Predicting the Hand-Arm Vibration Response Characteristics from the Handles With Coating Using a Lumped Parameter Model Designed

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Abstract: Hand operating tools are highly transmitting a large magnitude of vibration to the hand-arm system which leads to hand-arm vibration syndrome. The primary objectives of the study are to analytically predict the anti-vibration coating on the handles and to evaluate the vibration isolation effectiveness. A seven-degree-of-freedom (DOF) bio-mechanical model is developed based on the driving point mechanical impedance distributed to the hand-arm system. The proposed model is applied to predict the effectiveness of two different anti-vibration coating in terms of vibration transmitted to the finger skin, palm skin, fingers, palm, wrist, and the shoulder. The results are obtained as a vibration transmissibility magnitude in the three orthogonal directions ($x_h$, $y_h$, $z_h$). The results are also compared with five DOF human hand-arm models. The proposed model may also be useful for further analysis of anti-vibration coating materials and help designers to develop better handles for vibrating tools.

Keywords: Anti-vibration coating, Hand-arm vibration syndrome, Vibration transmissibility.

1 INTRODUCTION

Hand operating tools such as drills, grinders, road breakers are highly transmitting large magnitude of vibration to the hand-arm system. The vibration transmitted to the hand-arm system leads to hand-arm vibration syndrome (HAVS) (Griffin, 1990). The biodynamic properties of the hand–arm system are based on the vibrating tool and the dynamic behaviour of the tool or machine. To understand the mechanisms behind vibration-induced disorders, the biodynamic responses of the hand-arm system are to be considered and effective knowledge is required for the better development of assessing the vibration risk (Dong et al., 2005; Griffin, 1994). The influence of grip force and amplitude of vibration are quantified when the system subjected to sinusoidal excitations using the driving point mechanical impedance technique (DPMI) (Gurram et al., 1995). The range of mechanical equivalent and mechanical impedance models of the hand-arm system for three orthogonal directions ($x_h$, $y_h$ and $z_h$) are set by the international organization for standardization (ISO-10068, 1998; ISO-10068, 2012). Most of the research studies have considered vibration excitation at a single point in the hand-handle interface for deriving the driving-point biodynamic response data (Abrams et al., 1970; Besa et al., 2007). The anti-vibration gloves can be used to reduce the vibration exposure and essentially serve as a simple active suspension system between the hand and the tool (Dong et al., 2009).

Using the single point approach it is very difficult to predict the vibration transmissibility of anti-vibration gloves in the palm and the fingers. The deficiency of the single point approach has been overcome by two point approach method. In this approach, the hand-handle interface is separated into two distinct driving points which are palm and finger (Dong et al., 2005). More realistic simulations demonstrated using two point models are proposed by few researchers. Lumped parameter models of the hand-arm system have been proposed to simulate the distributed vibration response and to estimate the power absorptions among the sub-structures of the system (Dong et al., 2007). Two-point model and lumped parameter model provide a better estimation of the vibration transmissibility while using vibration reducing gloves (Dong et al., 2009). These two-point coupling models have been adopted in a proposed revision of the ISO standard (ISO-10068, 1998). Most of the researchers established two-point hand coupling approach for studying the distributed responses along the forearm direction ($z_h$) of the system (Dong et al., 2007). Limited experimental study is available in biodynamic response in finger and palm of the hand in the $x_h$ and $y_h$ orthogonal to the forearm direction (Dong et al., 2012). One of these models has been used to evaluate the absorbed power across the substructures of the hand-arm system along forearm direction (Dong et al., 2008). Most of the authors expanded the two point coupling hand model with more degree of freedom to predict the response in the arm-shoulder substructures (Adewusi et al., 2012).
This study primarily aims to predict the vibration response of the hand-arm system while using different anti-vibration coating to the vibrating tools or machines. Two point coupling hand model with, 5 DOF was added with additional 2 DOF using damping materials for coatings such as air glove material, gel glove material and the vibration transmissibility was predicted on the orthogonal directions of the palm skin, palm, fingers skin, fingers, palm, wrist and the shoulder. And also the human hand five DOF model was compared with the results. The results are used to identify the biodynamic response and to understand the associations with the dynamic properties of the hand-arm system. These observations are also useful for efficient modeling of anti-vibration coating materials used in vibrating tools.

2 METHODS

2.1 Hand-Arm System Model with Anti-Vibration Coating

The structure of the human hand-arm model is shown in Figure 1 with anti-vibration coating by assuming two point coupling between hand and the handle. Hand gripping the vibrating handle is considered as a clamp like mechanical system. This clamp like mechanical system is divided into two major parts. The first part comprises of the palm-wrist-forearm with substructures and is represented by $M_5$, $M_3$ and $M_1$ coupled through $k_5$, $k_3$ and $c_5$, $c_3$. In which, the $M_5$ represents the effective mass of coating material and $M_1$ represent the skin mass of palm in contact with the coating material. Mass $M_1$ and $M_0$ represent the equivalent mass of palm-wrist-forearm and upper-arm shoulder structure connected through another spring damping element $k_1$ and $c_1$. Mass $M_0$ is coupled to fixed ground through another spring damping element $k_0$ and $c_0$.

The second part constitutes the finger positioned on another side of the handle and is represented by three masses $M_6$, $M_4$ and $M_2$ coupled through spring damping elements $k_6$, $k_4$ and $c_6$, $c_4$. Mass $M_6$ represents the effective mass of coating material and $M_4$ represents the skin mass of the finger in contact with the coating material. The remaining finger tissues and finger bones are represented by the effective mass $M_2$.

The hand-arm system model is simulated to evaluate the biodynamic responses under vibration along the $x_h$, $y_h$ and $z_h$ directions. Assuming coating masses $M_5$ and $M_6$ are fixed to the handle, the seven DOF model is considered as five DOF model. The equations of motion of the system subjected to handle excitation are expressed in the matrix form as,

$$[M][\ddot{x}] + [C][\dot{x}] + [K][x] = [F]$$  \hspace{1cm} (1)

Where $[M]$ is mass matrix, $[C]$ is damping matrix, $[K]$ is stiffness matrix, $[F]$ is forcing vector and $[x]$ is vector response coordinates ($x_0$, $x_1$, $x_2$, $x_3$, $x_4$).

2.2 Frequency Domain Method

The equations of motion are solved using frequency domain (FD) to determine the vibration response of different substructures considered in the model. Since the response of the model is depend on the frequency and the model is considered as a linear system with harmonic excitation FD method is used. By performing a Fourier transformation on Eq. (1) the following matrix form of equation can be obtained:

$$\{X_m(j\omega)\} = [K] - j\omega^2[M] + j\omega[C]^{-1}[F(j\omega)]$$  \hspace{1cm} (2)

where $\{X_m(j\omega)\}$ and $\{F(j\omega)\}$ are the complex Fourier transformation vectors of $\{x\}$ and $\{F\}$, respectively, in Eq. (2), and $\omega$ is the excitation frequency. Vector $\{X_m(j\omega)\}$ contains complex displacement responses from the mass segments as a function of $\omega$. The forcing vector $F(j\omega)$=$\{0, 0, (k_5-\omega c_5)Y(j\omega), (k_6-\omega c_6)Y(j\omega), 0\}$.

2.3 Transmissibility

The vibration response is determined using the vibration transmissibility of different substructures in the model. The transmissibility of the model is defined as a ratio of vibration measured on the substructure mass to the input vibration of the vibrating tool. The vibration transmissibility, $TR(\omega)$, is a complex function given by,

$$TR(\omega) = \frac{X_m(j\omega)}{Y(j\omega)}; \text{ for } m = 0,1,2,3,4.$$  \hspace{1cm} (3)
3 RESULTS AND DISCUSSIONS

The equation of motion of the proposed model is solved to determine the biodynamic response of the hand-arm model. Parameters of the response based model and the coating materials in the three orthogonal directions (x_h, y_h, z_h) are given in Table 1 and Table 2, based on experimental data. Figure 2 illustrates the biodynamic response characteristics of the elbow-shoulder, palm, palm skin, fingers and fingers skin for three orthogonal directions (x_h, y_h, z_h). The results are obtained in the coating model A and coating model B as a center frequency of 1/3-octave bands in the 10-1000 Hz range and are compared with the five DOF system model (Dong et al., 2007). Figure 2 (a) illustrates the comparison of vibration transmissibility magnitude in the x-direction of the elbow, palm, and fingers with coating model A and five DOF model. Coating A model elbow and five DOF elbow show the peak magnitude approximately to 20 Hz. But the magnitude of the vibration transmitted to the elbow with the coating material is slightly low when compared with five DOF model. The magnitude response of the palm with coating material A and five DOF does not show a peak. The peak magnitude of response in the fingers was found above 100-110 Hz. The vibration transmitted to the fingers is significantly reduced in coating A model.

Table 1. Parameters of the response based model in the three orthogonal directions (x_h, y_h, z_h) based on experimental data (Dong et al., 2007).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Vibration Direction</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>x_h</td>
<td>y_h</td>
</tr>
<tr>
<td>M_0</td>
<td>kg</td>
<td>0.300</td>
</tr>
<tr>
<td>M_1</td>
<td>kg</td>
<td>0.188</td>
</tr>
<tr>
<td>M_2</td>
<td>kg</td>
<td>0.079</td>
</tr>
<tr>
<td>M_3</td>
<td>kg</td>
<td>0.015</td>
</tr>
<tr>
<td>M_4</td>
<td>kg</td>
<td>0.014</td>
</tr>
<tr>
<td>K_0</td>
<td>N/m</td>
<td>1152</td>
</tr>
<tr>
<td>K_1</td>
<td>N/m</td>
<td>5648</td>
</tr>
<tr>
<td>K_2</td>
<td>N/m</td>
<td>10</td>
</tr>
<tr>
<td>K_3</td>
<td>N/m</td>
<td>41,749</td>
</tr>
<tr>
<td>K_4</td>
<td>N/m</td>
<td>114,031</td>
</tr>
<tr>
<td>C_0</td>
<td>N s/m</td>
<td>10.2</td>
</tr>
<tr>
<td>C_1</td>
<td>N s/m</td>
<td>36.2</td>
</tr>
<tr>
<td>C_2</td>
<td>N s/m</td>
<td>67.2</td>
</tr>
<tr>
<td>C_3</td>
<td>N s/m</td>
<td>55.9</td>
</tr>
<tr>
<td>C_4</td>
<td>N s/m</td>
<td>76.0</td>
</tr>
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</table>
Figure 2 (b) shows the comparison of vibration response in the y-direction of the hand-arm system with coating model A and five DOF model. The response shows that there is no much vibration reduction in elbow, palm and fingers when compared with coating model A and five DOF model. The almost similar response was found in both the models.

Table 2. Parameters of glove materials used as a coating material (Dong el al., 2009).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Coating A</th>
<th>Coating B</th>
</tr>
</thead>
<tbody>
<tr>
<td>M_s</td>
<td>kg</td>
<td>0.0020</td>
<td>0.0650</td>
</tr>
<tr>
<td>M_a</td>
<td>kg</td>
<td>0.0010</td>
<td>0.0674</td>
</tr>
<tr>
<td>K_s</td>
<td>N/m</td>
<td>177385</td>
<td>286537</td>
</tr>
<tr>
<td>K_a</td>
<td>N/m</td>
<td>327301</td>
<td>454779</td>
</tr>
<tr>
<td>C_s</td>
<td>N s/m</td>
<td>88.8</td>
<td>158</td>
</tr>
<tr>
<td>C_a</td>
<td>N s/m</td>
<td>75.2</td>
<td>106</td>
</tr>
</tbody>
</table>

The comparison between coating model A and five DOF model and its response in the z-direction is shown in Figure 2 (c). The resonance frequency occurs near at 16 Hz in both the models. The vibration transmissibility magnitude was slightly reduced in coating model A because of the coating effect. The similar effect follows in the palm, and the peak frequency was around 22 Hz in both the models. The vibration transmissibility magnitude in fingers while compared to the five DOF model remains same while compared to the five DOF model. From the Fig. 3 (b) the coating B model and five DOF give an almost same response in the y-direction. The peak magnitude in the elbow-shoulder, palm and fingers remains same in all the frequencies in the elbow for both the model. For palm and elbow, the resonance frequency is approximately 20 Hz for both the model. There is less vibration reduction found in the elbow and palm because of the coating effect. The significant amount of vibration is reduced in fingers in the coating B model compared to five DOF model. From the Fig. 3 (b) the coating B model and five DOF model compared to five DOF model. From the Fig. 3 (c) shows that the majority of the vibration over 100 Hz gets concentrated on the finger mass and so the peak magnitude of the vibration transmissibility on the fingers is above 150 Hz. Coating material B effectively reduced the vibration magnitude in fingers while compared to the five DOF model and there is very less response found in the elbow and palm in the z-direction. The response of the finger skin and palm skin in the three orthogonal directions are shown in Fig. 3 (d) and the transmissibility is between 0.3-1.0. From the above results both the coating models are effectively reducing the vibration transmissibility magnitude above 100Hz. In both the models finger vibration magnitude has been effectively reduced when compared to the elbow-shoulder and palm. So the coating models are more effective for reducing higher frequency vibration. During the low frequency vibration there was less vibration reduction found in the both the models.

The vibration response results of coating model B and five DOF model in the x-direction are shown in Figure 3 (a). The magnitude of vibration remains same in all the frequencies in the elbow for both the model. For palm and elbow, the resonance frequency is approximately 20 Hz for both the model. There is less vibration reduction found in the elbow and palm because of the coating effect. The significant amount of vibration is reduced in fingers in the coating B model compared to five DOF model. From the Fig. 3 (b) the coating B model and five DOF give an almost same response in the y-direction. The peak magnitude in the elbow-shoulder, palm and fingers remains same while compared to the five DOF model. From the Fig. 3 (c) shows that the majority of the vibration over 100 Hz gets concentrated on the finger mass and so the peak magnitude of the vibration transmissibility on the fingers is above 150 Hz. Coating material B effectively reduced the vibration magnitude in fingers while compared to the five DOF model and there is very less response found in the elbow and palm in the z-direction. The response of the finger skin and palm skin in the three orthogonal directions are shown in Fig. 3 (d) and the transmissibility is between 0.3-1.0. From the above results both the coating models are effectively reducing the vibration transmissibility magnitude above 100Hz. In both the models finger vibration magnitude has been effectively reduced when compared to the elbow-shoulder and palm. So the coating models are more effective for reducing higher frequency vibration. During the low frequency vibration there was less vibration reduction found in the both the models.

![Graph](image1.png)

(a) Elbow-Shoulder, Palm and Fingers response on x-axis

![Graph](image2.png)

(b) Elbow-Shoulder, Palm and Fingers response on y-axis
Figure 2. Comparison of vibration response using coated model A and five DOF model.

Figure 3. Comparison of vibration response using coated model B and five DOF model.
4 CONCLUSIONS

This study has enhanced the understanding of hand-arm vibration biodynamics during the coatings given to the handles. Two different coatings have been given to the handles and the vibration response results are compared with five DOF model. From the results obtained from the both coating model A and coating model B, it is concluded that the vibration transmissibility magnitude is effectively reduced in the fingers when compared with the five DOF model. The benefit of the coating model is by considering the palm skin and finger skin as a DOF, the response of the palm skin and finger skin can also be predicted. The coating models are also useful for developing better coating materials for handles and to predict the vibration response of the hand-arm system.

REFERENCES


