Main Parameters Analysis of Ball Screw Shock Absorber on Suspension System Performance

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Abstract

A ball screw regenerative shock absorber was designed for the relief of the vehicle vibration and the energy recovery of the vehicle vibration. The effect of its main parameters on the suspension system was numerically analyzed. According to the principle of the ball screw regenerative suspension system, a mathematical model of the ball screw regenerative shock absorber was established regarding the ball screw rotational inertia, the motor rotational inertia, the screw lead and the radius of the screw nut. A suspension dynamic model based on the ball screw regenerative shock absorber was developed combining the road model and the two-degrees-of-freedom suspension dynamic model. Using a triangle pulse input condition and a random road input condition, through changing value of parameters with an interval of 2% of the initial value, the influences of parameters, including the ball screw rotational inertia, the motor rotational inertia, the screw lead and the radius of the screw nut, on the ball screw suspension performance were investigated. Finally, the parameter sensitivity was studied using the one parametric variation method. It was found that the most significant factor affecting the suspension performance is the screw nut radius, followed by the screw lead, while the effects of the ball screw's moment of inertia and the motor's moment of inertia are less significant.

1. Introduction

The environment protection has attracted increasing attention in the worldwide. The automotive industry is also increasingly focusing on the improvement of the vehicle energy efficiency and the energy conservation. Therefore, an increasing number of scholars have performed investigation on the suspension vibration energy recovery.

Okada firstly studied the vehicle vibration energy recovery and proposed an electromagnetic energy regenerative system. The feasibility of the electromagnetic energy regenerative suspension was theoretically analyzed [1]. The issue that the motor cannot provide effective damping force at a low speed of the suspension movement was deeply investigated. It was proposed that the system was still able to generate electricity by using a boost chopper at low-speed operation [2, 3]. Following the study by Okada, Suda proposed a rack-and-pinion regenerative suspension, and theoretically analyzed the feasibility of this design. The relationships between the load circuit resistance and the suspension damping performance as well as the regeneration performance were analyzed [4, 5]. Subsequently, Suda and Nakano proposed a self-powered active control suspension [6, 7], and conducted theoretical calculations. Bose Corporation [8] and Levent Power Corporation [9] developed their own electromagnetic suspension and the regenerative shock absorber, respectively, however, no publication has been found due to the technical confidence. Zuo Lei [10] developed a rack-and-pinion regenerative shock absorber, and created a prototype of the system. Li Zongjie [11] derived the mathematical model of the prototype, tested the external characteristics of the shock absorber, and finally performed vehicle tests. Wang Weihua, et al. [12, 13, 14] proposed an active suspension design using a rack and pinion mechanism and a DC servo motor, combined with an overrunning clutch installed between the gear rack and the power generator. This design can effectively overcome the shortcoming that the motor continuously reversed in the previous ball screw mechanism. Xing Chen [15] designed a linear motor active suspension system that can achieve the active control of the suspension and the energy recovery, and the optimal damping coefficient was studied. Bart L.J. Gysen et al. [16, 17, 18] deeply investigated the linear motor regenerative shock absorber, and developed a prototype for vehicle tests. Xu Lin [19, 20] proposed a hydro-electric regenerative shock absorber design, which used a hydraulic rectifier bridge to lead off the oil in the cylinder tube of the shock absorber. The oil always flowed in one direction, driving the hydraulic motor-generator to generate electricity.

The energy recovery of the regenerative suspension system has practical significance only when the damping capacity of the regenerative suspension reaches the conventional suspension. Therefore, this study investigated the influencing factors of the ball screw regenerative suspension performance. The effects of the parameters on the performance of the suspension system were explored by changing the main parameters of the ball screw shock absorber.

2. The Mathematical Model of the Ball Screw Suspension

The principle diagram of the ball screw regenerative suspension is shown in Fig. 1. As shown in Fig. 1, the ball screw regenerative shock absorber is the key component which converts the vertical linear motion of the suspension into the rotary motion using the ball screw, and drives the motor rotation for power generation.

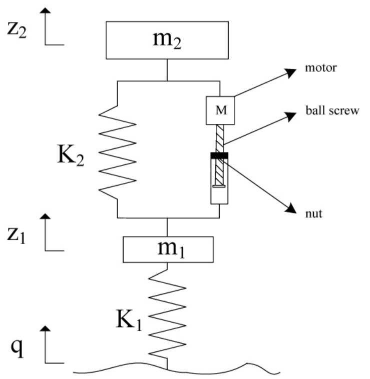


Fig.1. Schematic diagram of the ball-screw regenerative suspension

2.1. The Mathematical Model of the Ball Screw Shock Absorber

2.1.1. The Motor Model

The damping force of the conventional shock absorber is a linear force. In the electromagnetic regenerative shock absorber, however, the rotary motor is used for energy recovery and damping. Due to the rotational motion of the motor, the output is torque. Therefore, the mutual transformation between the movements of the ball screw and the nut is required.

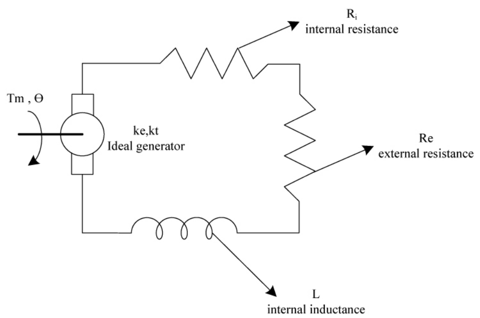


Fig.2. Schematic diagram of the electromagnetic generator

As shown in Fig.2, the relationship between the current in the generator coil and the moment is:

$$\tau_i = k_t i \tag{1}$$

where, k_t is the motor torque constant.

According to Newton's second law, it can be drawn that:

$$\tau_m - \tau_i = J_m \frac{d^2\theta}{dt^2} \tag{2}$$

where, τ_m is the input torque of the motor; J_m is inertia of the rotor. According to Kirchhoff's voltage law, it can be drawn that:

$$U_{emf} - L\frac{di}{dt} - iR = 0 \tag{3}$$

where, the back electromotive force is $U_{emf}=k_e\,(d\,\Theta\,/dt)$; L is the internal inductance of the motor; and R is the sum of the motor resistance R_i and load resistance R_e.

Summarizing Eqs. (1), (2) and (3), the kinetic equation of the motor can be obtained as:

$$k_e\frac{d\theta}{dt} = \frac{L}{k_t}\frac{d}{dt}\tau_m - J_m\frac{d^2\theta}{dt^2} + \frac{R}{k_t}\tau_m - J_m\frac{d^2\theta}{dt^2} \tag{4}$$

where, k_e is the voltage constant of the motor.

The Laplace transform of the above equation leads to:

$$T_m = J_m\Theta s^2 - c_m\Theta s + k_m\Theta \tag{5}$$

in which, the equivalent damping factor and the stiffness are expressed as follows:

$$c_m = \frac{k_t k_e R}{R^2 + L^2\omega^2} \tag{6}$$

$$k_m = \frac{k_t k_e L\omega^2}{R^2 + L^2\omega^2} \tag{7}$$

Considering that the vibration frequency caused by the road surface is typically between 1-10 Hz, the inductance of the motor is very small with respect to the resistance ($L\omega \ll R$). Therefore, the effect of the motor inductance can be ignored, leading to the equivalent stiffness $k_m \approx 0$. The equivalent damping can be expressed as:

$$c_m = \frac{k_t k_e}{R} \tag{8}$$

2.1.2. The Mathematical Model of the Damping Force in the Shock Absorber

The damping force of the traditional automobile shock absorber is a linear force. On the other hand, the ball screw shock absorber uses the rotary motor as the regenerative and damping element, resulting in that the output is torque. Therefore, it is required for the conversion from the rotational motion between the ball screw and the nut to the equivalent linear motion.

The transformation equation between the rotary motion and the linear motion, as well as the transformation equation between the torque and the force are expressed as follows:

$$\omega = \frac{2\pi}{l}\dot{z} \tag{9}$$

$$T = \frac{l}{2\pi}F \tag{10}$$

where, ω is the rotational angular velocity; $\dot{z}$ is the speed of the linear motion; T is the torque; and F is the linear force.

Based on the above derivation of the motor model, combining Eqs (9) and (10), the damping force model of the ball screw shock absorber is proposed as:

$$F=\left(\frac{2\pi}{l}\right)^2\left(J_m+J_b\right)\ddot{z}+\left(\frac{2\pi}{l}\right)\left(\frac{k_b^2k_ek_t}{r^2\eta_bR}\right)\dot{z} \tag{11}$$

where, J_m and J_b are the rotational inertia of the regenerative motor and the screw, respectively; k_b is the drive ratio of the ball screw; η_b is the transmission efficiency of the ball screw; l is the screw lead; and r is the radius of the screw nut.

2.2. The Model of the Ball Screw Suspension

According to the system block diagram shown in Fig. 1, regarding Eq. (11) and Newton's second law, the kinetic equation of the ball screw suspension can be drawn as:

$$\begin{cases} m_2\ddot{z}_2+F+K_2\left(z_2-z_1\right)=0 \\ m_1\ddot{z}_1-F+K_2\left(z_1-z_2\right)+K_1\left(z_1-q\right)=0 \end{cases} \tag{12}$$

where, m_2 is the sprung mass; m_1 is the non-sprung mass; K_2 is the stiffness of the suspension spring; K_1 is the tire stiffness; and q is the vertical displacement of the road surface.

According to equation (11), the equivalent mass and equivalent damping of regenerative shock absorber can be expressed respectively as:

$$\mathrm{m}_r=\left(\frac{2\pi}{l}\right)^2\left(J_m+J_b\right) \tag{13}$$

$$c_r=\frac{2\pi k_b^2k_ek_t}{lr^2\eta_bR} \tag{14}$$

And the $\dot{z}$ and $\ddot{z}$ in the equation (11) is the suspension dynamical displacement, which can be expressed respectively as:

$$\dot{z}=\dot{z}_2-\dot{z}_1 \tag{15}$$

$$\ddot{z}=\ddot{z}_2-\ddot{z}_1 \tag{16}$$

So the two degree of freedom equation of ball screw regenerative suspension can be written as:

$$\begin{cases} m_2\ddot{z}_2+m_r\left(\ddot{z}_2-\ddot{z}_1\right)+c_r\left(\dot{z}_2-\dot{z}_1\right)+K_2\left(z_2-z_1\right)=0 \\ m_1\ddot{z}_1+m_r\left(\ddot{z}_1-\ddot{z}_2\right)+c_r\left(\dot{z}_1-\dot{z}_2\right)+K_2\left(z_1-z_2\right)+K_1\left(z_1-q\right)=0 \end{cases} \tag{17}$$

Then the matrix form of equation(17) as followed:

$$\begin{bmatrix} m_1+m_r & -m_r \\ -m_r & m_2+m_r \end{bmatrix}\begin{Bmatrix}\ddot{z}_1\\ \ddot{z}_2\end{Bmatrix}+\begin{bmatrix} c_r & -c_r \\ -c_r & c_r \end{bmatrix}\begin{Bmatrix}\dot{z}_1\\ \dot{z}_2\end{Bmatrix}+ \begin{bmatrix} K+K_t & -K \\ -K & K \end{bmatrix}\begin{Bmatrix}z_1\\ z_2\end{Bmatrix}=\begin{Bmatrix}K_tq\\ 0\end{Bmatrix} \tag{18}$$

3. Simulation of the Ball Screw Shock Absorber

The mathematical model of the damping force in the ball screw shock absorber was calculated and simulated using Matlab. In the simulation, a sinusoidal signal, shown as below, was used as the input:

$$x(t)=A\sin\left(2\pi ft\right) \tag{19}$$

where, A is the amplitude of the sinusoidal signal; and f is the frequency of the sinusoidal signal.

As a case, the damping force in the ball screw shock absorber was simulated with a piston stroke of 30 mm and frequencies of 1 Hz, 2 Hz, 3 Hz, 4 Hz and 5 Hz. The indication characteristics of the ball screw shock absorber from the simulations are shown in Fig. 3.

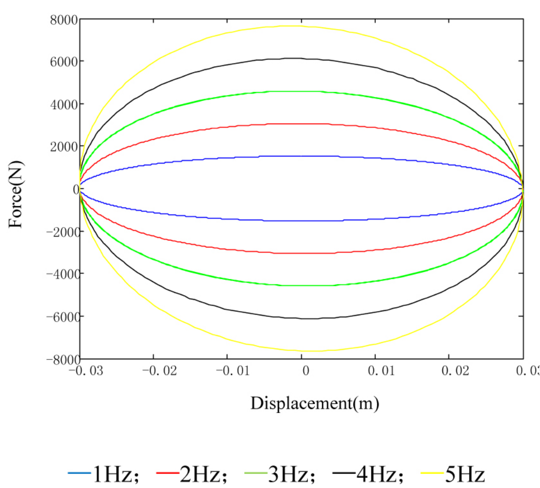


Fig.3. Simulation result of indicator diagram characteristic curve of ball-screw regenerative shock absorber

4. Simulation of the Ball Screw Suspension System Performance

According to the developed damping force model of the ball screw shock absorber, it is clear that the influencing factors of the damping force include the motor rotational inertia, the ball screw rotational inertia, the screw lead, the radius of the screw nut, the voltage constant of the motor, the torque constant of the motor, the drive ratio of the ball screw and the transmission efficiency. Since the parameters including the voltage constant and the torque constant of the motor, as well as the drive ratio and the transmission efficiency of the ball screw should not be changed, these parameters are not considered.

4.1. The Condition with Triangular Pulse Input

Simulations were conducted using a commercial vehicle as an example. In the simulations, the vehicle drives through triangular bumps with a constant speed of 50 km/h. The maximum sprung mass acceleration, maximum dynamic suspension displacement and maximum dynamic tire displacement are adopted as the indicators to investigate the performance of the ball screw suspension. The technical parameters of the commercial vehicle in the simulations are shown in Table 1.

Table.1. A commercial vehicle parameters

Vehicle parameters	Value	Unit
Spring mass	2680	kg
Unspring mas	232	kg
Suspension stiffness	147500	N/m
Suspension damping	7200	N．s/m
Tire stiffness	1500000	N/m

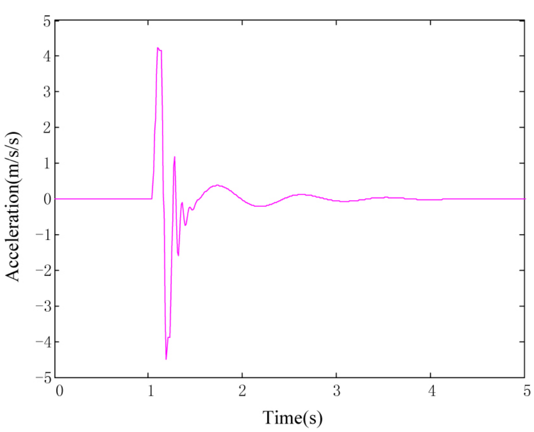


Fig.4. Different screw lead on body acceleration

Combining Eqs. (13),(14) and (18), the model of the ball screw suspension system was built using MATLAB/Simulink. The effects of the parameter changes on the suspension performance were studied by changing the initial values of the motor rotational inertia, the ball screw rotational inertia, the screw lead and screw nut radius with an interval of 2%. The time domain curve of different screw lead on body acceleration as shown in Fig.4, and the effect of screw lead on max acceleration as shown in Fig.5. The others results of simulation list as table show in Tab.2, 3, 4, 5.

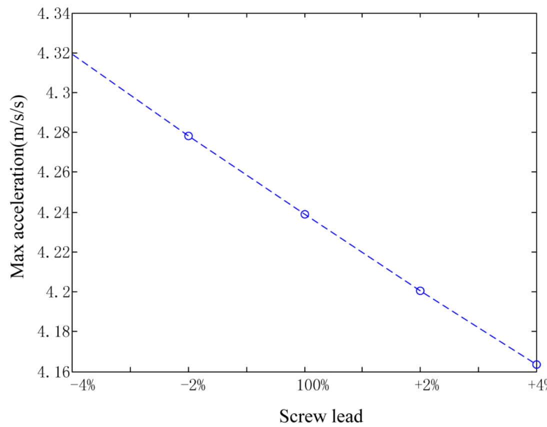


Fig.5. Effects of screw lead on max acceleration

Table.2. Effects of screw radius on suspension performance

Screw radius	Body acceleration	Suspension deflection	Tire displacement
-4%	3.077944	0.023566	0.017808
-2%	3.0406	0.02368	0.017862
100%	3.00524	0.023787	0.017913
+2%	2.972165	0.023889	0.017961
+4%	2.942653	0.023998	0.018006

Table.3. Effects of screw lead on suspension performance

Screw lead	Body acceleration	Suspension deflection	Tire displacement
-4%	3.031019	0.023844	0.017954
-2%	3.017862	0.023815	0.017933
100%	3.00524	0.023787	0.017913
+2%	2.993118	0.02376	0.017894
+4%	2.982266	0.023734	0.017875

From the statistical data shown in Tables 2, 3, 4, 5, it can be seen that the maximum acceleration of the vehicle body decreases with the increase of the motor rotational inertia, the ball screw rotational inertia screw nut radius and the screw lead. The maximum suspension travel increases with the increase of the motor rotational inertia, the ball screw rotational inertia and screw nut radius, decreases with the screw lead. The maximum tire displacement increases with the increase of the motor rotational inertia, the ball screw rotational inertia and screw nut radius decreases with the screw lead.

Table.4. Effects of rotation inertia of screw on suspension performance

Rotation inertia of screw	Body acceleration	Suspension deflection	Tire displacement
-4%	3.005316	0.0237861	0.0179119
-2%	3.005278	0.0237868	0.0179122
100%	3.005239	0.0237874	0.0179125
+2%	3.005201	0.0238881	0.0179129
+4%	3.005163	0.0238887	0.0179133

Table.5. Effects of rotation inertia of motor on suspension performance

Rotation inertia of motor	Body acceleration	Suspension deflection	Tire displacement
-4%	3.0100169	0.02370884	0.01786897
-2%	3.0076251	0.02374817	0.01789078
100%	3.005239	0.0237874	0.0179125
+2%	3.0028602	0.02382667	0.0179343
+4%	3.000487	0.02386583	0.017956

4.2. The Condition with Random Road Input

The road model was built using white noise filtering method. The simulated road surface displacement was obtained by the transform from a zero mean Gaussian white noise:

$$\dot{q} = -2\pi f_0 q + 2\pi n_0 \sqrt{G_q(n_0)u} w_t \tag{20}$$

where, q is the displacement of the road surface; f_0 is the lower cut-off frequency; n_0 is the spatial frequency; $G_q(n_0)$ is the power spectral density of the road surface for the reference spatial frequency of n_0; u is the vehicle speed; and w_t is a zero mean Gaussian white noise.

The time domain curve of different rotation inertia of motor on body acceleration as shown in Fig.6, and the effect of rotation inertia of motor on RMS acceleration as shown in Fig.7. The others results of simulation list as table show in Tab.6, 7, 8, 9.

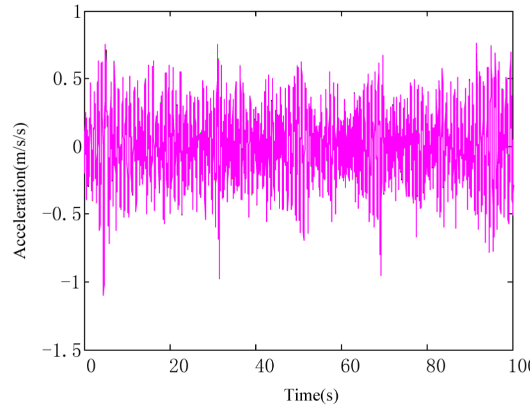


Fig.6. Different rotation inertia of motor on body acceleration

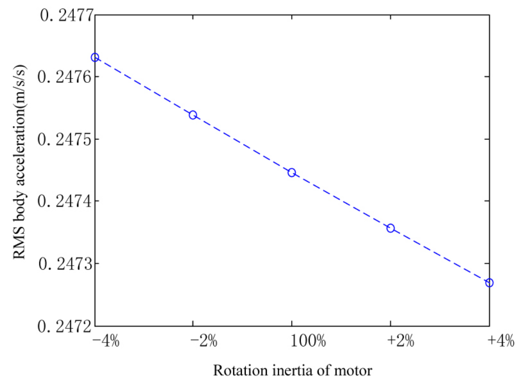


Fig.7. Effects of rotation inertia of motor on body acceleration

Table.6. Effects of screw radius on suspension performance

Screw radius	Body acceleration	Suspension deflection	Tire displacement
-4%	0.2408	0.0040	0.00111
-2%	0.2441	0.0041	0.00113
100%	0.2474	0.0042	0.00115
+2%	0.2509	0.0043	0.00118
+4%	0.2545	0.0044	0.00120

Table.7. Effects of screw lead on suspension performance

Screw lead	Body acceleration	Suspension deflection	Tire displacement
-4%	0.2437	0.004084	0.001133
-2%	0.2456	0.004132	0.001143
100%	0.2474	0.004178	0.001153
+2%	0.2494	0.004223	0.001164
+4%	0.2513	0.004268	0.001174

Table.8. Effects of rotation inertia of screw on suspension performance

Rotation inertia of screw	Body acceleration	Suspension deflection	Tire displacement
-4%	0.24745	0.00417759	0.00115338
-2%	0.247448	0.004177589	0.00115339
100%	0.247447	0.004177588	0.001153395
+2%	0.247445	0.004177587	0.001153402
+4%	0.247444	0.004177586	0.001153409

Table.9. Effects of rotation inertia of motor on suspension performance

Rotation inertia of motor	Body acceleration	Suspension deflection	Tire displacement
-4%	0.24763	0.00417772	0.0011525
-2%	0.247538	0.00417766	0.001153
100%	0.247447	0.00417759	0.0011534
+2%	0.247357	0.00417752	0.0011538
+4%	0.247269	0.00417745	0.0011542

From the statistical data shown in Tables 6, 7, 8, 9, it can be seen that the RMS value of the vehicle body acceleration deceases with the increase of the motor rotational inertia and the ball screw rotational inertia, and increases with the increase of the screw lead and the radius of the screw nut. The RMS value of dynamical suspension displacement deceases with the increase of the motor rotational inertia and the ball screw rotational inertia, and increases with the increase of the screw lead and the radius of the screw nut. The RMS value of tire dynamical displacement increases with the increase of the motor rotational inertia, the ball screw rotational inertia, screw nut radius and the screw lead.

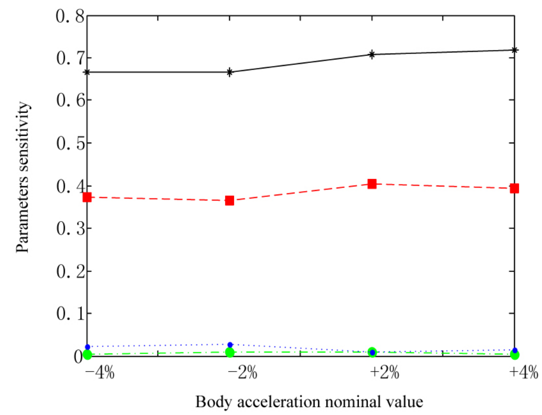
4.3. Parameter Sensitivity Analysis

To determine the influence intensity of the parameters in the ball screw regenerative shock absorber on the suspension performance, the parameter sensitivity of the ball screw rotational inertia, the motor rotational inertia, the screw lead and the radius of the screw nut for the performance indicators of the ball screw regenerative suspension was studied using the one parametric variation method. One parameter's sensitivity was investigated by changing the parameter with an interval of 2% of the initial value for each time and the invariableness of other parameters. The dependence of the RMS values of the vehicle body acceleration, the suspension dynamic travel and the tire dynamic displacement on this parameter was studied. The parameter sensitivity is defined as:

$$s = \left| \frac{(\Delta y / y_0)}{(\Delta x / x_0)} \right| \tag{21}$$

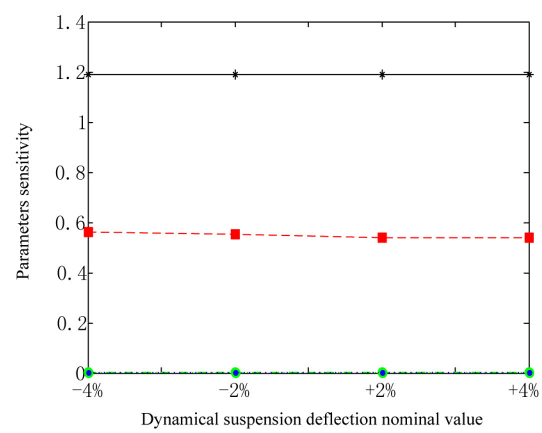
where, s is the parameter sensitivity with respect to the indicator; Δy is the change amount of the indicator; Δx is the change amount of the parameter; x0 is the initial value of the parameter; and y0 is the initial indicator parameter corresponding to x0.

A larger sensitivity indicates a more significant effect of the parameter on the evaluating indicator. The parameter sensitivity of the ball screw regenerative suspension is shown in Figs. 8, 9, 10.



black- nut radius; red-screw lead; green-ball screw rotational inertia; blue- screw motor rotational inertia

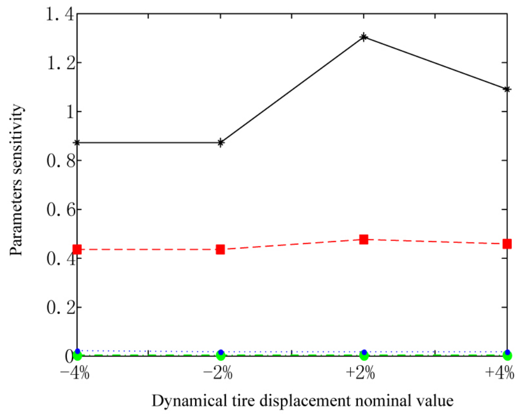
Fig.8. Sensitivity of body acceleration



black- nut radius; red-screw lead; green-ball screw rotational inertia; blue- screw motor rotational inertia

Fig.9. Sensitivity of dynamical suspension deflection

From Figs 8, 9, 10, it can be seen that the most significant factor affecting the performance indicator of the ball screw regenerative suspension is the screw nut radius, followed by the screw lead, while the effects of the ball screw's moment of inertia and the motor's moment of inertia on the suspension performance are less significant.



black- nut radius; red-screw lead; green-ball screw rotational inertia; blue- screw motor rotational inertia

Fig.10. Sensitivity of dynamical tire displacement

5. Conclusions

In this study, a mathematical model of the ball screw shock absorber was established regarding various factors including the ball screw rotational inertia and the motor rotational inertia. Based on this model, the damping force with a 1.67 Hz sinusoidal displacement input was numerically calculated. Combined with the two-degrees-of-freedom suspension dynamic model, the performance of the ball screw regenerative suspension and the effects of parameters on the performance were investigated taking triangle pulse input and random road input as cases.

(1). The simulation results with a triangular pulse input condition indicate that maximum acceleration of the vehicle body decreases with the increase of the motor rotational inertia, the ball screw rotational inertia screw nut radius and the screw lead. The maximum suspension travel increases with the increase of the motor rotational inertia, the ball screw rotational inertia and screw nut radius, decreases with the screw lead. The maximum tire displacement increases with the increase of the motor rotational inertia, the ball screw rotational inertia and screw nut radius decreases with the screw lead. The simulation results with a random road input condition indicate that the RMS value of the vehicle body acceleration deceases with the increase of the motor rotational inertia and the ball screw rotational inertia, and increases with the increase of the screw lead and the radius of the screw nut. The RMS value of the suspension travel deceases with the increase of the motor rotational inertia and the ball screw rotational inertia, and increases with the increase of the screw lead and the radius of the screw nut. The RMS value of the tire displacement increases with the increase of the motor rotational inertia, the ball screw rotational inertia, nut radius and the screw lead.

(2). The influence intensity of the parameters on the suspension performance was investigated by changing the screw lead, the radius of the screw nut, the ball screw rotational inertia and the motor rotational inertia with an interval of 2% of the initial value. The results indicate that the most significant factor affecting the suspension performance is the screw nut radius, followed by the screw lead, while the effects of the ball screw's moment of inertia and the motor's moment of inertia are less significant.

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