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Analytical Investigation of Tire-Road Contact Characteristics for Wheelchair Robots Safely Running

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ABSTRACT

To effectively improve the tire grounding behaviors of wheelchair robots, an analytical method is proposed to analyze and optimize the tire grounding safety. Firstly, taking the cushion and tires as the vibration isolation elements with stiffness and damping, the vertical vibration model of the human-wheelchair robot is established. Then, taking the random excitation as the typical input, the formulae of the TDD (tire dynamic deflection) frequency response function H and the RMS (root mean square) response are derived and the response coefficient λ is proposed. Moreover, the influence laws of system parameters on H and λ are revealed. Thirdly, based on λ, the analytical optimization model for the cushion system damping ratio ξ_2 is established. Finally, a case study and numerical simulation were carried out. The results show that the relative deviation of the cushion optimal damping is about 0.3%.

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1. INTRODUCTION

Wheelchair robot is a kind of mobile robots [1, 2]. Wheelchair robot is the advanced product of wheelchairs. Various wheelchair robots belong to medical devices. They are widely used in hospitals and rehabilitation institutions [3].

On relatively flat roads, wheeled mobile mode is quite advantageous [4, 5]. The shape and structure of wheels depend on the nature of the ground and the carrying capacity of wheelchair robots. At present, wheelchair robots are mostly equipped with inflatable tires. The road excitation decreases the recovery rate of rehabilitation patients. More seriously, the excessive vibration reduces the tire grounding safety [6]. A good tire grounding is the guarantee for wheelchair robot running safely. In recent years, the enormous demand for wheelchairs leads to higher performance requirements [7-9]. How to improve effectively the tire grounding safety of wheelchair robots has aroused a growing public attention [10].

To better study the grounding behaviors of tires, scholars focus on the related research, for example, the tire model and the tire characteristics. Geng et al. proposed a research approach specifically designed for the measurement, identification and modelling of damping in pneumatic tires [11]. Dąbek et al. [12] researched tire models for studies of wheeled mobile robot dynamics. Levratti et al. [13] made an experimental evaluation of a novel tire workshop assistant robot. These studies provide useful references for improving the tire grounding safety of wheelchair robots. However, there are few studies on the analytical safety analysis and optimization of tire grounding behaviors for wheelchair robots undergoing road irregularities.

In this paper, in order to improve effectively the tire grounding behaviors for wheelchair robots under the random excitation, an analytical method is proposed to analyze and optimize the tire grounding safety.

2. HUMAN-WHEELCHAIR ROBOT MODEL

A simplified model of the human-wheelchair robot was created, as shown in Figure 1 [14]. In Figure 1, m_2 and m_1 are the human body mass and the wheelchair body mass, respectively; C_2 and C_1 are the damping of the cushion

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and the tire, respectively; K_2 and K_1 are stiffness coefficients of the cushion and the tire system, respectively; z_2 and z_1 are the corresponding displacements; q is the road excitation.

The differential equation set of the vibration model can be expressed as follows:

$$\begin{cases} m_2\ddot{z}_2 + C_2(\dot{z}_2 - \dot{z}_1) + K_2(z_2 - z_1) = 0 \\ m_1\ddot{z}_1 + C_2(\dot{z}_1 - \dot{z}_2) + K_2(z_1 - z_2) + C_1(\dot{z}_1 - \dot{q}) \\ +K_1(z_1 - q) = 0 \end{cases} \tag{1}$$

The random road model can be expressed as follows [14]:

$$\dot{q}(t) = -2\pi n_{00} u q(t) + 2\pi n_0 \sqrt{G_q(n_0) u}\, w(t) \tag{2}$$

where, n_0 represents the reference space frequency and n_0=0.1 m^{-1}; u represents the running speed; n_{00} represents the lower cut-off space frequency and n_{00}=0.011 m^{-1}; t represents time; $\dot{q}(t)$ represents the road excitation velocity; $w(t)$ represents the Gaussian white noise with zero mean; $G_q(n_0)$ represents the road roughness coefficient.

3. ANALYTICAL FORMULAE OF TIRE DYNAMIC DEFLECTION RESPONSES

The characteristic parameters are adopted as follows [14]:

$$r_k = \frac{K_1}{K_2},\ r_m = \frac{m_2}{m_1},\ \omega_2 = \sqrt{\frac{K_2}{m_2}},\ \omega_1 = \sqrt{\frac{K_1}{m_1}},\ \xi_2 = \frac{C_2}{2\sqrt{m_2 K_2}},$$

$$\xi_1 = \frac{C_1}{2\sqrt{m_1 K_1}},\ \eta = \frac{\omega_1}{\omega_2} = \sqrt{r_k r_m}$$

where, ω_1 and ω_2 are the natural circular frequencies; ξ_1 and ξ_2 are the damping ratios of the tire system and the cushion system, respectively; r_k is the stiffness ratio of the tire stiffness to the cushion stiffness; r_m is the mass ratio of the human body mass to the wheelchair body mass.

Based on the model in Figure 1, the tire dynamic deflection (TDD) f_d is defined as follows:

$$f_d = z_1 - q \tag{3}$$

Based on Equations (1) and (3), the frequency response function $H(j\omega)$ between the TDD f_d and the road velocity excitation $\dot{q}$ can be obtained as follows:

$$H(j\omega) = \frac{j\omega\cdot[-\omega_2^2(1+r_m)] - \omega^2\cdot[-2(1+r_m)\xi_2\omega_2] - j\omega^3\cdot(-1)}{\omega_2^4\eta^2 + j\omega\cdot 2\omega_2^3\eta(\xi_1+\xi_2\eta) - \omega^2\cdot(1+\eta^2+r_m+4\xi_2\xi_1\eta)\omega_2^2 - j\omega^3\cdot 2(\xi_2+\xi_1\eta+\xi_2 r_m)\omega_2 + \omega^4} \tag{4}$$

The RMS TDD f_d can be expressed as follows:

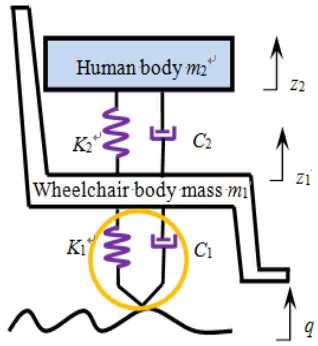


Figure 1. The vibration model of the wheelchair robot

$$\sigma_{f_d} = \sqrt{\frac{1}{2\pi}\int_{-\infty}^{+\infty} 2\pi^2 G_q(n_0) n_0^2 u |H(j\omega)|^2 d\omega} \tag{5}$$

By the integral calculation, Equation (5) can be further expressed as follows:

$$\sigma_{f_d} = \sqrt{G_q(n_0) n_0^2 v \pi^2 \frac{(A_0A_3 - A_1A_2) + A_1(-2B_1 - B_2^2) - A_3B_1^2}{A_0A_3^2 + A_1^2 - A_1A_2A_3}} \tag{6}$$

where, $A_0 = \omega_2^4\eta^2$, $A_1 = 2\omega_2^3\eta(\xi_1+\xi_2\eta)$, $A_2 = (1+\eta^2+r_m+4\xi_2\xi_1\eta)\omega_2^2$, $A_3 = 2(\xi_2+\xi_1\eta+\xi_2 r_m)\omega_2$, $B_1 = -\omega_2^2(1+r_m)$, $B_2 = -2(1+r_m)\xi_2\omega_2$, $\eta = \sqrt{r_k r_m}$.

The identical transformation of Equation (6) can be expressed as follows:

$$\sigma_{f_d} = \lambda\sqrt{G_q(n_0) n_0^2 u} \tag{7}$$

where, the coefficient λ is defined as the TDD coefficient of wheelchair robots and its unit is s$^{0.5}$.

According to Equation (7), the coefficient λ can be expressed as follows:

$$\lambda = \pi\sqrt{\frac{(A_0A_3 - A_1A_2) + A_1(-2B_1 - B_2^2) - A_3B_1^2}{A_0A_3^2 + A_1^2 - A_1A_2A_3}} \tag{8}$$

4. INFLUENCE ANALYSIS OF SYSTEM PARAMETERS ON THE TIRE GROUNDING SAFETY

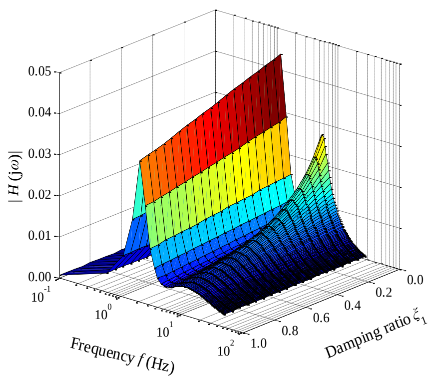
To effectively improve the tire grounding behaviors for wheelchair robots under the random excitation, the influence laws of system parameters on the frequency response function H and the TDD coefficient λ are revealed in this section. The values of the physical parameters for the human-wheelchair system are shown in Table 1. Based on Table 1, the values of the characteristic parameters were calculated, as shown in Table 2. Based on the values for the human-wheelchair robot system in Table 2, using Equations (4) and (8), the influences of ξ_1, ξ_2, r_m, r_k, and f_2 on the tire grounding safety were calculated, as shown in Figures 2~6.

TABLE 1. The values of the physical parameters

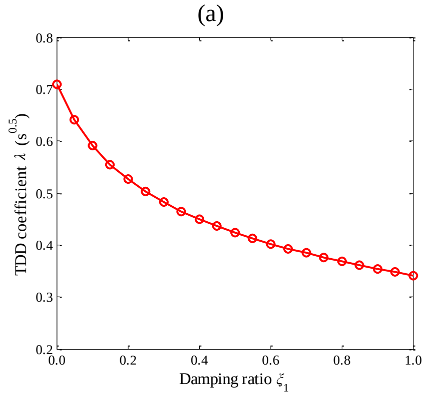
Parameter	Value
m_2 (kg)	75
m_1 (kg)	25
C_2 (Ns/m)	438
K_2 (N/mm)	16
K_1 (N/mm)	80
C_1 (Ns/m)	566

TABLE 2. The values of the characteristic parameters

Parameter	Value
ξ_2	0.2
ξ_1	0.2
r_m	3
r_k	5
f_2 (Hz)	2.4
η	3.9

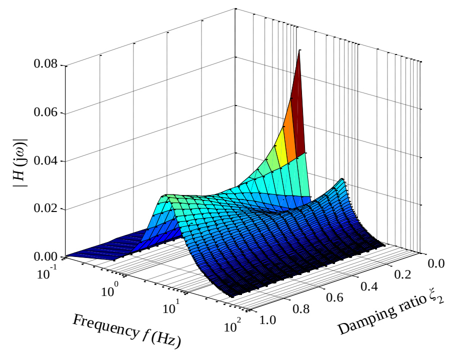


(a)



(b)

Figure 2. The influence of the tire system damping ratio ξ_1 on the tire grounding safety: (a) the surface of $|H(\mathrm{j}\omega)|$ versus the frequency f and the damping ratio ξ_1, (b) the curve of the response coefficient λ versus the damping ratio ξ_1



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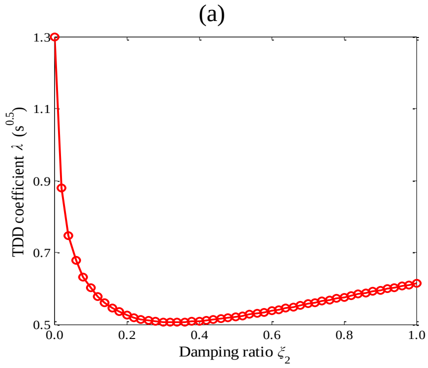
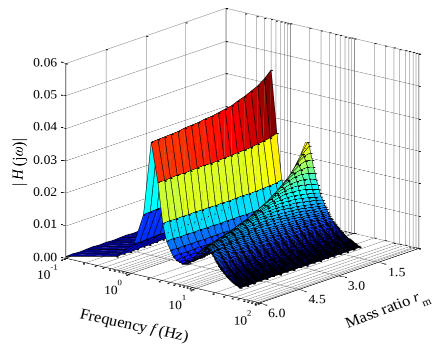


(b)

Figure 3. The influence of the cushion system damping ratio ξ_2 on the tire grounding safety: (a) the surface of $|H(\mathrm{j}\omega)|$ versus the frequency f and the damping ratio ξ_2, (b) the curve of the response coefficient λ versus the damping ratio ξ_2



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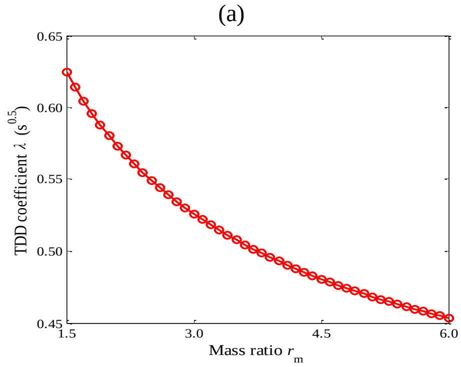
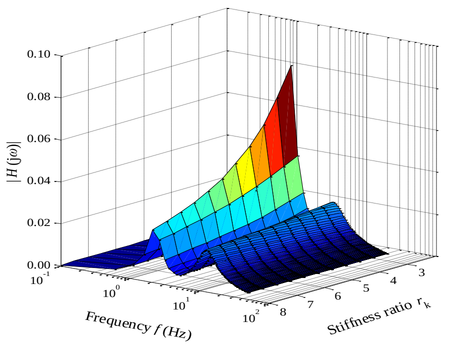


(b)

Figure 4. The influence of the mass ratio r_m on the tire grounding safety: (a) the surface of $|H(\mathrm{j}\omega)|$ versus the frequency f and the mass ratio r_m, (b) the curve of the response coefficient λ versus the mass ratio r_m



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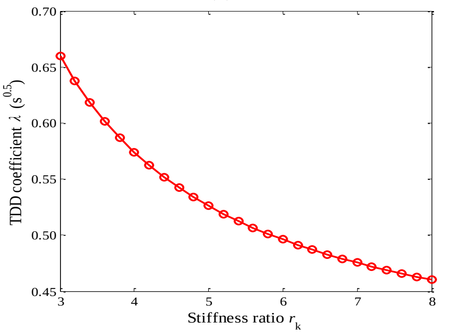
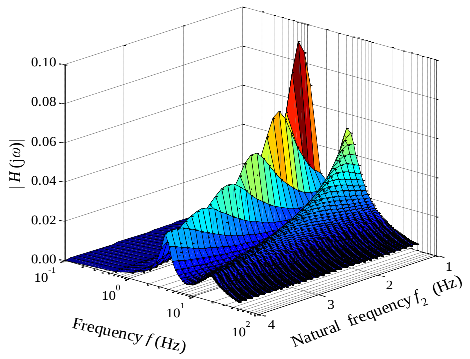
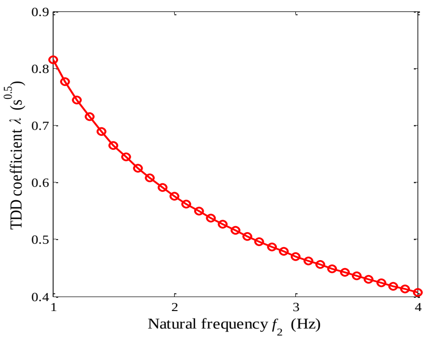


(b)

Figure 5. The influence of the stiffness ratio r_k on the tire grounding safety: (a) the surface of $|H(j\omega)|$ versus the frequency f and the stiffness ratio r_k, (b) the curve of the response coefficient λ versus the stiffness ratio r_k



(a)



(b)

Figure 6. The influence of the natural frequency f_2 on the tire grounding safety: (a) the surface of $|H(j\omega)|$ versus the frequency f and the natural frequency f_2, (b) the curve of the response coefficient λ versus the natural frequency f_2

From Figure 2(a), it can be seen that the resonance frequencies of the human body and the wheelchair body are 2.4 Hz and 9.0 Hz, respectively. Moreover, increasing the tire system damping ratio ξ_1 is beneficial to the attenuation of the resonance peak of $|H(j\omega)|$. Figure 2(b) shows that with the increase of the damping ratio ξ_1, the TDD coefficient λ nonlinearly decreases. The results prove that using the larger damping tire is beneficial to improve the tire grounding safety. Figure 3(a) depicts that increasing the cushion system damping ratio ξ_2 helps to attenuate the resonance peak of $|H(j\omega)|$, however, it causes the amplitude increase in the non-resonant region between 2.4 Hz and 9.0 Hz. Figure 3(b) illustrates that with the increase of the damping ratio ξ_2, the coefficient λ sharply decreases first and then slowly increases. Thus, when the value of ξ_2 is too large or too small, it is not conducive to improving the tire grounding safety. Figure 4 proves that increasing the mass ratio r_m is conducive to improving the grounding safety. From Figure 5(a), it can be seen that increasing the stiffness ratio r_k can effectively suppress the resonance peak at the resonance frequency of the human body. Figure 5(b) shows that with the increase of the stiffness ratio r_k, the TDD coefficient λ nonlinearly decreases. Thus, increasing the stiffness ratio r_k can help to improve the tire grounding safety. From Figure 6(a), it can be seen that with the increase of the natural frequency f_2, the low frequency resonance peak moves to the right and sharply decrease. Figure 6(b) illustrates that is the TDD coefficient λ is nonlinear with the natural frequency f_2 and the greater the natural frequency, the smaller the coefficient λ is. Thus, increasing the natural frequency f_2 can also help to improve the tire grounding safety.

5. ANALYTICAL OPTIMIZATION METHOD

This study selects ξ_2 as the optimization variable. The optimization objective is to minimize λ. This optimization problem can be expressed as follows:

$$\min\{J(\xi_2)\} = \min\{\lambda\} \tag{9}$$

The following constraint must be satisfied:

$$0 < \xi_2 < 1 \tag{10}$$

Take the derivative of the TDD coefficient λ with respect to ξ_2 and let the derivative equal zero, obtain a 4 order equation about ξ_2:

$$T_4\xi_2^4 + T_3\xi_2^3 + T_2\xi_2^2 + T_1\xi_2 + T_0 = 0 \tag{11}$$

where, $T_0 = -\xi_1^2 r_m(4\xi_1^2 + r_k r_m)$, $T_1 = -2\xi_1 r_m \eta(4\xi_1^2 + r_m + 1)$,

$$T_2 = 4\xi_1^2(4\xi_1^2 r_m + 4\xi_1^2 + r_m^2 r_k + 2r_m r_k - r_m^2 - 2r_m - 1) + (2r_m r_k - r_m^2 r_k^2 + 2r_m^2 r_k - r_m^3 - 3r_m^2 - 3r_m - 1),$$

$T_3 = 8\xi_1\eta(r_m + 1)(4\xi_1^2 + r_m r_k)$,

$T_4 = 4r_m r_k (r_m + 1)(4\xi_1^2 + r_m + 1)$, $\eta = \sqrt{r_k r_m}$

The optimum damping C_{2op} of the cushion system can be calculated by following expression:

$$C_{2op} = 2\xi_{2op}\sqrt{K_2 m_2} \tag{12}$$

6. CASE STUDY AND NUMERICAL SIMULATION VERIFICATION

A case study and numerical simulation verification were carried out in this section. The system parameters of a commercially available wheelchair robot are as follows: K_2=16 N/mm, K_1=80 N/mm, m_1=25 kg, C_1=566 Ns/m. According to the average weight of adults, selecting m_2=75 kg. The running condition is as follows: u=1.6 m/s, the cement road roughness coefficient $G_q(n_0)=256\times10^{-6}$ m^{-3}.

6. 1. Case Study Based on the above analytical optimization method in section 5, the optimal damping ratio ξ_{2op}=0.33 and the optimal damping C_{2op}=727Ns/m for the cushion system. According to Equation (11), when the wheelchair robot runs on the cement road with $G_q(n_0)=256\times10^{-6}$m^{-3} and u=1.6 m/s, the RMS TDD values under different values of ξ_2 can be calculated. The RMS TDD reaches the minimum when the damping ratio ξ_2=0.33 and the minimum is $[\sigma_{fd}]_{min}$=1.0mm. In addition, according to the analytical optimization results, it can be seen that the optimal damping ratio of the cushion system is about 0.3, which avoids the blindness of traditionally choosing the damping ratio between 0~1. It is worth noting that the range of the cushion system damping ratio for ride comfort is about 0.25~0.45. Thus, the cushion with ξ_{2op}=0.33 does not reduce ride comfort.

6. 2. Numerical Simulation Verification The time domain displacement q generated by the random road model is used as the simulation input. For the numerical simulation optimization, the optimization objective is to minimize the RMS TDD σ_{fd}. The cushion system damping C_2 is taken as the optimization variable. The genetic algorithm in Matlab software was selected as the optimization algorithm. When σ_{fd} reaches the minimum 1.0 mm, C_2=725 Ns/m. Thus, the optimal damping is C_{2op}=725 Ns/m. The relative deviation between the value of C_{2op} calculated from the analytical method and that from the numerical simulation method is 0.3%. The comparison result shows that the analytical optimization method is effective. The analytical optimization model has nothing to do with u and $G_q(n_0)$, so it is not necessary to establish a numerical simulation model for multiple simulation and optimization. In addition, compared with taking the specific parameter C_2 as the optimization variable, the analytical optimization method takes the dimensionless damping ratio ξ_2 as the optimization variable, which has more theoretical guidance value.

7. CONCLUSIONS

This paper proposed an analytical method to analyze and optimize the tire grounding safety. The results of this study demonstrate the following: The TDD coefficient λ is only determined by the parameters of the human-wheelchair robot system. For wheelchair robots running on random roads, the smaller the λ value is, the better the tire grounding safety is. When the value of ξ_2 is too large or too small, it is not conducive to improving the tire grounding safety. An analytical optimization method for the cushion system damping ratio ξ_2 was established. The comparison result shows that the analytical optimization method is effective.

8. ACKNOWLEDGMENT

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9. REFERENCES

1. Kanjanawanishkul, K., "Path following and velocity optimizing for an omnidirectional mobile robot", ***International Journal of Engineering, Transactions A: Basics***, Vol. 28, No. 4, (2015), 537–545.
2. Korayem, M.H., Azimirad, V., and Peydaie, P., "Investigation on the Effect of Different Parameters in Wheeled Mobile Robot Error (TECHNICAL NOTE)", ***International Journal of Engineering - Transactions A: Basics***, Vol. 20, No. 2, (2007), 195–210.
3. Travlos, V., Patman, S., Wilson, A., Simcock, G., and Downs, J., "Quality of Life and Psychosocial Well-Being in Youth With Neuromuscular Disorders Who Are Wheelchair Users: A Systematic Review", ***Archives of Physical Medicine and Rehabilitation***, Vol. 98, No. 5, (2017), 1004–1017.
4. Kundu, A.S., Mazumder, O., Lenka, P.K., and Bhaumik, S., "Design and Performance Evaluation of 4 Wheeled Omni Wheelchair with Reduced Slip and Vibration", ***Procedia Computer Science***, Vol. 105, No. 105, (2017), 289–295.
5. Requejo, P., Maneekobkunwong, S., McNitt-Gray, J., Adkins, R., and Waters, R., "Influence of hand-rim wheelchairs with rear suspension on seat forces and head acceleration during curb descent landings", ***Journal of Rehabilitation Medicine***, Vol. 41, No. 6, (2009), 459–466.
6. Hischke, M., and Reiser, R.F., "Effect of Rear Wheel Suspension on Tilt-in-Space Wheelchair Shock and Vibration Attenuation.", ***PM & R : the journal of injury, function, and rehabilitation***, (2018), DOI: 10.1016/j.pmrj.2018.02.009.
7. Silva, L.C.A., Dedini, F.G., Corrêa, F.C., Eckert, J.J., and Becker, M., "Measurement of wheelchair contact force with a low cost bench test", ***Medical Engineering & Physics***, Vol. 38, No. 2, (2016), 163–170.
8. Ababou, A., Ababou, N., Morsi, T., and Boukhechem, L., "Test Bench for Analysis of Harmful Vibrations Induced to Wheelchair

Users", In Proceedings of the International Conference on Biomedical Electronics and Devices, SCITEPRESS - Science and and Technology Publications, (2014), 147–153.

9. Miyawaki, K., and Takahashi, D., "Investigation of whole-body vibration of passenger sitting on wheelchair and of passenger sitting on wheelchair loaded on lifter", In International Symposium on Micro-NanoMechatronics and Human Science (MHS), IEEE, (2016), 1–6.

10. Wang, S., Zhao, L., Hu, Y., and Yang, F., "Impact Responses and Parameters Sensitivity Analysis of Electric Wheelchairs", ***Electronics***, Vol. 7, No. 6, (2018), 87–104.

11. Geng, Z., Popov, A.A., and Cole, D.J., "Measurement, identification and modelling of damping in pneumatic tyres", ***International Journal of Mechanical Sciences***, Vol. 49, No. 10, (2007), 1077–1094.

12. Dąbek, P., and Trojnacki, M., "Tire Models for Studies of Wheeled Mobile Robot Dynamics on Rigid Grounds – A Quantitative Analysis for Longitudinal Motion", In International Conference on Systems, Control and Information Technologies 2016 (SCIT 2016), Springer, Cham, Vol. 543, (2017), 409–424.

13. Levratti, A., Riggio, G., De Vuono, A., Fantuzzi, C., and Secchi, C., "Safe navigation and experimental evaluation of a novel tire workshop assistant robot", In IEEE International Conference on Robotics and Automation (ICRA), IEEE, (2017), 994–999.

14. Zhao, L., Yu, Y., Zhou, C., Li, X., and Yang, F., "Modeling and analytic optimization of dynamic comfort for wheelchair robots undergoing random roads", ***International Journal of Modeling, Simulation, and Scientific Computing***, (2018), DOI: 10.1142/S1793962318500447.

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چکیده

برای بهبود موثر و بهبود رفتارهای پایه ریش تراش روبات‌های صندلی چرخدار، یک روش تحلیلی برای تحلیل و بهینه‌سازی ایمنی پایه‌ی تایر صندلی چرخدار پیشنهاد شده است. اولاً، استفاده از کوسن و لاستیک‌ها را به عنوان عناصر جداسازی لرزش با سفتی و سقوط، مدل ارتعاش عمودی از روبات چرخشی انسان ساخته شده است. سپس، با توجه به تحرک تصادفی به عنوان ورودی معمولی، فرمول های پاسخ TDD (تابع نفوذ پویای تایر) عملکرد پاسخ H و RMS (میانگین مربع مربع) پاسخ می‌گیرند و ضریب پاسخ λ پیشنهاد می‌شود. علاوه بر این، قوانین نفوذ پارامترهای سیستم در H و λ مشخص می‌شود. سوم، بر اساس λ مدل بهینه‌سازی تحلیلی برای نسبت ساییدگی سیستم ξ_2 ایجاد شده است. در نهایت، یک مطالعه موردی و شبیه‌سازی عددی انجام شد. نتایج نشان می‌دهد که انحراف نسبی محدوده مطلوب کاهشی حدود ۰/۳٪ داشته است.

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