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Study on Influence of Design Parameters of Drum's Metal Rubber Isolation System of Tandem Vibratory Roller on Ride Comfort

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Abstract - *This study presents an analysis of the effect of the design parameters of drum's metal rubber isolation system of tandem vibratory roller on ride comfort. To analyze these effects, a tandem vibratory roller dynamic model with 7 degrees of freedom(*DOF*) is established under different operations of the vehicle. Also, the root mean square (r.m.s) accelerations of the vertical driver and pitch cab are chosen as objective functions. The parameters of drum's metal rubber isolation systems such as stiffness and damping coefficients are respectively analyzed and evaluated in terms of objective functions. Not only do the study results evaluate the effect of the design parameters of drum's metal rubber isolation system on ride comfort, but they also suggest a theoretical basis for the design of drums' isolation system to improve ride comfort of cab and driver.*

Key Words: Tandem vibrating roller, Drum, Metal rubber isolation system, Design parameter, Ride comfort

1. INTRODUCTION

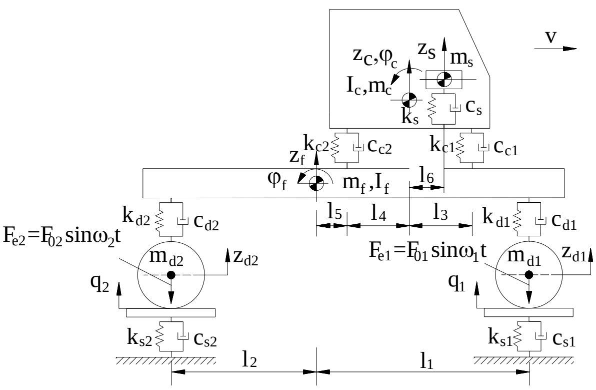
Vibration roller market has increasingly required working capacity as well as ride comfort. Thus, in order to reduce the effect of vibration to operators, identification and elimination of vibration sources are the most important tasks to achieve optimum design. Vibratory roller is a compactor which has one or more drums for compacting soil ground, asphalt and other materials. The operating principle of the vibratory roller is a combination of static and dynamic forces (weight and vibrations). A dynamic test and analysis of vibration roller, an equivalent finite element model building, and some dynamic simulations are carried out to find out the main reason causing vibratory roller's sloshing when it moves down the road surface at low speed. The auxiliary vibration isolator for cabin for reducing vibration in low frequency range is designed [1]. To improve the vibratory roller ride comfort, a multi-objective optimization method based on the improved genetic algorithm NSGA-II was proposed to optimize the design parameters of cab's isolation system when vehicle operates under the different conditions [2]. To evaluate the ride comfort of the vibratory roller with the different cab's isolation mounts such as with the traditional rubber mounts, hydraulic mounts and pneumatic mounts, a three-dimensional nonlinear dynamic model is established. 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 are chosen as objective functions in the low-frequency range [3]. To improve the ride comfort of the off-road vibratory roller, 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 based on the analysis of the physical contacts 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, 12]. The rest of this paper is organized as follows: a half vehicle dynamic model for a tandem vibratory roller with 7 (DOF) is established under different operating conditions to analyze the effects of the design parameters of drum's metal rubber isolation systems to ride comfort in section 2. Vehicle ride comfort criteria are presented in section 3. Simulation and discussion are presented in section 4 and the conclusions are given in section 5.

2. DYNAMIC MODEL OF VIBRATION ROLLER

To simulate and analyze the effects of the design parameters of drum's metal rubber isolation systems on ride comfort, a tandem vibratory roller is selected as the study object and a half vehicle dynamic model of a tandem vibratory roller with 7 (DOF) is shown in Fig-1 (b).

In Fig-1(b): k_{sj}, k_{dj}, k_{cj}, k_s and c_{sj}, c_{dj}, c_{cj}, c_s are the stiffness and damping coefficients of the elastic soil grounds, drum's metal rubber isolation systems, cab's isolation systems, driver's seat suspension system, respectively; l_i are the distances; m_{dj}, m_f, m_c and m_s are the mass of the vibrating drums, frame, cab and driver's seat, respectively; I_f and I_c are the moment of inertia with respect to the y of the frame and cab, respectively; z_{dj}, z_f, z_c and z_s are the vertical displacement of the drum, frame, cab and driver'seat, respectively; φ_f and φ_c are the pitch angle displacements of the frame and cab, respectively; q_j is the excitation of road surfaces; $F_{ej}=F_{0j}\sin\omega_j t$ (N) are the force excitation of the vibrating drums, v is vehicle speed (i=1÷6, j=1÷2).

(a) Side view of tandem vibratory roller



(b) Dynamic model

Fig-1: Tandem vibratory roller

The vehicle dynamic equations can be formulated in different ways. One of the most popular methods is the Lagrange equation type II. For the dynamic model showed in Fig- 1 (b), the general dynamic differential equation for the tandem vibratory roller is represented as the standard form of matrix equation with two cases.

Case 1: Vehicle moves into the workshop

$$M\{\ddot{z}\}+C\{\dot{z}\}+K\{z\}=C_d\{\dot{q}\}+K_d\{q\} \quad (1)$$

In this equation, M, C, C_d and K, K_d the (5×5) mass, damping and stiffness coefficient matrices; respectively, $\{\ddot{z}\},\{\dot{z}\},\{z\}$ are the (5×1) vector of acceleration, velocity and displacement ; $\{q\}$ is the (5×1) vector of excitation of road surface.

Case 2 : Vehicle operates in the workshop

$$M\{\ddot{z}\}+C\{\dot{z}\}+K\{z\}=\{F_t\} \quad (2)$$

In this equation, M, C and K are the (7×7) mass, damping and stiffness coefficient matrices respectively; $\{\ddot{z}\},\{\dot{z}\},\{z\}$ are the (7×1) vector of acceleration, velocity and displacement; $\{F_t\}$ is the [7x1] force excitation of vibration drums.

Determination of excitation forces

To determine the excitation forces acting on the frame according to vehicle's operating conditions, the two cases are selected to analyze the effects of the design parameters of drum's metal rubber isolation systems on ride comfort.

Case 1: Vehicle moves into the workshop

In this case, the wheels contact with many different types of road surfaces such as rigid road surfaces, soft road surfaces, elastic-plastic road surfaces, etc [1-3]. However, the rigid road surface is chosen and the wheels contact on the rigid road surface with ISO class D (poor) according to the standard ISO 8068[7, 8, 11, 12] is shown in Fig-2. The vertical excitation forces acting on the front rear frames are defined as

$$F_{dj}=k_{dj}(z_{fj}-z_{dj})+c(\dot{z}_{fj}-\dot{z}_{dj}) \quad (3)$$

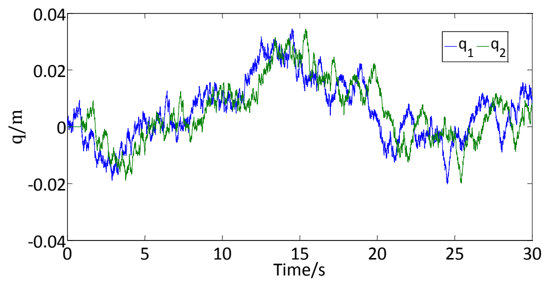


Fig- 2: Road surface roughness ISO class D according to ISO 8068.

Case 2: Vehicle operates in the workshop

In real working conditions, a vibratory roller operates on various kinds of soil ground such as elastic-plastic soil ground, plastic soil ground, etc[12,13]. The linear elastic characteristics of the soil ground (k_{sj}=const and c_{sj}=const) are considered when vehicle operates on original place (v=0) with low frequency comparison (f=48Hz) and high frequency comparison (f=54 Hz). The vertical excitation forces acting on the front and rear frames are defined as Eq.(4) and The vertical excitation forces of vibration drums are shown in Fig-3 with f=48Hz for front drum and f=54 Hz for rear drum.

$$F_{dj}=F_{sj}-F_{ej}=k_{sj}z_{dj}+c_{sj}\dot{z}_{dj}-F_{0j}\sin\omega_j t \quad (4)$$

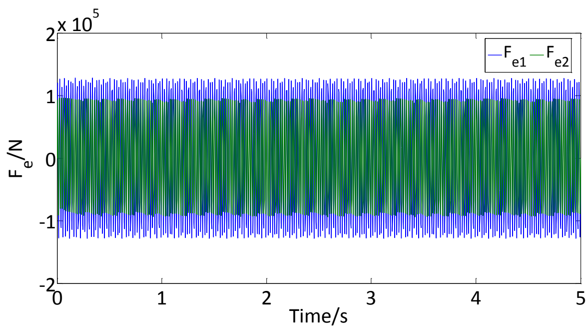


Fig-3: The vertical excitation forces of vibration drums

3. VEHICLE RIDE COMFORT CRITERIA

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

$$a_w = \left[\frac{1}{T} \int_0^T a_w{}^2(t)dt \right]^{1/2} \quad (5)$$

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 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.(5); 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

With the view to analyzing and evaluating the effects of the design parameters of drum's metal rubber isolation systems on driver ride comfort when vehicle operates under two cases, Matlab/Simulink software is used with the vehicle simulation parameters [6,10,11] to solve Eq.(1) and Eq.(2) presented in section 2. Fig-4 and Fig-5 show the acceleration responses of the vertical driver's seat and pitch angle of the cab when vehicle operates in case 1 (vehicle moves on road surface ISO class D at the speed of 15km/h).

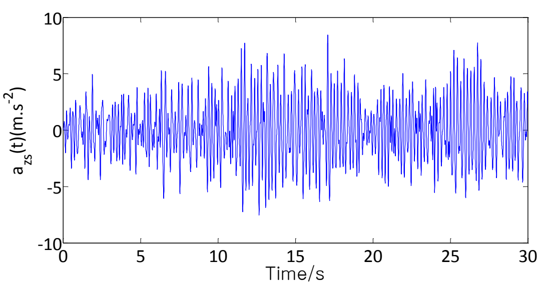


Fig-4: Acceleration response of the vertical driver's seat

Fig-4 and Fig-5 show the values of the weighted r.m.s acceleration of the vertical driver's seat and pitch angle of the cab as a_{wzs}= 2.597m/s² and a_{wphi}= 3.344 (rad/s²). Those values of a_w are extremely uncomfortable conditions for driver comfort (according to Tab.1).

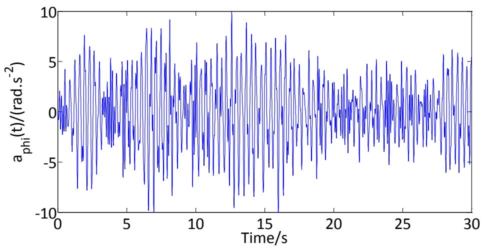
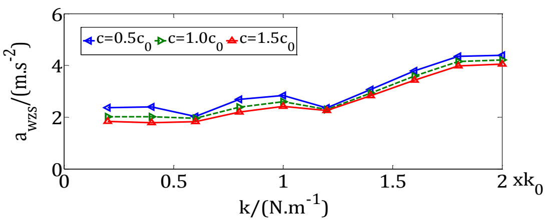


Fig-5: Acceleration response of pitch angle of the cab

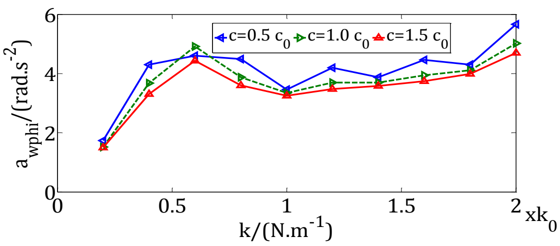
Both stiffness and damping parameters of drum's metal rubber isolation systems have important influences on vehicle ride comfort when vehicle operates in case 1 and case 2. In order to analyze them, discussions will be presented in the following section.

Case1: Vehicle moves into the workshop

Influence of drum's metal rubber isolation system stiffness coefficient on vehicle ride comfort: It is an important factor that influences the vehicle ride comfort. To analyze its effect on a_{wzs} and $a_{w\varphi}$ values, the values of the isolation stiffness coefficients k=[0.2 0.4 0.6 0.8 1 1.2 1.4 1.6 1.8 2.0]xk_0, where $k_0=[k_{d1}, k_{d2}]^T$ and the values of the isolation damping coefficients c=[0.5 1 1.5]xc_0, where $c_0=[c_{d1}, c_{d2}]^T$ are analyzed when vehicle moves on the ISO class D (poor road surface) condition and the vehicle speed of 15 km/h, where k_0 and c_0 are used to designate the metal rubber isolation system stiffness and damping coefficients in the reference document[10]. The influence of the isolation system stiffness coefficients on a_{wzs} and $a_{w\varphi}$ values are shown in Fig-6.



(a) Driver's seat

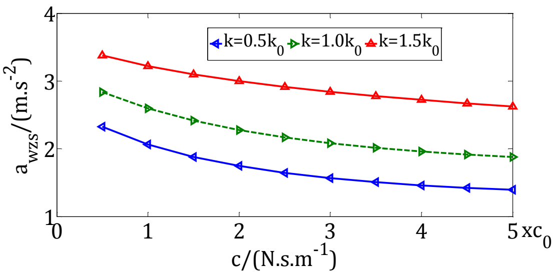


(b) Pitch angle of the cab

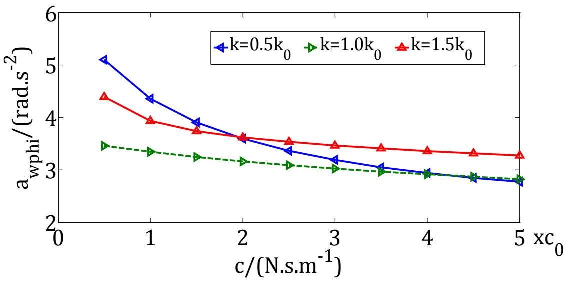
Fig-6: Influence of drum's metal rubber isolation system of stiffness coefficients on driver ride comfort

It is shown in Fig.6 that when the value of the isolation stiffness coefficient increases, the a_{wzs} and $a_{w\varphi}$ values tend to increase, which makes the negative effects on ride comfort of driver. The a_{wzs} and $a_{w\varphi}$ values increase quickly when the values of the damping coefficients are $c=0.5c_0$.

Influence of drum's metal rubber isolation system damping coefficient on vehicle ride comfort: It is another important factor that influences the ride comfort. To analyze its effect on the a_{wzs} and $a_{w\varphi}$ values, the values of the isolation damping coefficients c=[0.5 1.0 1.5 2 2.5 3.0 3.5 4.0 4.5 5.0]xc_0 (adding hydraulic damper for drum's metal rubber isolation systems), where $c_0=[c_{1r}, c_{1l}, c_{2r}, c_{2l}]^T$ and the values of the isolation stiffness coefficients k=[0.5 1 1.5]xk_0, where $k_0=[k_{d1}, k_{d2}]^T$ are analyzed when vehicle moves on the road surface ISO class D (poor) condition and the speed of 15 km/h. The influences of the isolation system damping coefficients on a_{wzs} and $a_{w\varphi}$ values are shown in Fig-7.



(a) Driver's seat



b) Pitch angle of the cab

Fig-7: Influence of drum's metal rubber isolation system damping coefficients on driver ride comfort

Fig-7 shows that the isolation damping coefficient increases from 0.5 to 2.5c_0, the a_{wzs} and $a_{w\varphi}$ values tend to decrease, which makes driver's ride comfort considerably improve.

Case 2: Vehicle operates in the workshop

The design parameters of the drum's metal rubber isolation systems such as stiffness and damping coefficients are studied in case 1 when vehicle compresses on original place with the elastic soil grounds (k_{s1} = 1x10^7 N/m, c_{s1} = 2.1x10^5 N.s/m and k_{s2}= 1.2x107N/m, c_{s2}=2.8x10^5 N.s/m) and low frequency comparison for front drum (f=48Hz) and high frequency comparison (f=54 Hz) for rear drum. Table-2 shows the effects of the isolation stiffness coefficients on a_{wzs} and $a_{w\varphi}$ values and Table -3 is for the effects of the isolation damping coefficients on a_{wzs} and $a_{w\varphi}$ values.

Table-2: The effects of the isolation system stiffness coefficients on a_{wzs} and $a_{w\varphi}$ values when vehicle compresses on original place with the elastic soil grounds and low frequency comparison for front drum (f=48Hz) and high frequency comparison (f=54 Hz) for rear drum.

k(N/m)	c=0.5xc$_0$(N.s/m)		c=1.0xc$_0$(N.s/m)		c=1.5xc$_0$(N.s/m)	
	a_{wzs}	a_{wphi}	a_{wzs}	a_{wphi}	a_{wzs}	a_{wphi}
k=0.2xk$_0$	0.019	0.017	0.019	0.017	0.017	0.016
k=0.4xk$_0$	0.031	0.031	0.028	0.018	0.027	0.021
k=0.6xk$_0$	0.039	0.028	0.036	0.028	0.034	0.029
k=0.8xk$_0$	0.046	0.027	0.042	0.024	0.042	0.026
k=1.0xk$_0$	0.048	0.028	0.047	0.026	0.048	0.029
k=1.2xk$_0$	0.052	0.029	0.051	0.029	0.055	0.033
k=1.4xk$_0$	0.054	0.031	0.054	0.031	0.057	0.034
k=1.6xk$_0$	0.056	0.032	0.056	0.033	0.059	0.036
k=1.8xk$_0$	0.058	0.033	0.059	0.034	0.063	0.039
k=2.0xk$_0$	0.059	0.033	0.061	0.035	0.065	0.037

Table-3: The effects of the isolation system damping coefficients on a_{wzs} and $a_{w\varphi}$ values when vehicle compresses on original place with the elastic soil grounds and low frequency comparison for front drum (f=48Hz) and high frequency comparison (f=54 Hz) for rear drum.

c(N.s/m)	k=0.5xk$_0$(N/m)		k=1.0xk$_0$(N/m)		c=1.5xk$_0$(N/m)	
	a_{wzs}	a_{wphi}	a_{wzs}	a_{wphi}	a_{wzs}	a_{wphi}
c=0.5xc$_0$	0.036	0.023	0.048	0.028	0.055	0.032
c=1.0xc$_0$	0.032	0.029	0.047	0.026	0.055	0.032
c=1.5xc$_0$	0.033	0.020	0.048	0.029	0.058	0.035
c=2.0xc$_0$	0.029	0.026	0.045	0.025	0.056	0.034
c=2.5xc$_0$	0.028	0.022	0.044	0.027	0.054	0.032
c=3.0xc$_0$	0.026	0.021	0.043	0.025	0.053	0.032
c=3.5xc$_0$	0.025	0.020	0.041	0.023	0.054	0.032
c=4.0xc$_0$	0.024	0.018	0.041	0.025	0.050	0.032
c=4.5xc$_0$	0.023	0.016	0.041	0.025	0.053	0.045
k=5.0xk$_0$	0.024	0.019	0.043	0.031	0.051	0.039

From the results in Table- 2, we can see that the stiffness values of drum's metal rubber isolation system increase, and the a_{wzs} and $a_{w\varphi}$ values tend to increase, which leads to the decrease in driver's ride comfort. In contrary, the damping values of the drum's metal rubber isolation systems go up, the a_{wzs} and $a_{w\varphi}$ values tend to reduce, which bring about the improvement of driver's ride comfort (Table -3). Table-2 and Table-3 indicate that the values of weighted r.m.s acceleration of the vertical driver's seat and pitch angle of the cab are comfortable conditions for driver comfort (according to Tab.1).

5. CONCLUSIONS

In this study, a half vehicle dynamic model of a tandem vibratory roller is proposed for simulating and analyzing the influence of the design parameters of drum's metal rubber isolation systems of tandem vibratory roller on the ride comfort when vehicle operates under different conditions. The major conclusions can be drawn from the analysis and evaluation results as follows:

i) Case 1: Vehicle moves into the workshop. This operating condition is an influential factor in driver's comfort. To improve ride comfort and the driver's health, metal rubber isolation system of the drum 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 or optimal design parameters for the dynamic system of vibratory Roller[2, 3, 15].
ii) Case 2: Vehicle operates in the workshop. The values of weighted r.m.s acceleration of the vertical driver's seat and pitch angle of the cab are comfortable conditions for driver comfort although it is not a hard operating condition [6, 12,14].
iii) The study results can be used for the searchers and vehicle manufacturers for further considerations in designing the isolation systems for vibratory roller dynamic system.

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