Influence of Design Parameters of Cab's Isolation System on Vibratory Roller Ride Comfort under the Deformed Ground Surfaces

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Abstract - *A 3D nonlinear dynamic model of a single drum vibratory roller based on the analysis of nonlinear geometric characteristics of wheel-deformation of soil ground contact is proposed in this study when vehicle moves into the workshop. The weighted r.m.s acceleration responses of the vertical driver's seat, pitch and roll angle of the cab are chosen as objective functions. Matlab/Simulink software is used to simulate the nonlinear dynamic models and calculate the objective functions. The stiffness and damping coefficients of the cab's isolation system are analyzed respectively. Not only are the results of this study evaluated the effects of the cab's isolation system on vehicle comfort ride, but they also work out the optimal values for the stiffness and damping coefficients to improve vehicle ride comfort when vehicle moves on the deformed ground surfaces.*

Key Words: Single drum vibratory roller, Cab, Rubber isolation system, Design parameter, Ride comfort

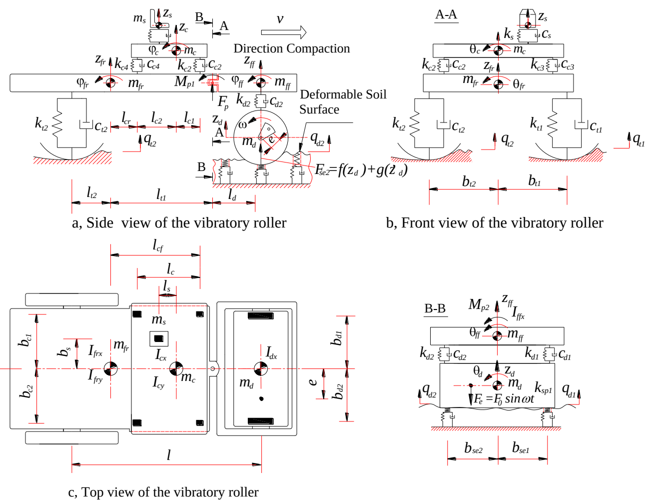
1. INTRODUCTION

Structurally, the vibratory roller is not often equipped with a suspension system to link the axle and the frame, the vibration excitation sources are transmitted through the cab's isolation system and seat suspension system. Therefore, the cab's isolation system has been specially studied by researchers to improve working conditions for operator. Dynamic test and analysis of vibration roller, equivalent finite element model building and dynamic simulations are taken into account to find out the main reason causing vibratory roller's sloshing when it moves at low speed on road surface and the auxiliary vibration isolator for cabin to reduce vibration in low frequency range [1]. In order to improve the vibratory roller ride comfort, the design parameters of cab's isolation system are conducted and optimized based on the improved genetic algorithm NSGA-II [2]. The different cab's isolation mounts such as the traditional rubber mounts, hydraulic mounts and pneumatic mounts are proposed to evaluate the ride comfort of the vibratory roller based on a three-dimensional nonlinear dynamic model, the power spectral density (PSD) and the weighted root mean square (RMS) of acceleration responses of the vertical driver's seat, cab's pitch, and roll vibrations [3]. An optimal fuzzy-PID control method for semi-active cab's hydraulic mounts is analyzed to prevent vibration sources transmitting to the cab [4]. A kind of Magneto-rheological (MR) damper, which has been widely used in automotive and bridge damping and applied to a vibratory road roller to control drum's isolation system based on 2-DOF non-line model, is designed [5]. To evaluate the riding comfort of a vibratory roller under the different soil grounds, the nonlinear dynamics model of the single drum vibratory roller is established according to the analysis of the contact physics of the wheel with different soil grounds to evaluate the influence of the different road conditions, operating conditions, and vehicle speeds on the driver's ride comfort [6]. A 12-degrees-of-freedom in-plane ride dynamic model of a single-drum compactor is formulated through integrations of the models of various components such as driver seat, cabin, roller drum and drum isolators, chassis and the tires. The simulation results indicate minor beneficial effect of a suspended rear axle, while the drum isolator and suspension seat reveal the most significant potential benefits [7]. A 3D nonlinear dynamic model of a single drum vibratory roller is established based on Adam D. and Kopf F's elastic-plastic soil model and Bekker hypothesis of the soft soil ground. Also an experiment was carried out when vehicle operates and moves under four different operating conditions. The numerical simulation results for ride comfort analysis were compared with the experimental results, after that the ride comfort of off-road vehicle is analyzed according to the ISO 2631: 1997 (E) standard [8].

In this study, the design parameters of cab's isolation system such as the stiffness and damping coefficients are analyzed respectively to work out their effects on vehicle ride comfort based on the 3D nonlinear dynamic model of a single drum vibratory roller using the nonlinear geometric characteristics of wheel-deformation of soil ground contact [8] when vehicle moves into the workshop. The wheel-deformation soil surface contact model is established to analyze the vertical excitation force acting on the vehicle frame using Bekker's hypothesis of soft soil ground [10] when vehicle moves into the workshop. The weighted r.m.s acceleration responses of the vertical driver's seat, pitch and roll angle of the cab are chosen as the objective functions to analyze the influence of the design parameters of cab's isolation on vehicle ride comfort.

2. DYNAMIC MODEL OF VIBRATION ROLLER

A single drum vibratory roller with the rubber isolation systems of drum, cab and seat suspension system are selected for vehicle dynamic analysis. A 3-D nonlinear dynamic model [2, 8] is used based on the analysis of the interaction between the vibratory roller and soft soil ground, as shown in Fig-1.



a, Side view of the vibratory roller
b, Front view of the vibratory roller
c, Top view of the vibratory roller

Fig-1: Dynamic model of vibratory roller[2,8]

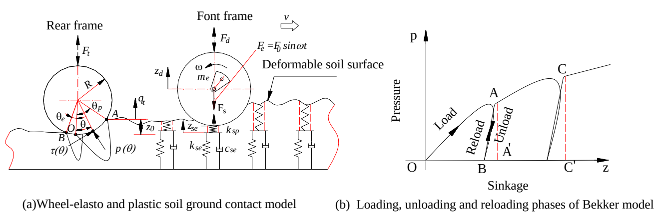
In Fig-1, m_d, m_{ff}, m_{fr}, m_c and m_s are the mass of the vibrating drum, frame-front, frame-rear, cab and driver's seat, respectively; I_{dx}, I_{ffx}, I_{frx}, I_{cx} and I_{fry}, I_{cy} are the moment of inertia with respect to the x of the vibrating drum, front frame , the moment of inertia with respect to the x and y axes of rear frame and cab, respectively; k_s and c_s are the stiffness and damping of driver's seat suspension system; k_{ci} and c_{ci} are the stiffness and damping of the left and right side of cab's isolation system, respectively; k_{tj} and c_{tj} are the stiffness and damping of the left and right side of tires, respectively; k_{dj} and c_{dj} are the stiffness and damping of the left and right side of tires, respectively; z_d, z_{ff}, z_{fr}, z_c and z_s are the vertical displacements at centre of gravity of the drum, the frame-front, the frame-rear, cab and driver's seat, respectively; θ_d, θ_{ff}, θ_{fr} and θ_c are the roll angle displacements of the drum, the frame-front, the frame-rear and cab, respectively; φ_{fr} and φ_c are the pitch angle displacements of the frame-rear and cab, respectively; q_{tj}, and q_{tj} are the left and right excitation of road surface roughness, respectively; l_{tj}, l_d, l, l_{cj}, l_c, l_{cf}, l_{cr}, l_s and b_{sej}, b_{dj}, b_{tj}, b_{cj}, b_s are the distances; $F=F_0\sin(\omega t)$ is the force excitation of the vibrating drum; F_0 is the amplitude of force excitation; ω is the angular frequency of the vibrator; e is the eccentricity of the rotating mass; F_p and M_{p1}, M_{p2} are the coupling force in the vertical direction and the coupling moments in the front - rear, left- right direction at the point of intersection, respectively; v is the vehicle speed (i=1÷4, j=1÷2).

The equations of vehicle motion can be formulated in different ways such as Lagrange's equation, Newton-Euler equation, Jourdain's principle. However, in order to facilitate the description of vehicle dynamic systems using computer simulation, a combined method of the multi-body system theory and D'Alembert's principle is chosen in this study. The multi-body system theory is used to separate the system into subsystems which are linked by the force and moment equations. D'Alembert's principle is used to set up force and moment equations to describe vehicle dynamic subsystems. For the dynamic model showed in Fig-1, the general dynamic differential equation for the single drum vibratory roller is represented as the standard form of matrix equation

$$m\{\ddot{z}\}+c\{\dot{z}\}+k\{z\}=\{F_t\} \quad (1)$$

where, m, k and c indicate the mass matrix, stiffness matrix and damping matrix of vehicle and seats, respectively; the $\ddot{z}$, $\dot{z}$ and z respectively refer to the acceleration, velocity, displacement vectors of vehicle and seats; F_t is the vector of wheel-deformation soil surface forces.

When vehicle moves on elastic-plastic soil surface after each compaction, the vertical excitation force acting on the vehicle frame and the rear wheels gradually change from elastic-plastic to elastic soil surface. In this study, the wheel-deformation soil surface contact model with wheels commonly known as "hard" wheels is established based on Bekker's hypothesis of the soft soil ground to analyze the vertical excitation force acting on the rear frame. Wheel-elasto and plastic soil ground contact model is shown in Fig- 2.



(a)Wheel-elasto and plastic soil ground contact model (b) Loading, unloading and reloading phases of Bekker model

Fig- 2: Wheel-elasto and plastic soil ground contact model [8]

Rear wheel- deformation soil surface contact

Loading phase, the vertical reaction force of tire F_{tg1} can be determined as

$$F_{tg1}=B\left[\int_0^{\theta_p} p(\theta)R\cos\theta d\theta+\int_0^{\theta_p}\tau(\theta)R\sin\theta d\theta\right] \quad (2)$$

Unloading phase, the vertical reaction force of tire F_{tg2} can be determined as

$$F_{tg2}=B\left[\int_0^{\theta_e} p_1(\theta)R\cos\theta d\theta+\int_0^{\theta_e}\tau(\theta)R\sin\theta d\theta\right] \quad (3)$$

The total vertical reaction force of the tire- deformation soil surface contact is defined as

$$F_{tg} = F_{tg1} + F_{tg2} \quad (4)$$

After obtaining Eq. (4), the equations of the contact between the left and right tire and the deformed soil are defined as

$$\begin{cases} F_{t1} - F_{tg1} + m_{t1} g = 0 \\ F_{t2} - F_{tg2} + m_{t2} g = 0 \end{cases} \quad (5)$$

In this formula, m_{tj} is the mass of tire; F_{tgj} is the vertical reaction forces of the left and right tire- deformation soil surface contact.

Front wheel- deformation soil surface contact

Similar to rear wheel- deformation soil surface contact, the equations of the contact between the left and right drums and the deformed soil are defined as

$$\begin{cases} F_{d1} - F_{dg1} + m_{d1} g = 0 \\ F_{d2} - F_{dg2} + m_{d2} g = 0 \end{cases} \quad (6)$$

m_{dj} is the mass of tire; F_{dgj} is the vertical reaction forces of the left and right tire- deformation soil surface contact.

3. VEHICLE RIDE COMFORT CRITERIA

A number of methods for example, frequency-domain method, time-domain method can be applied to evaluate the vehicle ride comfort. According to ISO 2631-1 (1997) [9], in this study, the vibration evaluation based on the basic evaluation methods including measurements of the weighted root-mean-square (r.m.s.) acceleration defined as

$$a_w = \left[\frac{1}{T} \int_0^T a_w^2(t) dt \right]^{1/2} \quad (7)$$

In this formula, $a_w(t)$ is the weighted acceleration (translational and rotational) as a function of time, m/s^2; T is the duration of the measurement, s.

For indications of the likely reactions to various magnitudes of overall vibration in the public transport and vehicle, a synthetic index-called weighted r.m.s acceleration, a_w can be calculated from formula Eq.(7); besides, the r.m.s. value of the acceleration in vehicle would be compared with the values in Table-1.

Table- 1: Comfort levels related to a_w threshold values

a_w/(m.s^2)	Comfort level
< 0.315	Not uncomfortable
0.315÷0.63	A little uncomfortable
0.5 ÷ 1.0	Fairly uncomfortable
0.8 ÷ 1.6	Uncomfortable
1.25 ÷ 2.5	Very uncomfortable
> 2	Extremely uncomfortable

4. SIMULATION AND DISCUSSION

To solve the nonlinear differential equations presented in this study, Matlab /Simulink software is used to analyze the influence of the design parameters of cab's isolation on vehicle ride comfort with a set of parameters of the single drum vibratory roller by the references[11] and elastic-plastic soil ground in Table-2.

Table -2. Different soft soil ground surface parameters

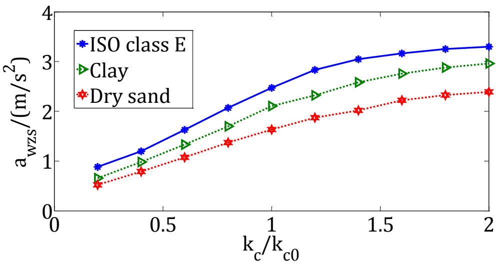
Par.	Hum. (%)	n	k_c/(N/m^{n+1})	k_ϕ /(N/m^{n+1})	C/Pa	ϕ(^{0})
Dry sand	0	0.71	6.94×10^3	0.506×10^6	1.3×10^3	28
Clay	55	0.7	1.603×10^4	1.262×10^6	2.07×10^3	10

In this study, the design parameters of cab's isolation system such as stiffness and damping coefficients are considered to analyze effect on the values of the weighted r.m.s acceleration responses of the vertical driver's seat (a_{wzs}), pitch and roll angle of the cab (a_{wphic} and a_{wtetac}) when vehicle moves into the workshop under different deformed ground surfaces. The multi-pass effect of the vibratory roller in the wheel-soft soil ground interaction is one of the most important effects and two or more wheels are running in the same rut. In order to consider the effect of multiple possibility on vehicle ride comfort, this study uses the Bekker's test results [10]. The front wheel passes through the soil surface density and parameters and the rear wheel moves on the new soil ground. Discussions will be presented in the following section.

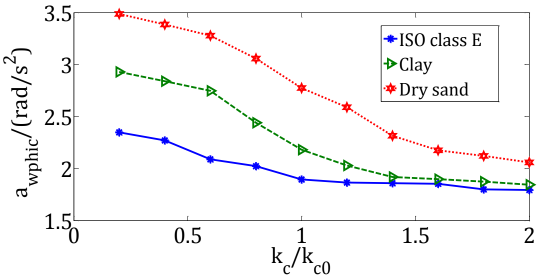
Effect of stiffness coefficients of cab's isolation system

To analyze the effect of stiffness coefficients of cab's isolation system on a_{wzs}, a_{wphic} and a_{wtetac} values, the values of the stiffness coefficients of the cab's isolation system k_c=[0.2, 0.4, 0.6, 0.8, 1.0, 1.2, 1.4, 1.6, 1.8, 2.0]xk_{c0}, $k_{c0}=[k_{c1}, k_{c2}, k_{c3}, k_{c4}]^T$ are analyzed when vehicle moves on the different deformed ground surface conditions such as ISO class E (very poor road surface)[12,13], dry sand and clay ground surfaces and at the speed of 8 km/h. In this case, k_{c0} is used to designate the cab's isolation system stiffness coefficients in the reference document [10]. The influence of the isolation system stiffness coefficients on a_{wzs}, a_{wphic} and a_{wtetac} values is shown in Fig-3.

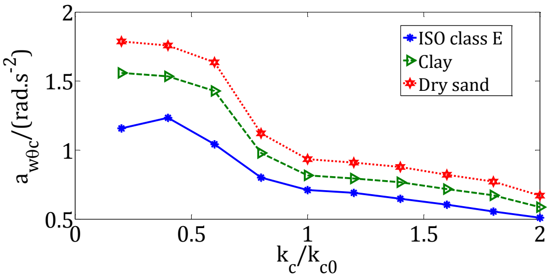
We can see from Fig-3(a) that the deformed ground surface becomes softer and the cab's isolation stiffness coefficient increases, the a_{wzs} value is significantly reduced, which causes the operator's seat ride comfort to be improved. However, it can be seen from Fig-3(b), (c) the deformed ground surface becomes softer, the isolation stiffness coefficient increases, the a_{wphic} and a_{wtetac} values increase, and the cab's sloshing is significantly increased, reducing the operator's ride comfort in the direction of forward motion.



(a) Driver's seat



(b) Pitch angle of cab

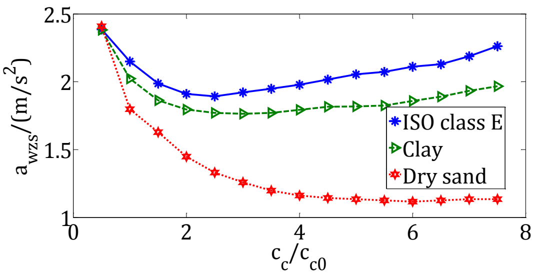


(c) Roll angle of cab

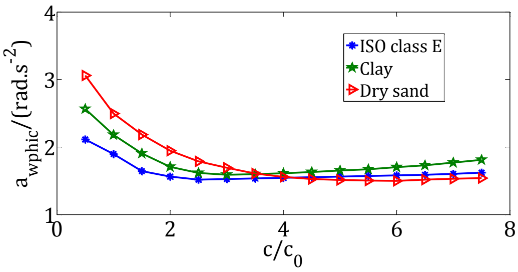
Fig-3: Influence of cab's isolation system stiffness coefficients on driver ride comfort

Effect of damping coefficients of cab's isolation system

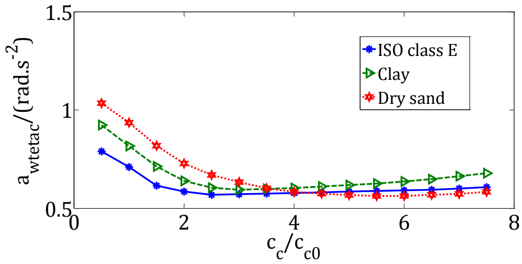
To analyze the effect of damping coefficients of cab's isolation system on a_{wzs}, a_{wphic} and a_{wtetac} values, the values of the damping coefficients of the cab's isolation system c_c=[0.5, 1.0, 1.5, 2.0, 2.5, 3.0, 3.5, 4.0, 4.5, 5.0 5.5 6.0 6.5 7.0 7.5]xc_{c0}, where $c_{c0}=[c_{c1}, c_{c2}, c_{c3}, c_{c4}]^T$ are analyzed when vehicle moves under the same operation conditions as above, where c_{c0} is used to designate the cab's isolation system damming coefficients in the reference document[10]. The influence of the isolation system damping coefficients on a_{wzs}, a_{wphic} and a_{wtetac} values are shown in Fig-4. Fig-4 shows that the cab's isolation system damping coefficient increases from 0.5 to 3c_0, the a_{wzs}, a_{wphic} and a_{wtetac} values tend to decrease, which makes driver's ride comfort considerably improve. Like the above discussion, we can see from Fig-4(a) that the deformed ground surface becomes softer, the a_{wzs} value is significantly reduced, which causes the operator's seat ride comfort to be improved. However, the cab's sloshing is significantly increased, reducing the operator's ride comfort in the direction of forward motion (see Fig-4(c) and Fig-4(c)). At the same time, as shown in Fig-4, the values of cab's isolation system damping coefficients are about 2.0c_{c0}, 3.0c_{c0}, and 4.5c_{c0}, the a_{wzs}, a_{wphic} and a_{wtetac} values achieve the minimum values in term of improving the vehicle's ride comfort. To improve ride comfort and the driver's health, cab's isolation system is added to the hydraulic damping and applied to the semi-active drum/cab's hydraulic isolation system as well as magneto-rheological semi-active damper, magneto-rheological active damper [4, 5], the optimal design parameters for the vibration isolation system [14] or the auxiliary vibrations isolator for solving the low-frequency sloshing in the direction of forward motion [1].



(a) Driver's seat



(b) Pitch angle of cab



(c) Roll angle of cab

Fig-4: Influence of cab's isolation system damping coefficients on driver ride comfort

5. CONCLUSIONS

In this study, a 3D nonlinear dynamic model of a single drum vibratory roller using the nonlinear geometric characteristics of wheel-deformation of soil ground contact is applied to analyze the influence of the design parameters of cab's isolation on vehicle ride comfort such as the stiffness and damping coefficients when vehicle moves into the workshop. The major conclusions can be drawn from the analysis and evaluation results as follows:

i) The values of both stiffness and damping parameters of cab's isolation system change: the deformed ground

surface becomes softer and the cab's isolation stiffness coefficient increases, the a_{wzs} value is significantly reduced, which causes the operator's seat ride comfort to be improved. However, the a_{wphic} and a_{wtetac} values increase, the cab's sloshing is significantly increased, reducing the operator's ride comfort in the direction of forward motion.
ii) The cab's isolation system damping coefficient increases from 0.5 to 3c_0, the a_{wzs}, a_{wphic} and a_{wtetac} values tend to decrease, which makes driver's ride comfort considerably improve.
iii) Through the effect analysis, we propose the optimal design parameters for cab's isolation system of the single drum vibratory roller in the direction of improving the vehicle's ride comfort.

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