vibration needs to be made clear.

Usually the vibration effect is assessed based on the pressure changes at the lumbar vertebral endplates. It can hardly be measured, though the vibration response of the spinal column can be measured at the surface. Therefore, it is necessary to have the dynamic model of the human body which can interpret the vertebral behavior. One of the possible ways is to build a dynamic model which represents the vertebrae’s response.

This paper presents a multi-body modelling of seated human body. In the model the vertebrae are represented by rigid bodies and they are connected by revolute joints. The intervertebral disks are regarded as rotational springs and rotational dampers. The vibration experiment is conducted to measure the transmissibilities from the seat surface to the measurement points. The model is constructed so as to express the experimental transmissibilities. It is suggested that the multi-body dynamic model can be used to evaluate the vibration effect to the spinal column of the seated subject.

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Vibration Experiment

The vibration experiment is conducted to measure the transmissibilities of a seated human body. The subject is seated on a rigid surface, and is exposed to vibration in vertical direction (Z). The accelerations of the seat surface, forehead, mouth, cervical 5, 7, thoracic 1, 4, 8, lumbar 1, …, 5, and sacrum, are measured respectively (Fig. 1). A total of 25 transmissibilities is obtained; two transmissibilities in X and Z direction at each location are measured except at the forehead where only one in X is measured. Two sensors are fixed on a cardboard, which is mounted on the skin surface by the adhesive tape at each location as shown in Fig. 3. The rotation of the head is evaluated from the difference of two transmissibilities at the forehead and at the mouth in X direction on the assumption that the head holds rigid. The acceleration at the mouth is measured by a bite bar with two accelerometers fixed on it. The excitation wave is a random wave up to 20 Hz with the amplitude of 0.07 G rms. The measurement is iterated 5 times in the same condition. The duration time for each excitation is about 60 s. The reproducibility is examined at each measurement point. The reproducible data is used to obtain the averaged transmissibilities. The seated posture of the subject is measured by using a sliding gauge shown in Fig. 2; the geometrical coordinates of the vertebrae are obtained in the sagittal plane.

The accelerometers are used for the measurement of transmissibility. Two sensors are mounted on the skin surface by the adhesive tape at each location as shown in Fig. 3. This sensor system weighs about 2–3 g, which might affect the local vibration behavior. The effect of local tissue-accelerometer system is corrected from the transmissibility functions by the former presented approach3). Since the orientation of the accelerometer is tilted from the global coordinate, the tilted effect is compensated by applying the coordinate transformation.

Modal Parameter Estimation

Modal parameters are identified from the transmissibility functions. The Multi-reference Iterative Curve-fitting technique4) is used for the modal parameter estimation. The frequency range of interest is from 3 Hz to 20 Hz because the coherence function falls at the low frequency range around 0–3 Hz. In the estimation process it is assumed that the...
system is a linear viscously damped system. The 25 transmissibility functions are used simultaneously to get the global estimate of modal properties.

The representative transmissibilities are shown in Figs. 4 and 5. It is found that the synthesized lines agree well with experimental ones. It is understood that the dynamic characteristics of human body can be approximated to a linear viscously damped system under exposure to a stationary random excitation. The identified natural frequencies and modal damping ratios are summarized in Table 1.

**Table 1. Natural Frequencies and Modal Damping Ratios of Experimental Modal Parameters**

<table>
<thead>
<tr>
<th>Order</th>
<th>$f_r$ (Hz)</th>
<th>$\zeta_r$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>4.4</td>
<td>29</td>
</tr>
<tr>
<td>2</td>
<td>5.1</td>
<td>60</td>
</tr>
<tr>
<td>3</td>
<td>6.6</td>
<td>20</td>
</tr>
<tr>
<td>4</td>
<td>9.5</td>
<td>19</td>
</tr>
<tr>
<td>5</td>
<td>11.8</td>
<td>20</td>
</tr>
<tr>
<td>6</td>
<td>16.5</td>
<td>29</td>
</tr>
</tbody>
</table>

$f_r$: Natural frequency (damped). $\zeta_r$: Modal damping ratio.

Figure 6 shows the original shape of the spine at measurement locations. The two of typical mode shapes are shown in Figs. 7 and 8. In these figures the deformation is displayed with the sequence of phase-angles at every quarter period. It is shown that the spinal ‘S’ shape is bent around the lower thoracic vertebra at the 3rd mode. The contraction and expansion of the spinal column is observed in vertical direction at the 5th mode. It is suggested that both modes affect the lumbar spine by the compression and/or the bending deformation.

**Construction of Multi-body Model**

In order to model the physical property of the spinal column faithfully, it would be effective to consider the vertebrae as rigid bodies and intervertebral discs as rotational springs and dampers. This leads to the multi-body modelling of human body including the spinal column.

In this study a simplified model having 10 DOFs is built as shown in Fig. 9. It is a two dimensional model which behaves in a sagittal plane, and has a similar outline of ‘S’
character as the real spinal column. Number of rigid bodies is decided depending on the importance of the part for the evaluation of the vibration effect to the spine. The cervical curvature and thoracic curvature are expressed by one rigid body. The lumbar curvature is modeled by five rigid bodies, and the sacrum and coccyx is by one rigid body. Therefore, it consists of eight rigid bodies with the head included. The number in parenthesis in Fig. 9 represents the number of vertebrae in the actual human body. Connection of vertebrae is realized by revolute joint, and the dynamics of intervertebral disk is represented by the rotational spring and the rotational damper. The interface between the buttock and the seat is expressed by two sets of translational spring and damper in vertical directions, and one set in fore-and-aft direction. Therefore, the model has 8 DOFs in rotation, and 2 DOFs in translation, and 10 DOFs in total. The geometrical shape of the spinal column is obtained from the measurement (See Fig. 2). The shape and joint location of the lumbar vertebrae are decided by referring to the

**Fig. 7.** Mode Shape of the 3rd Mode (6.6 Hz).
Deformation displayed with the sequence of phase-angles at every quarter period. The spinal ‘S’ shape is bent around the lower thoracic vertebra.

**Fig. 8.** Mode Shape of the 5th Mode (11.8 Hz).
Deformation displayed with the sequence of phase-angles at every quarter period. The contraction and expansion of the spinal column is observed in vertical direction.

**Fig. 9.** Multi-body modelling of the spinal column.
literature\(^5\).

The model parameters, such as dimensions and inertia properties are set up based on the data of actual human bodies\(^6, 7\). The inertia effect of the viscera is taken into account by distributing the inertia quantity to each vertebra. The reliable parameters of rotational springs and dampers of intervertebral disks are hardly found in literatures. Therefore, these parameters need to be determined from the vibration experiment.

The optimal set of parameters is searched so that transmissibilities of the model fit to those of the experiment. The transmissibilities of the model is obtained by linearizing the input-output relationship under the assumption that the variation is small. The frequency range of interest is from 3 Hz to 20 Hz where several dominant modes of the seated subject are observed. The rectilinear response of the spinal column is obtained by transforming the rotational response of each revolute joint into the translational displacement. After the transformation, the analytical transmissibilities are compared to the experimental ones. Unknown parameters such as the coefficients of rotational springs and dampers are determined by the approach based on the least squares. Estimation is iterated until the parameters fall into the physically acceptable range.

The natural frequencies and modal damping ratios of dominant modes are summarized at Table 2. These characteristics are evaluated from the linearized equations of motion. The transmissibility obtained from the multi-body model is shown in Figs. 10 and 11. It is confirmed that the model represents the fundamental property of the subject although the fitness of the model depends on the transmissibility location.

### Discussion

In this paper, we focused on the construction of the multi-body model by the small degree-of-freedom model as much as 10 DOFs. The first two modes (4.3 Hz and 6.8 Hz) of the multi-body model correspond to those of the modal parameter model in terms of frequencies and damping ratios. However, the natural frequency of the third mode (13.9 Hz) is different from the modal parameter model. Therefore, the reliability of the model needs to be examined in the high frequency range, which is roughly above 10 Hz.

The fitness of the model depends on the transmissibility location as described above. Since the multi-body model has constraints at the revolute joints, it is not easy to find out the optimal set of parameters as in the case of modal parameter determination. The expansion of the DOF of the model will help to construct more faithful dynamic human model, where, for example, the cervical spine and the thoracic spine have independent DOFs.

The constructed model can be used for various purposes. As one of the examples the transient response analysis is illustrated. The response of the model to a half-sine wave

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\( f_r \): Natural frequency (damped). \( \zeta_r \): Modal damping ratio.

Fig. 10. Transmissibility of the Lumbar 1 (Z).

Fig. 11. Transmissibility of the Lumbar 5 (Z).
input is simulated. Figure 12 shows the half-sine input wave and the vertebral responses. The responses are the angular displacements at the revolute joints between the sacrum and the L5 (S–L5), and that between L4 and L5 (L4–L5). This shows the relative angular displacement between them.

Figure 13 illustrates the maximum values of relative displacements at the lumbar due to the half-sine input. It suggests that this input affects the intervertebral disk between L4 and L5 most among the five. By using the multi-body model constructed by the frequency response data, time history analysis like shock, transient or any input can be implemented.

The vibration effect on the spinal column is examined from another viewpoint. The magnitude of relative displacement is evaluated by the following.

\[ |L_i - L_j| = \sqrt{(X_i - X_j)^2 + (Z_i - Z_j)^2} \]  

|L_i – L_j|: transmissibility of the magnitude of relative displacement between the lumber \(i\) and \(j\)

\(X_i\): transmissibility of the point \(i\) in the fore-and-aft (X) direction

\(Z_i\): transmissibility of the point \(i\) in the vertical (Z) direction

The relative transmissibilities are shown in Fig. 14 where the locations of natural frequencies are also designated. It is understood that the vibration effects on intervertebral disks have frequency dependencies. In the resonant frequencies such as 6.6 Hz and 16.5 Hz some of relative transmissilities (L3–L4, L4–L5 and L5–S) show the moderate peaks. However this is not always the case with the location and the frequency.

The duration of the half sine input in Fig. 12 is \(t=0.042\) s where the dominant frequency component is \(1/(2t)=12\) Hz. This may be the reason that the relative angle displacement between L4–L5 shows the largest response because the L4–L5 also shows that largest relative transmissibility at the frequency of 12 Hz. Further examinations such as the dependency of the response to the input are involved in future works.

In order to use the model for the vibration risk assessment on the spinal column, the reliability of the model needs to be improved. In the sense, the multi-body model needs to be constructed more faithfully, which reflects the standard
physical properties. The order of the model is also to be increased; number of rigid bodies needs to correspond to the active number of vertebrae in the spine. This paper would be a basis for the further development of the multi-body model.

Conclusion

This study shows the vibration experiment of a seated human subject, the modal parameter estimation from transmissibility functions, and the multi-body modelling which explains the dynamic behavior of the subject. The purpose of model construction is to assess the vibration effect on the spinal column. It is suggested that the constructed model can evaluate the relative displacements between vertebrae, which can be a basis for the assessment of vibration risk. To expand the degrees of freedom of the multi-body model and to improve the accuracy of the model are involved in future works.

References