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ON THE MODELING AND OPTIMIZATION OF ANTI-VIBRATION GLOVES FOR HAND-ARM VIBRATION CONTROL

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ABSTRACT

Various studies in hand-arm vibrations have shown that isolators in the form of anti-vibration(AV) gloves are effective to reduce unwanted vibrations, transmitted to the human hand, from machines and hand tools. However, most of these studies are based on experimental or numerical analysis and hence, the level of effectiveness and optimum values of the glove's properties remain unclear. In this work, we analytically study the dynamics of hand-arm vibrations with and without a glove using the harmonic balance method. The considered analytical models for the hand-arm vibration comprise of lumped multi-degree of freedom system. The hand-tool interactions are modeled as linear spring and damper system for simplicity and accordingly, we obtain the equations governing the dynamics of the human-hand system. We perform parametric analysis using this bio-mechanical model of the hand-arm vibrations with and without a glove. The parametric analysis on the relative transmissibility (i.e., the ratio of transmissibilities with glove to without glove) shows the dependence of the transmissibility on the glove parameters. We observe that the effect of glove parameters on the relative transmissibility is not monotonous for the studied frequency range. This observation further motivates us to perform optimization of the glove parameters to minimize the overall transmissibility.

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INTRODUCTION

It is a well-known fact that prolonged exposure of vibrations to the human body is hazardous. These unwanted vibrations can be broadly classified in two categories; 1)whole body vibration (WBV), i.e., vibrations transmitted to the whole body through a supporting surface, and 2)segmental vibration, i.e., vibrations transmitted to a particular part of the body [1]. Since the prolonged effects and measurements of WBV (such as spinal disorders, Hemorrhoids, digestive problems) [2–4] are different from those of segmental vibrations (such as white fingers, muscle injuries, joint disorders) [5,6], they need to be studied and analyzed separately. Note that WBV has been studied extensively by researchers across the world and accordingly the solutions to minimize the levels of WBV, such as passive air suspension and active electromagnetic suspension, have been developed [2–4,7,8]. When the human hands are subjected to vibrations, the segmental vibration is termed as hand-arm vibration (HAV). Further, HAV causes hand-arm vibration syndrome (HAVS) which includes neurological disorders, vascular and musculoskeletal injuries. Therefore, it is necessary to understand the dynamics of HAV and accordingly develop methods to minimize it. This is the prime focus of the current paper.

HAVS happens due to the vibrations of power hand tools, used in different sectors such as mining, agriculture, construction, and manufacturing industries, further leading to neurological disorders, vascular and musculoskeletal injuries [9–12]. It has been found that these vascular injuries in the worker's hand using hand-held vibrating tools leads to 'white fingers', similar to the aging process [13]. HAVS is not limited to the workers in the mining or construction industry only. Prolonged exposure of vibration through daily equipment such as electric grass trimmer subjects the user to risks of HAVS [14]. Another primary source of HAVS is vibrating steering wheels [5,6,15]. Experimental works have demonstrated that low-frequency vibrations ($< 40\,Hz$) are more harmful to drivers of an off-road vehicle [6,16]. Hence, it is required to take preventive measures to limit the levels of HAV.

One of the simple and convenient ways to limit/minimize HAV is the use of anti-vibration (AV) gloves. Over the last two decades considerable efforts have been made to measure the effectiveness of AV gloves [17–22]. It has been observed that at high frequencies, the transmissibility of an AV glove increases with increasing glove dynamic stiffness [20] but decreases with increasing apparent mass of the part of the body in contact with the glove material [21]. Also, depending on the glove material, the transmission of vibration through a glove can be increased or decreased when increasing the grip force [22]. However, these AV gloves have shown excellent performance at high frequencies (i.e., > 150 Hz), but inferior performance at low frequencies [23, 24]. Therefore, a systematic analysis is required to understand the dynamics of the hand-arm system with and without gloves to measure the effectiveness of AV gloves.

To understand the dynamics of HAV with and without AV gloves different mathematical models, for simulating the bio-dynamics (distributed at the finger, palm of hands, and the upper arms) under vibrations, have been developed. These models are generally presented by multi-degree of freedom (MDOF) systems with hand-tool interaction modeled as a linear spring-mass-damper system [25–28]. Using these MDOF models for the hand-arm system, it was observed that the transmissibility of the system depends on the body posture, excitation magnitude and combination of grip and push forces [28]. However, to the best of our knowledge, these studies are based on numerical and experimental analysis. Also, none of the earlier works have systematically analyzed the optimum values of the glove material properties (viz., stiffness, mass, damping). Hence, the aim of this work is to analytically study the dynamic interactions of a gloved hand-arm and vibrating handle system and determine the optimum values of the AV glove to limit/minimize the transmissibility of HAV.

Towards realizing this goal, we have extended existing MDOF models of the hand-arm system by including a linear isolator in between the source of excitation and handle. For the sake of simplicity, the hand-tool interactions have been modeled through linear springs and viscous dampers and accordingly, the linear governing equations of motion have been presented. The harmonic balance method is used to analytically study the dynamic of the gloved hand-arm system in contact with a vibrating handle. Optimum values of the glove parameters have been obtained to minimize the transmissibility.

MATHEMATICAL FORMULATION

The schematic of a MDOF model of the hand-arm system, with and without gloves, is shown in Fig. 1. In this model, the hand is represented by a clamp-like structure. In the model, m_f and m_p represent the masses due to the fingers, and palm and wrist bone structures respectively. m_f and m_p are connected through linear viscous and spring elements (c_1, k_1), representing the visco-elastic properties of carpal and metacarpal bones. The masses due to the tissues and skin covering the fingers and palm-wrist, which is further in contact with the handle of vibrating equipment, are represented by m_{tf} and m_{tp} respectively. The tissue masses of the fingers and palm-wrist, i.e., m_{tf} and m_{tp} are coupled to m_f and m_p, respectively through linear viscous and spring elements (c_2, k_2) and (c_3, k_3) as shown in Figs. 1a and b. The mass of the bones, tissues and the skin of the forearm and upper arm are represented by the lumped mass m_0. Also, the linear viscous-elastic properties of the forearm and upper arm are lumped at the wrist (c_w, k_w). The body/trunk is modeled as a fixed surface and connected to mass m_0 through linear spring and viscous elements $(c_0\,\text{and}\,k_0)$. The handle of the vibrating equipment is modeled as lumped mass m_H which is in contact with the fingers and palm-wrist. The column, connecting the handle and the ground, is modeled as a rigid bar with equivalent linear spring (k_s) and viscous damper (c_s).

The schematic of the hand-arm system with an AV glove has been shown separately in Fig. 1b. The glove material between the handle and gloved-hand interface is represented by linear viscous (c_6, c_7) and spring elements (k_6, k_7) with lumped mass elements $(m_{g3}, m_{g4}, m_{g5}, m_{g6})$ distributed at the fingers and palm-side interface. The other side of the glove is represented by the additional masses $(m_{g1}$ and $m_{g2})$ with linear viscous damper (c_4) and stiffness (k_4) as shown in Fig. 1b. Note that the remaining parameters for this model are the same as the hand-arm system without gloves.

For this analytical model, $z(t)$ is the external excitation. The other generalized coordinates of the hand-arm system with a glove are chosen as the motion of the finger tissue and skin mass m_{tf} (z_{tf}), palm-wrist tissue and skin mass m_{tp} (z_{tp}), fingers mass m_f (z_f), palm-wrist mass m_p (z_p), handle mass m_H (z_H) and lumped fore-arm and upper-arm mass m_0 (z_0) along the $z-$ direction, making it a 6-DOF

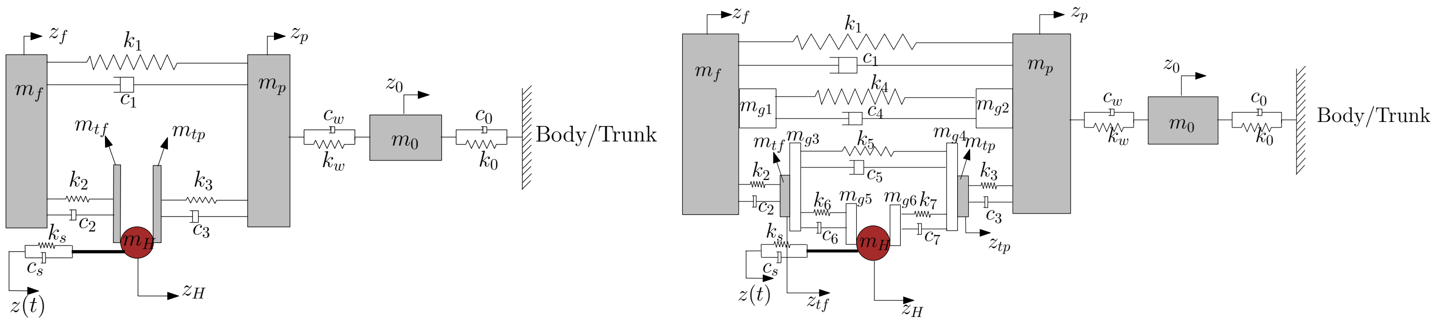


Figure 1: Schematic of hand-arm system (a) without glove, and (b) with glove.

system. However, it should be noted that for the case of the hand-arm system without a glove z_{tf} and z_{tp} will be the same as z_H; which further makes it a 4-DOF model. Having established all the generalized coordinate, we now use the energy method to obtain the equations governing the dynamics for both scenarios.

Case 1: For the case of the hand-arm system without a glove (Fig. 1a) the total kinetic energy (T) and potential energy (U) of the system are given by

$$T = \frac{1}{2}m_0\dot{z}_0^2 + \frac{1}{2}m_p\dot{z}_p^2 + \frac{1}{2}m_f\dot{z}_f^2 + \frac{1}{2}m_{tp}\dot{z}_{tp}^2 + \frac{1}{2}m_{tf}\dot{z}_{tf}^2 + \frac{1}{2}m_H\dot{z}_H^2\,, \tag{1a}$$

$$U = \frac{1}{2}k_0z_0^2 + \frac{1}{2}k_w\left(z_0 - z_p\right)^2 + \frac{1}{2}k_1\left(z_p - z_f\right)^2 + \frac{1}{2}k_2\left(z_H - z_f\right)^2 + \frac{1}{2}k_3\left(z_p - z_H\right)^2 + \frac{1}{2}k_s\left(z_H - z\right)^2. \tag{1b}$$

Accordingly, the Lagrange function for this system is defined as

$$L = T - U\,, \tag{2}$$

and the equations governing the dynamics of the system with time can be obtained from the Euler-Lagrange equation

$$\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{z}_i}\right) - \frac{\partial L}{\partial z_i} = F_i\,, \tag{3}$$

where $z_i's$ are generalized coordinates and F_i represents the forces in q_i coordinate. The generalized co-ordinates for the hand-arm system without gloves are $\{\mathbf{z}\} = [z_0, z_f, z_p, z_H]'$. Therefore, the equations of motion for the system in these coordinates can be obtained using Eq. (3) and given by

$$m_0\ddot{z}_0 + k_0z_0 + k_w\left(z_0 - z_p\right) = -c_0\dot{z}_0 - c_w\left(\dot{z}_0 - \dot{z}_p\right), \tag{4a}$$

$$m_f\ddot{z}_f + k_1\left(z_f - z_p\right) + k_2\left(z_f - z_H\right) = -c_1\left(\dot{z}_f - \dot{z}_p\right) - c_2\left(\dot{z}_f - \dot{z}_H\right) \tag{4b}$$

$$m_p\ddot{z}_p + k_w\left(z_p - z_0\right) + k_1\left(z_p - z_f\right) + k_3\left(z_p - z_H\right) = -c_w\left(\dot{z}_p - \dot{z}_0\right) - c_1\left(\dot{z}_p - \dot{z}_f\right) - c_3\left(\dot{z}_p - \dot{z}_H\right) \tag{4c}$$

$$\left(m_{tf} + m_{tp} + m_H\right)\ddot{z}_H + k_2\left(z_H - z_f\right) + k_3\left(z_H - z_p\right) + k_sz_H = -c_2\left(\dot{z}_H - \dot{z}_f\right) - c_3\left(\dot{z}_H - \dot{z}_p\right) - c_s\dot{z}_H + k_sz + c_s\dot{z}. \tag{4d}$$

On rearranging the terms in the above equations and writing in a matrix form, we get

$$[\mathbf{M}]\{\ddot{\mathbf{z}}\} + [\mathbf{C}]\{\dot{\mathbf{z}}\} + [\mathbf{K}]\{\mathbf{z}\} = \{\mathbf{F_{eq}}\} \tag{5}$$

where $[\mathbf{M}]$, $[\mathbf{C}]$ and $[\mathbf{K}]$ are (4×4) inertia, damping and stiffness matrices respectively, $\{\mathbf{F_{eq}}\}$ is (4×1) force vector and $\{\mathbf{z}\}$ is (4×1) generalized displacement coordinate vector. These matrices are defined in Appendix A. Before proceeding to analyze the system, we also present the equations of motion governing the dynamics of the hand-arm system with gloves.

Case 2: The total kinetic energy and potential energy of the hand-arm system with gloves are given as

$$T_1 = \frac{1}{2}m_0\dot{z}_0^2 + \frac{1}{2}\left(m_p + m_{g2}\right)\dot{z}_p^2 + \frac{1}{2}\left(m_f + m_{g1}\right)\dot{z}_f^2 + \frac{1}{2}\left(m_{tp} + m_{g4}\right)\dot{z}_{tp}^2 + \frac{1}{2}\left(m_{tf} + m_{g3}\right)\dot{z}_{tf}^2 + \frac{1}{2}\left(m_{g5} + m_{g6} + m_H\right)\dot{z}_H^2\,, \tag{6}$$

$$U_1 = \frac{1}{2}k_0z_0^2 + \frac{1}{2}k_w\left(z_0 - z_p\right)^2 + \frac{1}{2}k_1\left(z_p - z_f\right)^2 + \frac{1}{2}k_2\left(z_{tf} - z_f\right)^2 + \frac{1}{2}k_3\left(z_p - z_{tp}\right)^2 + \frac{1}{2}k_4\left(z_p - z_f\right)^2 + \frac{1}{2}k_5\left(z_{tp} - z_{tf}\right)^2 + \frac{1}{2}k_6\left(z_H - z_{tf}\right)^2 + \frac{1}{2}k_7\left(z_{tp} - z_H\right)^2 + \frac{1}{2}k_s\left(z_H - z\right)^2. \tag{7}$$

The Lagrange function for this system is defined as

$$L_1 = T_1 - U_1\,, \tag{8}$$

accordingly the Euler-Lagrange equation for this system will be

$$\frac{d}{dt}\left(\frac{\partial L_1}{\partial \dot{z}_{1i}}\right)-\frac{\partial L_1}{\partial z_{1i}}=F_i \tag{9}$$

where z_{1i} are generalized coordinates and F_i respresents the forces in z_{1i} coordinates. The generalized coordinates for the hand-arm system with gloves will be $\{\mathbf{z_1}\}=[z_0, z_f, z_p, z_{tp}, z_{tf}, z_H]'$. Hence, the equations of motion for the system in these coordinates can be obtained using Eq. (9) and given by

$$m_0\ddot{z}_0+k_0z_0+k_w(z_0-z_p)=-c_0\dot{z}_0-c_w(\dot{z}_0-\dot{z}_p) \tag{10a}$$

$$\begin{aligned}&(m_f+m_{g1})\ddot{z}_f+(k_1+k_4)(z_f-z_p)+k_2(z_f-z_{tf})\\&=-(c_1+c_4)(\dot{z}_f-\dot{z}_p)-c_2(\dot{z}_f-\dot{z}_{tf})\end{aligned} \tag{10b}$$

$$\begin{aligned}&(m_p+m_{g2})\ddot{z}_p+(k_1+k_4)(z_p-z_f)+k_3(z_p-z_{tp})\\&+k_w(z_p-z_0)=-(c_1+c_4)(\dot{z}_p-\dot{z}_f)-c_3(\dot{z}_p-\dot{z}_{tp})\\&-c_w(\dot{z}_p-\dot{z}_0)\end{aligned} \tag{10c}$$

$$\begin{aligned}&(m_{tp}+m_{g4})\ddot{z}_{tp}+k_5(z_{tp}-z_{tf})+k_3(z_{tp}-z_p)\\&+k_7(z_{tp}-z_H)=-c_5(\dot{z}_{tp}-\dot{z}_{tf})-c_3(\dot{z}_{tp}-\dot{z}_p)\\&-c_7(\dot{z}_{tp}-\dot{z}_H)\end{aligned} \tag{10d}$$

$$\begin{aligned}&(m_{tf}+m_{g3})\ddot{z}_{tf}+k_5(z_{tf}-z_{tp})+k_2(z_{tf}-z_f)\\&+k_6(z_{tf}-z_H)=-c_5(\dot{z}_{tf}-\dot{z}_{tp})-c_2(\dot{z}_{tf}-\dot{z}_f)\\&-c_6(\dot{z}_{tf}-\dot{z}_H)\end{aligned} \tag{10e}$$

$$\begin{aligned}&(m_{g5}+m_{g6}+m_H)\ddot{z}_H+k_6(z_H-z_{tf})+k_7(z_H-z_{tp})\\&+k_sz_H=-c_6(\dot{z}_H-\dot{z}_{tf})-c_7(\dot{z}_H-\dot{z}_{tp})-c_s\dot{z}_H+k_sz\\&+c_s\dot{z}.\end{aligned} \tag{10f}$$

Again, on rearranging the above equations and writing in a compact form, we get

$$[\mathbf{M_1}]\{\ddot{\mathbf{z}}_1\}+[\mathbf{C_1}]\{\dot{\mathbf{z}}_1\}+[\mathbf{K_1}]\{\mathbf{z_1}\}=\{\mathbf{F_{eq}}\}. \tag{11}$$

where, $[\mathbf{M_1}]$, $[\mathbf{C_1}]$ and $[\mathbf{K_1}]$ are (6×6) inertia, damping and stiffness matrices, respectively, $\{\mathbf{F_{eq}}\}$ is (6×1) force vector and $\{\mathbf{z}\}$ is (6×1) generalized displacement coordinate vector. These matrices are further defined in Appendix A. In the current work, we have used the method of harmonic balance to solve these coupled second order ODEs for the hand-arm system with and without gloves (Eqs. (11) and (5)). This is presented in the next section.

METHOD OF HARMONIC BALANCE

In this section, we briefly present the method of harmonic balance to solve the equations of motion governing the dynamics of the hand-arm system with and without gloves. For the current analysis, we employ a harmonic excitation in the form of

$$z(t)=Z_0\cos\omega t \tag{12}$$

where Z_0 and ω are the amplitude and frequency of the external excitation. We now look for the solutions synchronous with external excitation and without loss of generality we assume the solutions of Eqs. (5) and (11) in the form of

$$\{\mathbf{z}\}(t)=\{\mathbf{A}\}\cos\omega t+\{\mathbf{B}\}\sin\omega t \tag{13}$$

$$\{\mathbf{z}\}_1(t)=\{\mathbf{A1}\}\cos\omega t+\{\mathbf{B1}\}\sin\omega t \tag{14}$$

where $\{\mathbf{A}\}$ and $\{\mathbf{B}\}$ are (4×1) columns vectors with elements $A_i's$ and $B_i's$ $(i=1,2,3,4)$ whereas, $\{\mathbf{A1}\}$ and $\{\mathbf{B1}\}$ are (6×1) columns vectors with elements $A1_i's$ and $B1_i's$ $(i=1-6)$. On substituting $\mathbf{z}(t)$ and $\mathbf{z}_1(t)$ in Eqs (5) and (11), respectively, we get

$$\begin{aligned}&-\omega^2[\mathbf{M}]\{\mathbf{A}\}\cos\omega t-\omega^2[\mathbf{M}]\{\mathbf{B}\}\sin\omega t\\&-\omega[\mathbf{C}]\{\mathbf{A}\}\sin\omega t+\omega[\mathbf{C}]\{\mathbf{B}\}\cos\omega t+[\mathbf{K}]\{\mathbf{A}\}\cos\omega t\\&+[\mathbf{K}]\{\mathbf{B}\}\sin\omega t=\{\mathbf{F_{eq}}\},\end{aligned} \tag{15}$$

$$\begin{aligned}&-\omega^2[\mathbf{M}_1]\{\mathbf{A1}\}\cos\omega t-\omega^2[\mathbf{M}_1]\{\mathbf{B1}\}\sin\omega t\\&-\omega[\mathbf{C}_1]\{\mathbf{A1}\}\sin\omega t+\omega[\mathbf{C}_1]\{\mathbf{B1}\}\cos\omega t\\&+[\mathbf{K}_1]\{\mathbf{A1}\}\cos\omega t+[\mathbf{K_1}]\{\mathbf{B1}\}\sin\omega t=\{\mathbf{F_{eq}}\}.\end{aligned} \tag{16}$$

By equating the coefficients of sine and cosine on both sides of Eqs. (15) and (16) we obtain two sets of algebraic equations corresponding to the ungloved and gloved hand. On solving these linear algebaric equations we get $\{\mathbf{A}\}$, $\{\mathbf{B}\}$, $\{\mathbf{A1}\}$ and $\{\mathbf{B1}\}$, and accordingly, the amplitude vectors $\{\mathbf{z}\}$ and $\{\mathbf{z}_i\}$. The closed from expressions of the elements of these amplitude vectors are very complex and hence, for the sake of brevity are not reported. A detailed analysis of the system using these equations has been presented in the next section.

RESULTS AND DISCUSSION

In this section, parametric study is carried out to analyze the effectiveness of the anti-vibration gloves against the transmitted vibrations. The mechanical properties of the hand-arm system and glove for the simulations are presented in the Table 1. For the parametric analysis, the numerical values of m_{g4}, m_{g6}, k_7, c_7 are proportional to m_{g3}, m_{g5}, k_6, c_6 respectively. The first part of the analysis is to validate the obtained analytical solutions of the amplitudes ($z_i's$ and $z_{1i}'s$) using harmonic balance by comparing it against the numerical simulations of (5) and (11). The comparison between numerical solutions from Eqs. (5), (11) and analytical solutions from Eq. (14) are presented for

Table 1: Parameters of the hand-arm system and glove [26].

Parameter	Value	Units	Parameter	Value	Units	Parameter	Value	Units
m_0	6.015	(kg)	k_0	7567	N/m	c_0	106	Ns/m
m_p	1.4618	(kg)	k_w	2978	N/m	c_w	134	Ns/m
m_f	0.0958	(kg)	k_1	4221	N/m	c_1	52	Ns/m
m_{tp}	0.0338	(kg)	k_2	196038	N/m	c_2	122	Ns/m
m_{tf}	0.0186	(kg)	k_3	55564	N/m	c_3	126	Ns/m
m_{g1}	0.0674	(kg)	k_4	2417	N/m	c_4	1	Ns/m
m_{g3}	0.0651	(kg)	k_5	0	N/m	c_5	0	Ns/m
m_{g5}	0.0005	(kg)	k_6	454779	N/m	c_6	106	Ns/m
m_H	3	(kg)	k_s	940	N/m	c_s	79	Ns/m

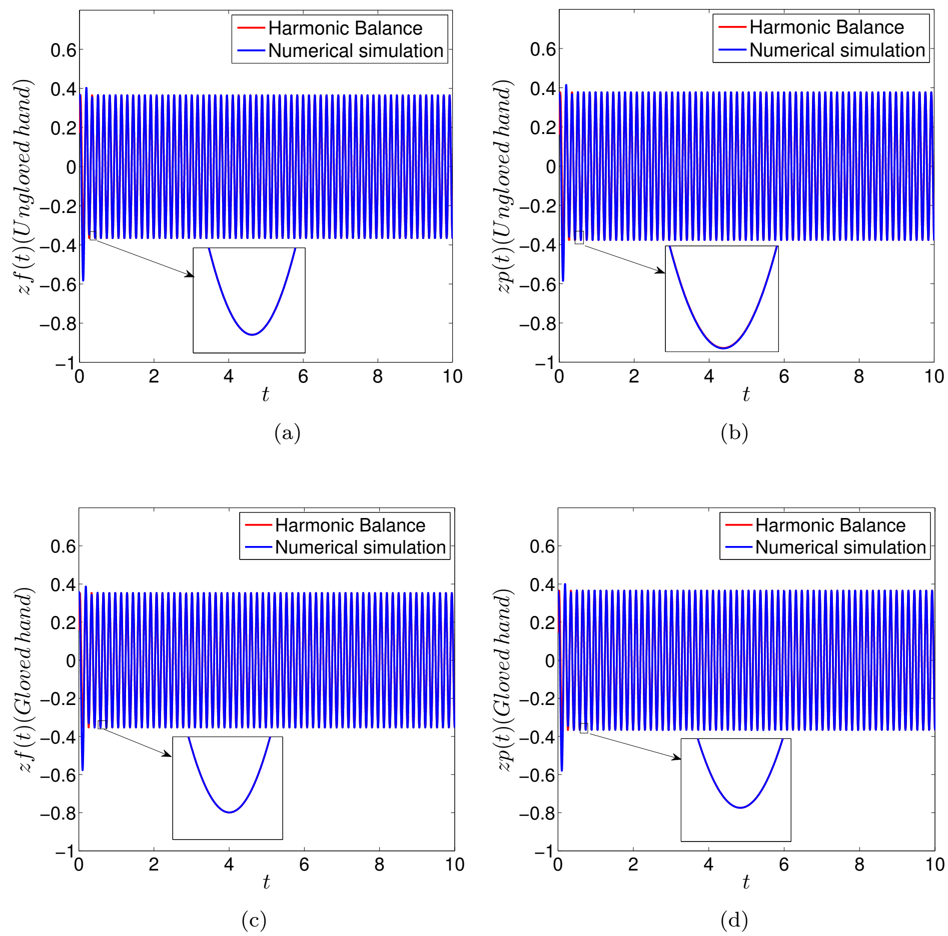
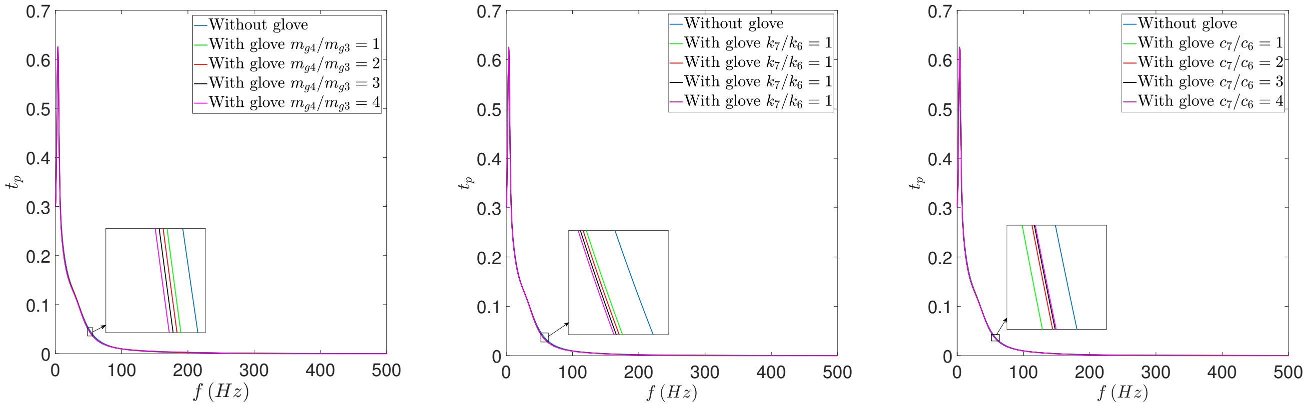


Figure 2: Responses of (a) fingers without gloves, (b) palm without gloves, (c) fingers with gloves, and (d) palm with gloves. The other parameters are chosen as $Z_0 = 1$, $m_{g2} = m_{g1}$, $m_{g4} = m_{g3}$, $m_{g6} = m_{g5}$, $k_7 = k_6$ and $c_7 = c_6$



(a) (b) (c)

Figure 3: Comparison of palm transmissibility curves with and without gloves with different parameters.

$m_{g2} = m_{g1}$, $m_{g4} = m_{g3}$, $m_{g6} = m_{g5}$, $k_7 = k_6$ and $c_7 = c_6$. The initial conditions for $z_i' s$ and $z_{1i}' s$ have been chosen corresponding to steady state response. For the numerical simulations of Eqs. (5) and (11), we have used the built-in command 'ode45' in Matlab with very tight absolute tolerance and relative tolerance ($1e^{-10}$).

To compare the analytical solutions from the method of harmonic balance and numerical solutions, we have used the palm and finger responses (z_p and z_f) as shown in Fig. 2. Figures 2a and 2b represent the responses of the palm and fingers without gloves while Figures 2c and 2d represent the responses of the palm and fingers with gloves. From Fig. 2 we can observe that there is an excellent agreement between the numerical simulations and analytical solutions for the given values of system parameters. This agreement further improves with the increase in time steps. Therefore, in the remainder of this work, we use the solutions from the method of harmonic balance for further analysis.

Having obtained the solution for the response of different parts of the hand-arm system, now we present the effect of different glove parameters on the transmissibility. The transmissibilities of the palm and finger without a glove are defined as

$$(t_p)_{without\,glove} = \frac{z_p}{Z_0}, \tag{17}$$

$$(t_f)_{without\,glove} = \frac{z_f}{Z_0}. \tag{18}$$

Similarly, the transmissibilities of the palm and fingers with a glove are defined as

$$(t_p)_{with\,glove} = \frac{(z_p)_{with\,glove}}{Z_0}, \tag{19}$$

$$(t_f)_{with\,glove} = \frac{(z_f)_{with\,glove}}{Z_0}. \tag{20}$$

The expressions for the transmissibilities of the palm and fingers, with and without a glove are very lengthy and hence, they are not reported here for the sake of brevity. Also, we present the transmissibility response for the palm only for the sake of brevity. The comparison of transmissibility of the palm with and without a glove for different glove parameters has been shown in Fig. 3. In this figure, the peak value of the curve represents the instance of primary resonance. However, the frequency corresponding to the second and third resonance is not evident. Also, from the figure, it seems that the transmissibility response of the palm with the glove is almost similar to the one without the glove and independent of the glove parameter. Therefore, to have a better understanding of the effectiveness of the AV glove and role of different glove parameters, we use the 'relative transmissibility' [26] which is defined as

$$T_p = \frac{(t_p)_{with\,glove}}{(t_p)_{without\,glove}}. \tag{21}$$

The effect of different glove parameters on the relative transmissibilities is depicted in Fig. 4. From these figures, it can be observed that the relative transmissibility curve shows the instance of the primary and secondary resonance more evident than the absolute transmissibility. Also, the effect of the glove parameter on the performance of the glove is more clearly visible through relative transmissibility. For instance, the masses of the glove in direct contact with the handle does not influence the transmissibility significantly. However, the other glove parameters, which are in direct contact with the hand, significantly influence the performance of the glove. It should also be noted that the effect of these parameters on the performance of the AV glove is not monotonous and changes from one frequency to another frequency. This observation is in consistency with earlier findings that the performance/effectiveness of the AV glove significantly depends on the application and consequently on the frequency of the external excitation. With this motivation, we optimize the glove parameters to minimize the

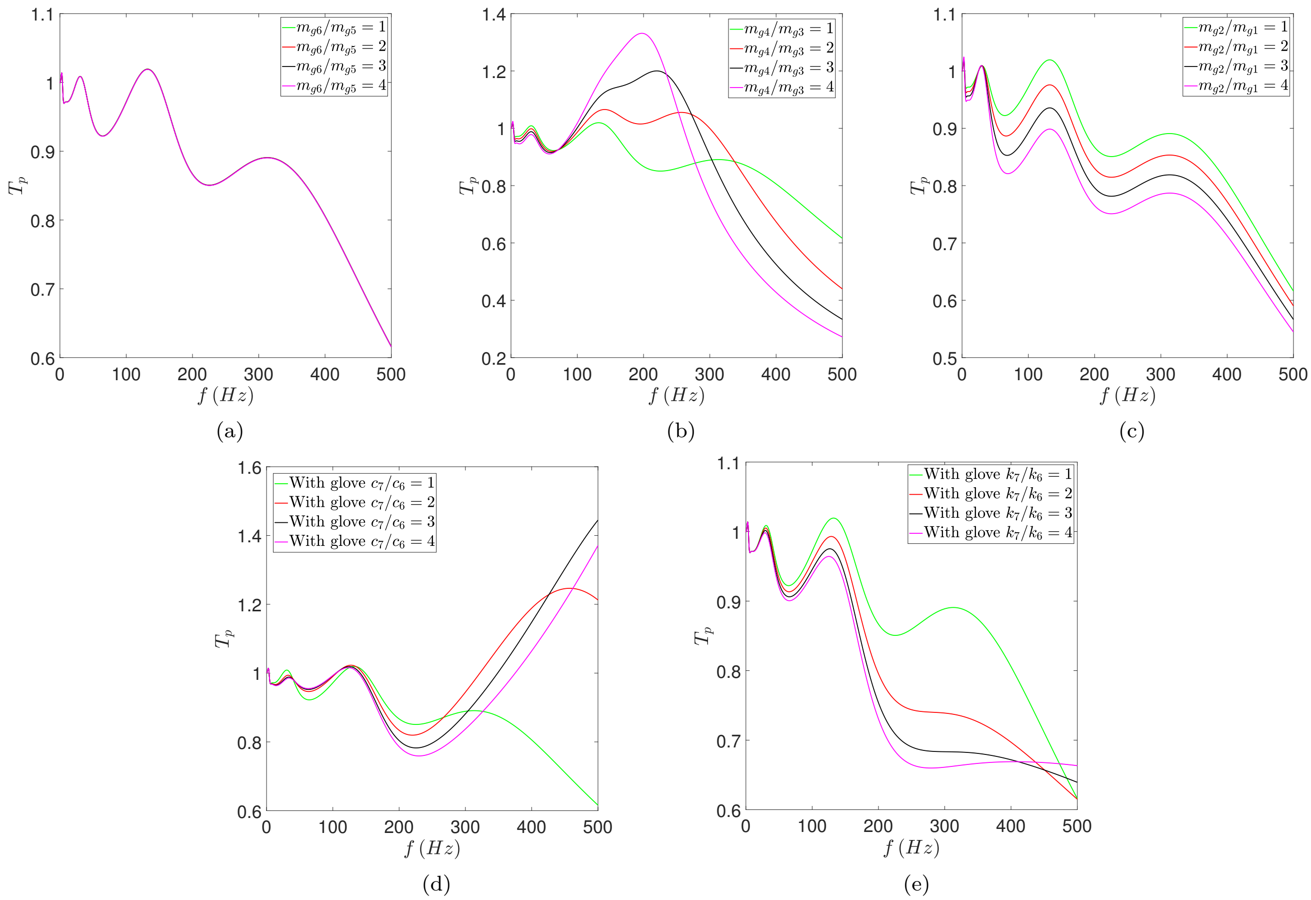


Figure 4: Comparison of relative palm transmissibility curves with different parameters.

overall transmissibility, which is presented in the next section.

OPTIMIZATION OF GLOVE PARAMETERS

In this section, we briefly present the outline of the optimization used in the current work. Since the transmissibilities of the palm and fingers are more crucial as compared to others, we optimize the palm and finger's transmissibilities only. For this purpose, we use Matlab's built-in function 'gamultiobj' to optimize two objective functions. 'gamultiobj' returns the values of parameters on the Pareto Front (set of points in parameter space that have noninferior objective function values) of the objective functions. We consider the frequency range from 0-500 Hz to optimize the overall relative transmissibility. The objective/fitness function for the 'gamultobj' is

$$objective\ function = min(Area\ under\ T_p\ curve, \tag{22}$$

$$Area\ under\ T_f\ curve,), \tag{23}$$

$$\{\mathbf{lb}\} \leq \{\mathbf{x}\} \leq \{\mathbf{ub}\} \tag{24}$$

where $\{\mathbf{x}\}$ represents the glove parameters to be optimized and are given by

$$\{\mathbf{x}\} = \{m_{g1}\, m_{g2}\, m_{g3}\, m_{g4}\, m_{g5}\, m_{g6}\, k_4\, k_5\, k_6\, k_7\, c_4\, c_5\, c_6\, c_7\}$$

$\{\mathbf{lb}\}$, and $\{\mathbf{ub}\}$ represent the lower and upper bound of the parameters, respectively, and given by

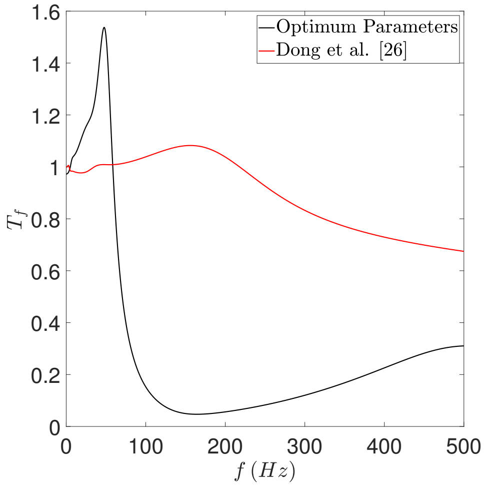
$$\{\mathbf{lb}\} = \{0.0001, 0.0001, 0.0001, 0.0001, 0, 0, \\ 10^5, 10^5, 10^5, 10^5, 10, 10, 10, 10\}$$

and

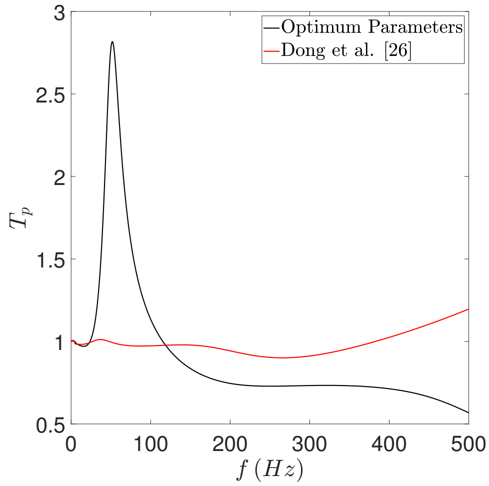
$$\{\mathbf{ub}\} = \{0.005, 0.01, 0.005, 0.01, 0.0001, 0.005, \\ 10^6, 10^6, 10^6, 10^6, 50, 50, 50, 50\}$$

Using these values as input arguments for 'gamultobj', we obtain the optimum value of the glove parameters as

$$\{\mathbf{x}\}_{optimum} = \{0.0011, 0.0098, 0.00015, 0.0099, 0, 0.0048, \\ 788764, 323467, 101677, 102020, \\ 27.5, 12.3, 31.5, 10.3\}.$$



(a)



(b)

Figure 5: Comparison of relative (a) finger transmissibility (b) palm transmissibility curves for the optimum glove parameters and glove parameters used in [26].

Using these optimum values of glove parameters we obtain the relative transmissibility of the fingers and palm and compare it with the values of the glove parameters used in [26]. The results are shown in Fig. 5. Comparing our results for isolating the unwanted vibrations at both palm and fingers to those of Dong et al., [26], we can observe that our optimum AV glove performs much better at higher frequencies and worst at lower frequencies (i.e., $<$100Hz), and attains the maximum value at 50.80Hz, which corresponds to one of the natural frequencies of the gloved hand-arm system. This observation suggests that an AV glove with the present optimum values will be an excellent candidate to isolate the unwanted vibration from power hand tools with higher excitation frequency and hence will protect workers from HAVS. On the other hand, for lower frequency hand tools, an AV glove with the optimum values by Dong et al., [26] will provide better vibration isolation.

CONCLUSION

We studied the vibration of the hand-arm system, using a bio-mechanical lumped parameter model of the system, with and without gloves. For the current analysis, the interaction between different parts of the human hand and hand-tool was considered to be linear for simplicity. These linear interactions were modeled as multiple linear springs and dampers, making the system a multi-degree of freedom system. The closed form solution for the responses of the hand-arm system was obtained using the method of harmonic balance. The obtained analytical expressions were validated using direct numerical simulations, and the results showed very good agreement. The effect of different glove parameters on the transmissibility of the palm was investigated with and without a glove. The results further suggested that the effect of the glove was not monotonous for the given frequency range. Therefore, it was necessary to analyze the glove parameter based on the application and frequency. With this motivation, we optimized the glove parameter for a frequency range with predefined upper and lower bound to minimize the overall transmissibility. We observed that for these optimum values the transmissibility at higher frequencies was minimum as compared to the values used in the earlier work. The implication here is that the obtained optimum values can be used to design AV gloves to protect workers from HAVS stemming from high frequency hand tools.

Appendix A: Expressions used in Eqs. (5) and (11)

$$[\mathbf{M}] = \begin{bmatrix} m_0 & 0 & 0 & 0 \\ 0 & m_f & 0 & 0 \\ 0 & 0 & m_p & 0 \\ 0 & 0 & 0 & m_{tf}+m_{tp}+m_H \end{bmatrix}$$

$$[\mathbf{C}] = \begin{bmatrix} c_0+c_w & 0 & -c_w & 0 \\ 0 & c_1+c_2 & -c_1 & -c_2 \\ -c_w & -c_1 & c_w+c_1+c_3 & -c_3 \\ 0 & -c_2 & -c_3 & c_2+c_3+c_s \end{bmatrix}$$

$$[\mathbf{K}] = \begin{bmatrix} k_0+k_w & 0 & -k_w & 0 \\ 0 & k_1+k_2 & -k_1 & -k_2 \\ -k_w & -k_1 & k_w+k_1+k_3 & -k_3 \\ 0 & -k_2 & -k_3 & k_2+k_3+k_s \end{bmatrix}$$

$$[\mathbf{F_{eq}}] = \begin{bmatrix} 0 \\ 0 \\ 0 \\ c_s\dot{z}+k_s\dot{z} \end{bmatrix}$$

$$[\mathbf{M_1}] = \begin{bmatrix} m_0 & 0 & 0 & 0 & 0 & 0 \\ 0 & m_f+m_{g1} & 0 & 0 & 0 & 0 \\ 0 & 0 & m_p+m_{g2} & 0 & 0 & 0 \\ 0 & 0 & 0 & m_{tp}+m_{g4} & 0 & 0 \\ 0 & 0 & 0 & 0 & m_{tf}+m_{g3} & 0 \\ 0 & 0 & 0 & 0 & 0 & m_{g5}+m_{g6}+m_H \end{bmatrix}$$

$$[\mathbf{C_1}] = \begin{bmatrix} \mathbf{C1} & \mathbf{C2} \\ \mathbf{C2^T} & \mathbf{C3} \end{bmatrix}$$

$$[\mathbf{C1}] = \begin{bmatrix} c_0+c_w & 0 & -c_w \\ 0 & c_1+c_4+c_2 & -c_1-c_4 \\ -c_w & -c_1-c_4 & c_1+c_4+c_3+c_w \end{bmatrix}$$

$$[\mathbf{C2}] = \begin{bmatrix} 0 & 0 & 0 \\ 0 & -c_2 & 0 \\ -c_3 & 0 & 0 \end{bmatrix}$$

$$[\mathbf{C3}] = \begin{bmatrix} c_3+c_5+c_7 & -c_5 & -c_7 \\ -c_5 & c_2+c_5+c_6 & -c_6 \\ -c_7 & -c_6 & c_6+c_7+c_s \end{bmatrix}$$

$$[\mathbf{K_1}] = \begin{bmatrix} \mathbf{K1} & \mathbf{K2} \\ \mathbf{K2^T} & \mathbf{K3} \end{bmatrix}$$

$$[\mathbf{K1}] = \begin{bmatrix} k_0+k_w & 0 & -k_w \\ 0 & k_1+k_4+k_2 & -k_1-k_4 \\ -k_w & -k_1-k_4 & k_1+k_4+k_3+k_w \end{bmatrix}$$

$$[\mathbf{K2}] = \begin{bmatrix} 0 & 0 & 0 \\ 0 & -k_2 & 0 \\ -k_3 & 0 & 0 \end{bmatrix}$$

$$[\mathbf{K3}] = \begin{bmatrix} k_3+k_5+k_7 & -k_5 & -k_7 \\ -k_5 & k_2+k_5+k_6 & -k_6 \\ -k_7 & -k_6 & k_6+k_7+k_s \end{bmatrix}$$

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