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Control of Electric Wheelchair Suspension System based on Biodynamic Response of Seated Human Body

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ABSTRACT

Electric wheelchair is one of the equipment to be used by the incapacitated and disable people. Constant exposure to vibration affects human comfort and health. Reducing the vibrations transmitted to the human body is important in the electric wheelchair design and becomes a healthcare industry demand. This paper deals with the study on vibration control of the electric wheelchair suspension system. A generalized model of the electric wheelchair suspension, including the biodynamic model of seated human body is presented. In order to achieve optimal suspension performance, an active control for wheelchair suspension is designed based on H-infinity control criterion. Numerical simulations are carried out to demonstrate the effectiveness of the proposed wheelchair suspension system. The simulation results show that the proposed control system can effectively attenuate the vibration amplitude and improve the wheelchair suspension performance. This control system could be used for electric wheelchair design and assist with improving human comfort.

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1. INTRODUCTION

Numerous research studies have focused on the ride comfort of vehicles which has effects on driver fatigue and health. Suspension systems are designed to reduce the transmission of vibration from road surface disturbances. Semi active and active suspension systems have been more attractive for researchers during the last several decades [1-10].

To minimize vertical vibration transmitted to a driver, an active seat suspension system is developed by Alfadhli et al. [7]. Performance of the active suspension is evaluated using experimental and simulation. Moghadam-Fard et al. [8] presented an active control of quarter car suspension system based on adaptive neuro fuzzy (ANFIS). Moaaz et al. [9] used fuzzy and PID control approach to investigate the performance of automotive active suspension system. It was found that controlled suspension can provide much better performance in the ride comfort compared with uncontrolled system. In the study by Nouby et al. [10] a quarter vehicle active suspension control model is developed. Suspension model controlled using H-infinity control approach.

Study performed in these literature [11-14] showed that human body is considered mainly as a rigid mass mounted on the suspension system. Human body exposed to vibrations is a complex dynamic system. An investigation of the dynamic response of human body helps to a better understanding of the effects of vibration on human comfort, and is important for the analysis and improvement of suspension system performance.

Modeling and analysis of the dynamic response of human body are interesting topics for research. To study the dynamic response of human body, many biodynamic models have been developed. These models could be mainly classified as lumped parameter, multi-body, and finite element models [15, 16]. For example, using beam, spring and mass elements, a 2-DOF model for human body is presented by Griffin [17]. Wei et al. [18] used two models of human body, 1-DOF and 2-DOF, to investigate the vibration transmissibility. It was observed that 2-DOF model provided better prediction. Tewari et al. [19] developed and investigated a 3-DOF model of tractor seat

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suspension. A dynamic model for a seated human body in a sitting posture is presented by Abbas et al. [20]. The vibration transmissibility and dynamic responses are evaluated. In the study conducted by Aisyah et al. [21], the suspensions seat transmissibility and seat effective amplitude transmissibility values for a seated human body exposed to vibration in tractor are investigated. Optimization based on genetic algorithms is used by Baumal et al. [22] to design and control an active suspension system. In the study by Desai et al. [23] a 2-dimensional, 20 DOF sitting posture multi-body model for seated human is developed, and model parameters are optimized by using genetic algorithm. Dong et al. [24] developed a 3-dimensional finite element model of the body-seat system to study the effect of sitting posture and seat on the dynamic response of human body.

Electric wheelchair is one of the equipment to be used by the incapacitated and disable people. The effects of vibration exposure and also longed wheelchair riding on user discomfort have been approved. Minimizing the vibrations transmitted to the wheelchair user is important in the electric wheelchair design and becomes a healthcare industry demand. It can be addressed through the suspension system design [25-27]. For example, Garcia-Mendez et al. [26], evaluated vibration exposure to wheelchair user for different types of wheelchair frames. They determined the effect of wheelchair suspension in reducing vibration transmitted to the body. In a study by Cooper et al. [27], vibrations in manual wheelchairs with and without suspension are investigated.

A thorough survey of literature indicates that although the wheelchair suspension performance is investigated, active control of wheelchair suspension and also the biodynamic response of wheelchair user are not considered. The purpose of this study is to apply suspension system in the design of wheelchair. In order to control and improve the wheelchair performance, active control of wheelchair suspension model by considering the biodynamic model of seated human body is proposed. Then, H-infinity static output feedback controller is designed to control and improve the wheelchair performance .

This paper is organized as follows. The model of a wheelchair suspension, including the seated human model, is described in section 2. Based on H-infinity control technique, active controller design is formulated. Section 3 presents the simulation results and controller performance evaluations. Finally, conclusions are given in section 4.

2. MODEL DESCRIPTION AND CONTROLLER DESIGN

2. 1. Biodynamic Model of Human Body

human body can be modeled as several rigid mass connected by sets of spring and damper. In this study, a 1-DOF model of human body is employed, proposed by Wei and Griffin in 1998 [18]. Analytical studies and experimental validations have shown that this model is suitable for studying the dynamic response of human body. In this model, the seated person is composed of a support structure "m_b" and a sprung mass "m_h", connected by spring, "k_h", and damper, "c_h". Schematic of this model is depicted in Figure 1.

2. 2. Wheelchair and Suspension model

A 2-DOF active suspension model is employed to investigate the dynamic response and control of electric wheelchair. This suspension system schema is shown in Figure 2. Sprung mass, m_s, is the mass of wheelchair chassis and seat. Unsprung mass, m_w, represents the wheel assembly mass. Tire is simulated by a spring with stiffness, k_t, and it is assumed that it always contacts with the road surface.

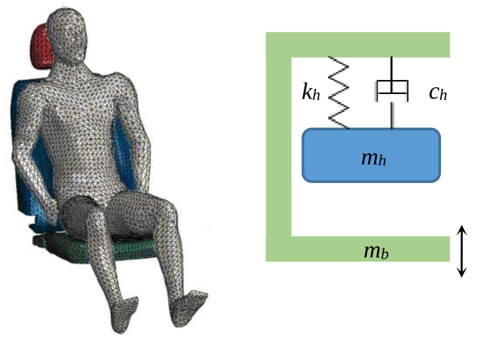

Figure 1. The biodynamic model of human body proposed by Wei et al. [13]

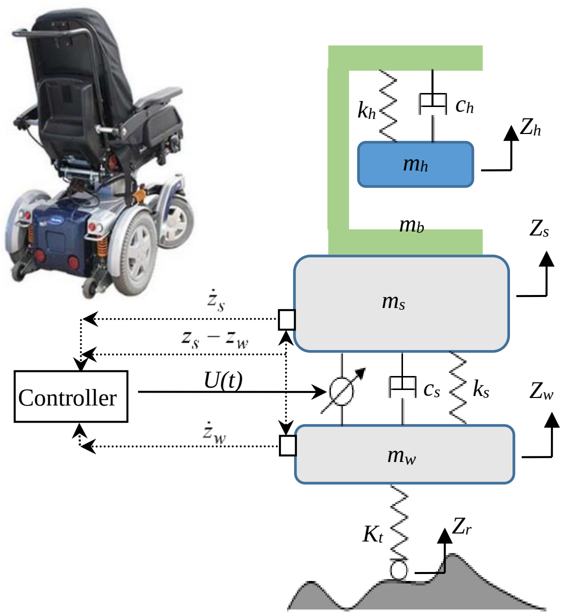

Figure 2. Wheelchair suspension model

k_s and c_s are stiffness and damping of the passive suspension component. The controller output *U(t)*, represents the input control force can be generated by the actuator.

The dynamic equation for the wheelchair suspension and human body can be derived as:

$$m_h \frac{d^2 z_h}{dt^2} = -k_h(z_h - z_s) - c_h\left(\frac{dz_h}{dt} - \frac{dz_s}{dt}\right) \tag{1-a}$$

$$(m_b + m_s)\frac{d^2 z_s}{dt^2} = k_h(z_h - z_s) + c_h\left(\frac{dz_h}{dt} - \frac{dz_s}{dt}\right)... \\ - k_s(z_s - z_t) - c_s\left(\frac{dz_s}{dt} - \frac{dz_w}{dt}\right) + U \tag{1-b}$$

$$m_w \frac{d^2 z_w}{dt^2} = k_s(z_s - z_w) + c_s\left(\frac{dz_s}{dt} - \frac{dz_w}{dt}\right)... \\ - k_t(z_w - z_r) - U \tag{1-c}$$

The state variables can be defined as: $x_1(t) = (z_h - z_s)$, $x_2(t) = dz_h / dt$, $x_3(t) = (z_s - z_w)$, $x_4(t) = dz_s / dt$, $x_5(t) = z_w$, $x_6(t) = dz_w / dt$. $w(t) = z_r$ represents road surface disturbance. The state space model for this suspension system can be written as:

$$\dot{x} = Ax + B_1 w + B_2 u \tag{2}$$

where:

$$A = \begin{pmatrix} 0 & 1 & 0 & -1 & 0 & 0 \\ -\frac{k_h}{m_h} & -\frac{c_h}{m_h} & 0 & \frac{c_h}{m_h} & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & -1 \\ \frac{k_h}{m_b + m_s} & \frac{c_h}{m_b + m_s} & \frac{-k_s}{m_b + m_s} & \frac{-c_h - c_s}{m_b + m_s} & 0 & \frac{c_s}{m_b + m_s} \\ 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & \frac{k_s}{m_w} & \frac{c_s}{m_w} & -\frac{k_t}{m_w} & -\frac{c_s}{m_w} \end{pmatrix}$$

$$B_1 = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & \frac{k_t}{m_w} \end{bmatrix}^T, B_2 = \begin{bmatrix} 0 & 0 & 0 & \frac{1}{m_b + m_s} & 0 & -\frac{1}{m_w} \end{bmatrix}^T$$

2. 3. Controller Design

To improve the suspension performance, this section is devoted to the controller design for the wheelchair suspension system. A static output feedback controller is considered as: *U=Ky*, where, y is the input of the controller. *K* and *U* are the controller gain matrix and the output of the controller, respectively. Measured signals feedback to the controller. The controller sends a signal to the actuator to generate a compensation force to eliminate vibration (Figure 2). Schematic of this control system is shown in Figure 3 [28]. The suspension deflection and also the seat and upper body velocity are measured variables which are selected as input variable to the controller. So, the control law can be expressed as:

$$U(t) = ky = \begin{bmatrix} k_1 & k_2 & k_3 \end{bmatrix} \begin{bmatrix} z_s - z_w \\ \dot{z}_s \\ \dot{z}_h \end{bmatrix} \tag{3}$$

For this suspension controller design, ride comfort and road holding are the main desired objective [6]. For this purpose, the control objectives are defined as: $\ddot{z}_h$, $\ddot{z}_s$ and, $z_w - z_r$, which are the controlled output, Z. Now, by considering the dynamic Equation (1), the control model for the wheelchair suspension can be described as:

$$\begin{pmatrix} \dot{x} \\ z \\ y \end{pmatrix} = \begin{pmatrix} A & B_1 & B_2 \\ C_1 & D_{11} & D_{12} \\ C_2 & D_{21} & D_{22} \end{pmatrix} \begin{pmatrix} x \\ w \\ u \end{pmatrix} \tag{4}$$

where:

$$C_1 = \begin{pmatrix} -\frac{\alpha_1 k_h}{m_h} & -\frac{\alpha_1 c_h}{m_h} & 0 & \frac{\alpha_1 c_h}{m_h} & 0 & 0 \\ \frac{\alpha_2 k_h}{m_b + m_s} & \frac{\alpha_2 c_h}{m_b + m_s} & \frac{-\alpha_2 k_s}{m_b + m_s} & \frac{-\alpha_2 (c_h + c_s)}{m_b + m_s} & 0 & \frac{\alpha_2 c_s}{m_b + m_s} \\ 0 & 0 & 0 & 0 & \alpha_3 & 0 \end{pmatrix}$$

$$D_{11} = \begin{pmatrix} 0 \\ 0 \\ -\alpha_3 \end{pmatrix}, D_{12} = \begin{pmatrix} 0 \\ \frac{\alpha_2}{m_b + m_s} \\ 0 \end{pmatrix}, C_2 = \begin{pmatrix} 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \end{pmatrix},$$

$$D_{21} = \begin{pmatrix} 0 \\ 0 \\ 0 \end{pmatrix}, D_{22} = \begin{pmatrix} 0 \\ 0 \\ 0 \end{pmatrix}$$

α_1, α_2, and α_3 are the weighting coefficients which represent the trade-off between the control objectives. Transfer function for the state space model of Equation (4) is obtained as:

$$P(s) = \begin{bmatrix} C_1 \\ C_2 \end{bmatrix} (sI - A)^{-1} \begin{bmatrix} B_1 & B_2 \end{bmatrix} + \begin{bmatrix} D_{11} & D_{12} \\ D_{21} & D_{22} \end{bmatrix} \\ = \begin{bmatrix} P_{11} & P_{12} \\ P_{21} & P_{22} \end{bmatrix} \tag{5}$$

For this static output feedback controller, the closed loop transfer function from the disturbance input *w(t)* to the controlled output Z, can be obtained as:

$$T_{zw}(s) = P_{11} + P_{12} K \left(I - P_{22} K\right)^{-1} P_{21} \tag{6}$$

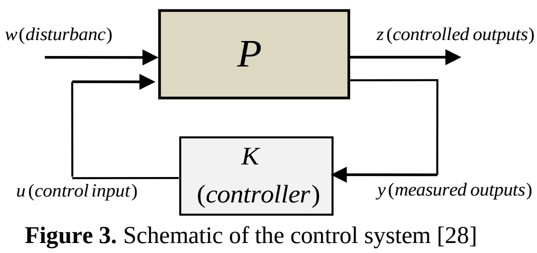

Figure 3. Schematic of the control system [28]

The active suspension controller is implemented by H-infinity control technique. The control objective is to determine a controller gain matrix $K=[k_1\ k_2\ k_3]$, in a way the system would be stable and the H-infinity norm of the closed loop transfer function $\|T_{zw}(j\omega)\|_\infty$, could be minimized. In practice, the actuator force is limited by its physical capability and should be considered in controller design. This limitation can be expressed as: $\|K\|_\infty \le K_{\max}$. Therefore, the H-infinity controller design problem for suspension can be expressed as the following constrained optimization problem [28, 29]:

$$\begin{aligned} &\min(\|T_{zw}(j\omega|k=[k_1\quad k_2\quad k_3]\ \|_\infty) \\ &\qquad s.t.:T_{zw}(s)\,is\,stable\,\&\,\|k\|_\infty \le k_{\max} \end{aligned} \tag{7}$$

This multi-objective minimization problem is formulated in MATLAB and solved by using particle swarm optimization (PSO) algorithm [30, 31].

3. SIMULATION RESULTS

In this section, in order to demonstrate the proposed controller performance, numerical simulations are conducted. The simulation parameters of the wheelchair suspension and human are listed in Table 1. In this simulation, the weighting coefficients and controller gain limitation for the actuator are considered as: $\alpha_1=\alpha_2=2$, $\alpha_3=1$, $\|K\|_\infty \le 200$ and $\|K\|_\infty \le 3000$, respectively. Optimization is performed using the PSO algorithm. H-infinity norms of transfer function are obtained as: $\|T_{zw}(j\omega)\|_\infty = 10376$ and $\|T_{zw}(j\omega)\|_\infty = 5467.7$. Also, the optimal controller gains are obtained as:

$$\begin{aligned} K_{opt,1} &= [-200\quad -200\quad 200]\quad st.\|K\|_\infty \le 200 \\ K_{opt,2} &= [142.48\quad -3000\quad 3000]\quad st.\|K\|_\infty \le 3000 \end{aligned} \tag{8}$$

The frequency responses of closed loop system (active suspension with optimal control gains $K_{opt,1}$ and $K_{opt,2}$) for upper body acceleration, lower body acceleration and tire deflection are compared with those of open loop system (passive suspension system without controller), and are depicted in Figures 4-6, respectively. Figures 4 and 5 present the frequency responses of the upper and lower body acceleration, respectively. As it can be seen, the proposed control system reduces body acceleration more effectively compared to the uncontrolled system especially in the resonance regions (Around 2.63, and 10.5 *Hz*).

In the resonance region (Around 10.5 *Hz*), the controller attenuates the upper body acceleration around 15% for controlled system with control gain $K_{opt,1}$, and also 52% for system with higher control gain $K_{opt,2}$. Also, about 16 and 56% amplitude reduction for the lower body acceleration is observed, compared with the closed loop system. As it can be seen, the best control performance has been achieved by using the optimal control gain $K_{opt,2}$. As expected, the control performance can be improved by using the higher control gain.

Figure 6 presents frequency responses of tire deflection. At resonance frequencies, around 2.63, and

TABLE 1. Parameters of the wheelchair and human body

Parameter	Unit	Value
m_h	kg	43.4
m_b	kg	8.8
m_s	kg	20
m_w	kg	30
c_h	N.s/m	1485
c_s	N.s/m	150
k_h	N/m	44130
k_s	N/m	31000
k_t	N/m	100000

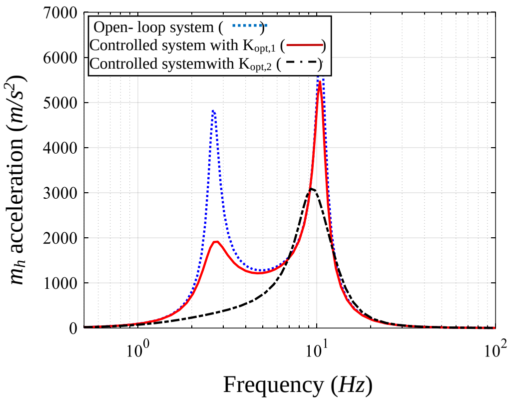

Figure 4. Frequency response of upper body acceleration

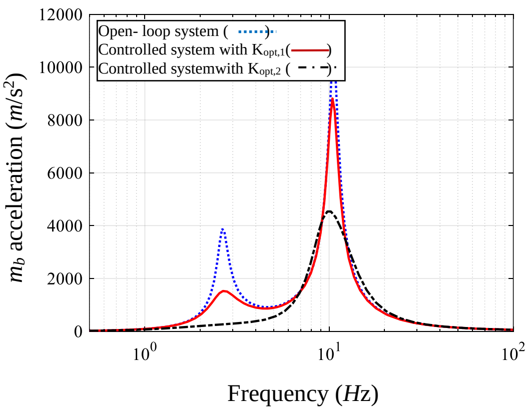

Figure 5. Frequency response of lower body acceleration

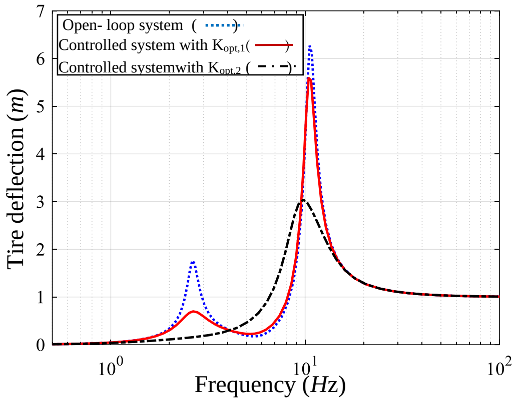

Figure 6. Frequency response of tire deflection

10.5 *Hz*, the active controller provides a significant vibration reduction. Comparing the controlled and uncontrolled system shows that the maximum amplitudes are attenuated 11 and 52% around the resonance (10.5 *Hz*). The maximum values of frequency responses for open loop and closed loop system are also listed in Table 2. The simulation results presented in Figures 4-6 and also Table 2 indicate that active suspension performance can be substantially improved by employing the proposed control strategy.

Furthermore, the optimal control gains are obtained for five values of the controller gain limitation. For obtained optimal control gains, the frequency responses of the upper body acceleration and also tire deflection are shown in Figures 7(a) and 7(b). As expected, the control performance can be improved by using the higher control gain. It is clear that the actuator force is limited by its physical capability and also increasing the controller gain more than a limit does not produce significant difference in optimal solution (see controlled system with $\|K\|_{\infty} \leq 5000$ and $\|K\|_{\infty} \leq 10000$). As a result, increasing the controller gain limitation, only to a given limit, is reasonable and of engineering justification.

Also, the simulations for controlled system with control gain $K_{opt,2}$ are performed in the time domain under random road excitation displacement. The road excitation displacement is shown in Figure 8. The simulation results for upper body acceleration, lower body acceleration and tire deflection are illustrated in Figures 9-11, respectively. It is seen from these figures that the proposed control system significantly reduces the vibration amplitude compared with the uncontrolled suspension system. The Root Mean Square (RMS) values of the time domain responses under the random road disturbance are also listed in Table 3. The decrease in the RMS values of the responses for active suspension is observed. Obviously, the proposed control system is effective and can provide much better performance compared to uncontrolled system.

TABLE 2. The maximum values of the frequency responses for controlled and uncontrolled system

	Uncontrolled system	Controlled system with $K_{opt,1}$	Improvement %	Controlled system with $K_{opt,1}$	Improvement %
Upper body acceleration (m/s^2)	6.38e3	5.44e3	15	3.07e3	52
Lower body acceleration (m/s^2)	1.04e4	8.7e3	16	4.53e3	56
Tire deflection (m)	6.26	5.57	11	3.01	52

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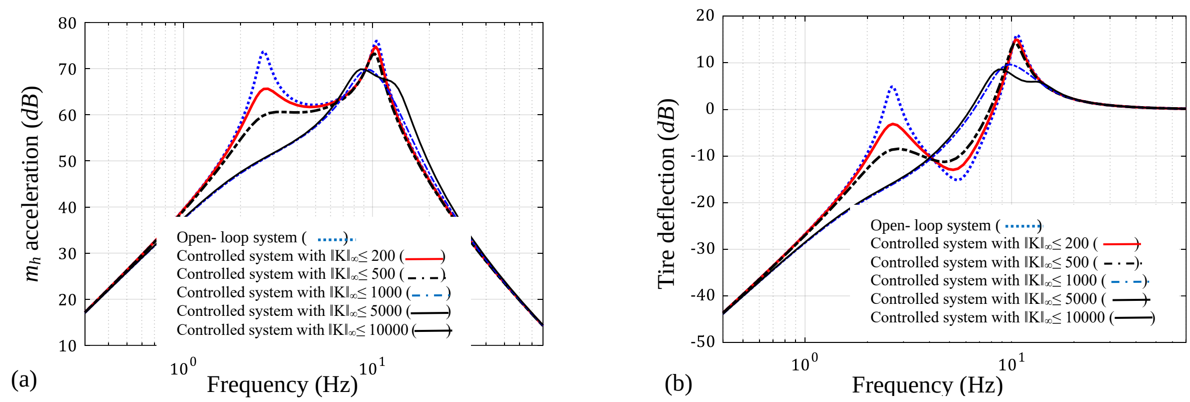

Figure 7. Frequency responses for different controller gain limitations. (a): upper body acceleration, and (b): tire deflection

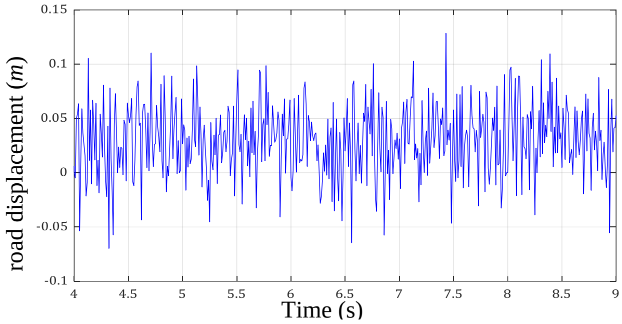

Figure 8. Road excitation displacement

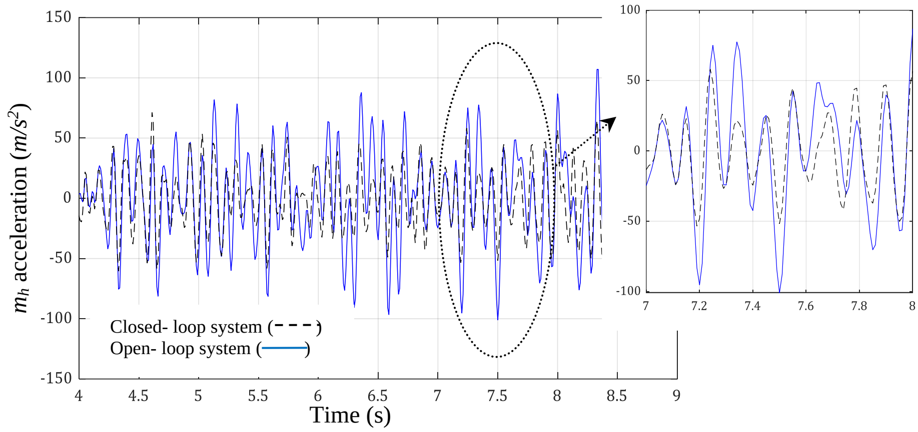

Figure 9. Time response of upper body acceleration under road excitation displacement

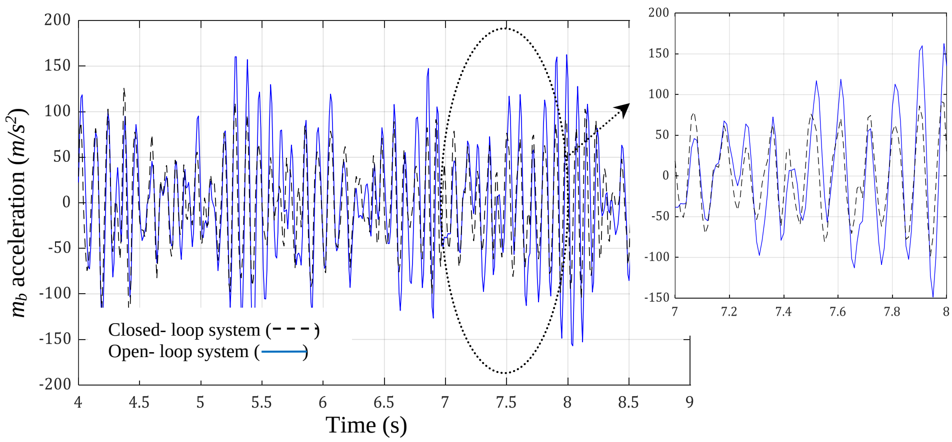

Figure 10. Time response of lower body acceleration under road excitation displacement

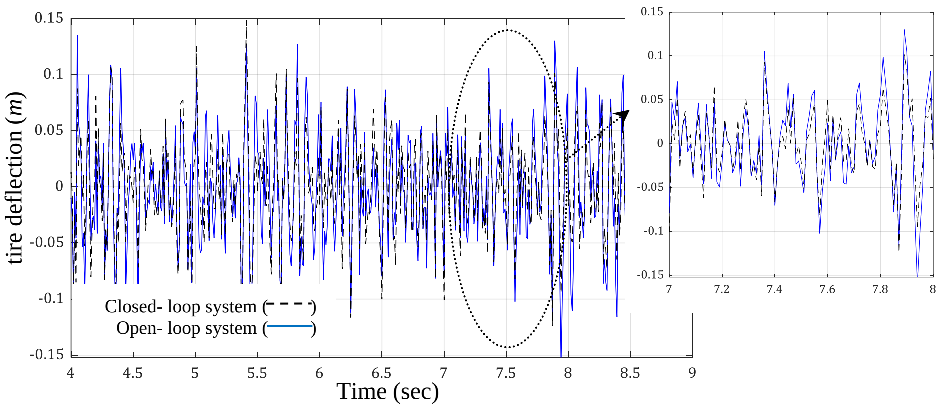

Figure 11. Time response of tire deflection under road excitation displacement

TABLE 3. RMS values of the wheelchair suspension response under road excitation displacement

	Uncontrolled System	Controlled System	Improvement %
Upper Body Acceleration	39.41	26.58	32
Lower Body Acceleration	57.22	41.86	27
Tire Deflection	0.047	0.042	11

4. CONCLUSION

In this paper, vibration control of an electric wheelchair suspension system has been evaluated. A 1-DOF model of human body has been employed in the design of active wheelchair suspension. A model of the wheelchair suspension, including the biodynamic model of seated human body presented. The static output feedback controller based on H-infinity control criterion was designed to control and improve the wheelchair performance. It has been demonstrated that the control system proposed in this study has significantly suppressed the vibration amplitude and improved the suspension performances. Results of this study could potentially help in the electric wheelchairs design and assist with improving ride quality and wheelchairs user health.

5. REFERENCES

1. Toloei, A., Zarchi, M., Attaran, B., "Numerical Survey of Vibrational Model for Third Aircraft based on HR Suspension System Actuator Using Two Bee Algorithm Objective Functions", ***International Journal of Engineering, Transactions C: Aspects***, Vol. 30, No. 6, (2017), 887-894. doi: 10.5829/ije.2017.30.06c.09
2. Rajamani, R., Larparisudthi, S., "On invariant points and their influence on active vibration isolation", ***Mechatronics***, Vol. 14, (2004), 175-198. doi: 10.1016/S0957-4158(03)00029-1.
3. Miaomiao, D., Dingxuan, Z., Yang, B., Lili, W., "Terminal sliding mode control for full vehicle active suspension systems", ***Journal of Mechanical Science and Technology***, Vol. 32, No. 6, (2018), 2851-2866. doi: 10.1007/s12206-018-0541-x.
4. Gohrle, C., Schindler, A., Wagner, A., Sawodny, O., "Design and vehicle implementation of preview active suspension controllers", ***IEEE Transactions on Control Systems Technology***, Vol. 22, No. 3, (2014), 1135-1142. doi: 10.1109/TCST.2013.2272342
5. Pang, H., Chen, Y., Chen, J., Liu, X., "Design of LQG controller for active suspension without considering road input signals", ***Shock and Vibration***, Vol. 2017, (2017), doi: 10.1155/2017/6573567
6. Du, H., Lam, J., Sze, K.Y., "Non-fragile output feedback H∞ vehicle suspension control using genetic algorithm", ***Engineering Applications of Artificial Intelligence***, Vol. 16, (2003), 667–680. doi: 10.1016/j.engappai.2003.09.008
7. Alfadhli, A., Darling, J., Hillis, A.J., "The control of an active seat with vehicle suspension preview information", ***Journal of Vibration and Control***, Vol. 24, No. 8, (2017), 1412-1426. doi: 10.1177/1077546317698285
8. Moghadam-Fard, H., Samadi, F., "Active Suspension System Control Using Adaptive Neuro Fuzzy (ANFIS), Controller", ***International Journal of Engineering, Transactions C: Aspects***, Vol. 28, No. 3, (2015), 396-401 doi: 10.5829/idosi.ije.2015.28.03c.08
9. Moaaz, Ahmad O., Ghazaly, Nouby M., "Fuzzy and PID Controlled Active Suspension System and Passive Suspension System Comparison", ***International Journal of Advanced Science and Technology***, Vol. 28, No. 16, (2019), 1721-1729.
10. Ghazaly, N., Sharkawy, A. Ali, A. & Abdel-Jaber, G., "H∞ Control of Active Suspension System for a Quarter Car Model", ***International Journal of Vehicle Structures and Systems***, Vol. 8. (2016), 35-40. doi: 10.4273/ijvss.8.1.07
11. Bovenzi, M., Hulshof, C.T., "An updated review of epidemiologic studies on the relationship between exposure to whole-body vibration and low back pain (1986-1997)", ***International Archives of Occupational and Environmental Health***, Vol. 72, No. 6, (1999), 351-365. https://doi.org/10.1007/s004200050387
12. Tiemessen, I.J., Hulshof, C.T.J., Frings-Dresen, M.H.W., "An overview of strategies to reduce whole-body vibration exposure on drivers: a systematic review", ***International Journal of***

Industrial Ergonomics, Vol. 37, No. 3, (2007), 245-256. https://doi.org/10.1016/j.ergon.2006.10.021

13. Hill, T.E., Desmoulin, G.T., Hunter, C.J., "Is vibration truly an injurious stimulus in the human spine?" ***Journal of Biomechanics***., Vol.42, No. 16 (2009), 2631-2635. https://doi.org/10.1016/j.jbiomech.2009.10.001
14. Salvendy, G., "Handbook of Human Factors and Ergonomics", 2nd Edition, John Wiley & Sons, Inc., New York, (2005).
15. Zhou, Z., Griffin, M.J., "Response of the seated human body to whole-body vertical vibration: biodynamic responses to mechanical shocks", ***Ergonomics***, Vol. 60, No. 3, (2017), 333-346. doi: 10.1080/00140139.2016.1179793
16. Toward, M.G.R., Griffin, M.J., "The transmission of vertical vibration through seats: Influence of the characteristics of the human body", ***Journal of Sound and Vibration***, Vol. 330, No. 26, (2011), 6526–6543. doi: 10.1016/j.jsv.2011.07.033
17. Kitazaki, S., Griffin, M.J., "A modal analysis of whole-body vertical vibration, using a finite element model of the human body", ***Journal of Sound and Vibration***, Vol. 200, No. 1, (1997), 83-103. doi: 10.1006/jsvi.1996.0674
18. Wei, L., Griffin, M.J., "The Prediction of seat transmissibility from measures of seat impedance", ***Journal of Sound and Vibration***, Vol. 214, No.1, (1998), 121-137. doi: 10.1006/jsvi.1998.1540
19. Tewari, V. K., Prasad, N., "Three-DOF Modelling of Tractor Seat-Operator System", ***Journal of Terramechanics***, Vol. 36, No. 4, (1999), 207-219. doi: 10.1016/S0022-4898(99)00008-7
20. Abbas, W., Abouelatta, O.B., El-Azab, M., Elsaidy, M., Megahed, A.A., "Optimization of Biodynamic Seated Human Models Using Genetic Algorithms", ***Engineering***, Vol. 2, (2010), 710-719. doi: 10.4236/eng.2010.29092
21. Adam, S. A. Abdul Jalil, N.A., "Vertical Suspension Seat Transmissibility and SEAT Values for Seated Person Exposed to Whole-body Vibration in Agricultural Tractor Preliminary Study", ***Procedia Engineering***, Vol. 170, (2017), 435- 442. doi: 10.1016/j.proeng.2017.03.070
22. Baumal, A. E., McPhee, J. J., Calamai, P. H., "Application of Genetic Algorithms to the Design Optimization of an Active Vehicle Suspension System", ***Computer Methods in Applied Mechanics and Engineering***, Vol. 163, No. 1, (1998), 87-94. doi: 10.1016/S0045-7825(98)00004-8
23. Desai, R., Guha, A., Seshu, P., "Multibody Biomechanical Modelling of Human Body Response to Direct and Cross Axis Vibration", ***Procedia Computer Science***, Vol. 133, (2018), 494–501. doi: 10.1016/j.procs.2018.07.062
24. Dong, R., He, L., Du, W., Cao, Z., Huang, Z., "Effect of sitting posture and seat on biodynamic responses of internal human body simulated by finite element modeling of body-seat system", ***Journal of Sound and Vibration***, Vol. 438, (2019), 543-554. doi: 10.1016/j.jsv.2018.09.012
25. Ding, D., Cooper, R. A., "Electric powered wheelchairs", ***IEEE Control Systems Magazine***, Vol. 25, No. 2, (April 2005), 22-34. doi: 10.1109/MCS.2005.1411382
26. Garcia-Mendez Y., Pearlman L. J., Boninger L.M., Cooper A.R., "Health risks of vibration exposure to wheelchair users in the community", ***The Journal of Spinal Cord Medicine***, Vol. 36, No.4 (2013), 365-375. doi: 10.1179/2045772313Y.0000000124
27. Cooper R. A., , Wolf E., Fitzgerald Sh.G., , Boninger M. L., Ulerich R., Ammer W.A., "Seat and Footrest Shocks and Vibrations in Manual Wheelchairs With and Without Suspension", Arch Phys Med Rehabil, Vol. 84, (2003), 96-102. doi: 10.1053/apmr.2003.50069
28. Farshidianfar, A., Saghafi, A., Kalami, S.M., Saghafi, I., "Active vibration isolation of machinery and sensitive equipment using H∞ control criterion and particle swarm optimization method", ***Meccanica***, Vol. 47, (2012), 437-453. doi: 10.1007/s11012-011-9451-z
29. Skogestad, S., Postlethwaite, I., "Multivariable feedback control: analysis and design", 2nd ed., Wiley Interscience, New York, (2005).
30. Schutte, J.F., Groenwold, A.A., "A study of global optimization using particle swarms", ***Journal of Global Optimization***, Vol. 31, (2005), 93–108. doi: 10.1007/s10898-003-6454-x
31. Zhan, Z., Zhang, J., Li, Y., Chung, H. S., "Adaptive Particle Swarm Optimization", ***IEEE Transactions on Systems, Man, and Cybernetics, Part B (Cybernetics)***, Vol. 39, No. 6, (2009), 1362-1381. doi: 10.1109/TSMCB.2009.2015956

Persian Abstract

چکیده

ویلچر برقی از جمله تجهیزات پرکاربردی است که توسط معلولین و افراد ناتوان مورد استفاده قرار می گیرد. قرار گرفتن مداوم بدن انسان در معرض لرزش همواره به عنوان یک عامل آزار دهنده مطرح می شود که تاثیراتی منفی بر راحتی و سلامت انسان دارد. کاهش ارتعاش منتقل شده به بدن انسان نقشی تعیین کننده و مهم در طراحی ویلچر داشته و به یک تقاضای مهم در حوزه مراقبت های بهداشتی تبدیل شده است. در این پژوهش، به منظور بهبود عملکرد ویلچرهای برقی، کنترل ارتعاش در سیستم تعلیق ویلچر و با درنظر گرفتن مدل بیودینامیکی بدن انسان ارائه شده است. برای دستیابی به عملکرد بهینه در سیستم تعلیق ویلچر، کنترل فعالی بر اساس معیار کنترل H∞ طراحی و مورد ارزیابی قرارگرفته‌است. نتایج شبیه سازی نشان می دهد که سیستم کنترلی پیشنهادی به طور موثر سبب کاهش پاسخ ارتعاشی بدن و درنتیجه بهبود عملکرد سیستم تعلیق می شود. بکارگیری این سیستم کنترلی در طراحی سیستم تعلیق ویلچرهای برقی به منظور بهبود راحتی سواری پیشنهاد می شود.