Study on dynamic characteristics of horizontal suspension in engineering vehicle seat based on rolling vibration isolation principle

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Abstract. The low frequency horizontal vibration of engineering vehicles is a part of multi-dimensional vibration, which causes driver’s occupational disease. Therefore, the design of low frequency horizontal vibration isolation is of great significance. The principle of rolling vibration isolation is applied to seat suspension for low frequency horizontal vibration isolation in this paper. The natural frequency characteristic model of horizontal suspension and the seat-human system dynamics model with horizontal suspension based on the Lagrangian equation are established. The dynamic characteristics of rolling horizontal suspension are studied on account of the established models. Results show that this horizontal suspension can achieve very low natural frequency so as to isolate the low frequency vibration in horizontal direction by the matching design of the rollers and concave dimensions. The vibration isolation characteristics of the front and back seat-human system are improved with the reduction of the rollers’ radius. The vibration isolation characteristic of the front and back seat-human system increases with the increase of the concave surfaces’ radius.

1. Introduction
Engineering vehicles work in the mine, site and other harsh environment with complicated working condition. Therefore, there exist severe multi-dimensional, low-frequency and large amplitude vibration, which cause all kinds of occupational diseases (backache, lumbago, stomach problem [1], etc.) and seriously affect the physical and mental health of drivers. The seat system is in direct contact with a large area of the driver’s body, and changing its parameters has little effect on the performance of the whole machine. Therefore, it’s particularly important to improve the comfort of driving [2] and good vibration isolation system can make it true.

Engineering vehicle seats are mainly composed of suspension, cushion and backrest. All three parts have important influence on the vibration comfort. The suspension is the main part in terms of vibration isolation. The current seat suspension type mainly includes: linear suspension [3], non-linear suspension [4-6], and active and semi-active suspension [7]. The widely used air spring suspension [8] is also a nonlinear suspension due to the nonlinear force-displacement characteristics of the spring.

There has been a lot of research on the engineering vehicle seat, mainly involving the vibration comfort of the seat (seat-man system) [9,10], Static and dynamic characteristics of seat suspension [11] and seat-man system dynamics model [12-14] etc.. The seat suspensions mentioned above mainly plays the role of isolating vertical vibration and most of them are vertical one-dimensional vibration isolation suspension. But the vibration of engineering machinery is multiple dimensions including...
vertical vibration, horizontal vibration, swing vibration, and so on [15]. The horizontal vibration isolation demand of some types of engineering vehicle seats is higher than that of vertical vibration isolation, such as the seat of excavator). Vibration in multiple directions causes health damage to the driver [16]. In the field of multi-dimensional vibration research, many researchers have long recognized that the difficulty of horizontal isolation design is that there needs to be very low natural frequency of horizontal vibration (0.7 Hz) [17], which is difficult to achieve in structure. In addition, a seat suspension with vertical and horizontal vibration isolation capability is designed [18]. Through a three-layer structure, it realized vibration isolation in three directions (from vertical to left and right). Due to the complexity of the structure, engineering transformation has not been realized in the past years.

Rolling vibration isolation system has a history of more than 100 years, mainly used in buildings, large equipment and other seismic isolation [19,20]. The rolling vibration isolation principle is applied to low frequency vibration isolation of seat horizontal vibration suspension in this paper firstly. It can realize low frequency vibration isolation in horizontal plane to four directions. The working principle is to achieve the isolation of horizontal vibration by rolling the roller in the upper and lower concave surface. The types of rollers are spherical, ellipsoid and cylindrical. The concave surface of a concave part is spherical, conical, inclined plane and variable curvature. The rolling vibration isolation system is divided into single-layer and double-layer systems [21]. The low frequency vibration isolation can be achieved by the reasonable curvature design and roller curvature. This system is applied to seat horizontal vibration suspension in this paper, and the low frequency vibration isolation can be realized in two horizontal directions through a layer structure. The dynamic model of seat-human coupling in front and back direction is established to study the effect of key design parameters of horizontal vibration isolation system on vibration isolation performance of seat-human coupling system in front and back direction.

2. Modeling of natural frequency characteristic

The suspension principle in this paper is shown in figure 1. Four spherical rollers are installed between the top and bottom concave surfaces. The upper and the lower concave structure curvature can be the same or different, and the curvature of the concave from the middle to the edge of the radius of curvature may change. If radius of curvature in the middle of the area is big, the horizontal seat–human system has low natural frequency, and the ability of low-frequency vibration isolation is strong. The rollers can be prevented to roll out the concave structure due to the small curvature radius of edge area, which can limit the rollers positions. The horizontal vibration natural frequency of seat-human system is the key index. When designing horizontal suspension, low-frequency excitation can be isolated, the natural frequency must be lower. The model of seat-human horizontal vibration natural frequency is established in the following discussion. The human body is assumed to be a rigid body, the quality is m.

![Figure 1. Schematic diagram of horizontal suspension.](image1)
![Figure 2. Diagram of force analysis.](image2)

Figure 2 shows the static force diagram of the roller at any position. Its gravity is negligible since
the roller is small compared with the human body mass. The contact points between the roller center and the upper and lower concave surface form a three-point line. Their extended line \( c \) passes through the centers of the concave surface \( O_1 \) and \( O_2 \).

In the horizontal direction, the equation of free vibration of human body is:

\[
m\ddot{x} = ma = mg \sin \theta
\]  

Where, \( \theta \) is the Angle between the central connection, the former three-point line, and the vertical direction. \( \sin \theta \) can be expressed as a function of the human body's horizontal displacement \( x \), the process is as follows.

\( A \) and \( B \) are the highest and lowest points of the upper and lower concave surfaces respectively. The horizontal distance between \( A \) and \( B \) is the horizontal displacement of the seat suspension, which can be obtained by geometric relations:

\[
x = x_1 + x_2
\]  

Where, \( x_1 \) and \( x_2 \) are the horizontal displacement of the upper and lower concave surfaces respectively relative to the roller center. And their geometrical relation can be found easily:

\[
\frac{x_1}{(R - r)} = \sin \theta
\]  

\[
\frac{x_2}{(R' - r)} = \sin \theta
\]  

Where, \( R \) is the curvature radius of the lower concave surface; \( R' \) is the curvature radius of the upper concave surface and \( r \) is the radius of the roller.

Substitute equations (3) and (4) into equations (2)

\[
x = (R - r) \sin \theta + (R' - r) \sin \theta = (R + R' - 2r) \sin \theta
\]  

Substitute equations (5) into equations (1)

\[
m\ddot{x} = \frac{mgx}{(R + R' - 2r)}
\]  

According to equation (6), the natural angular frequency of the horizontal vibration isolation system is

\[
\omega_n = \sqrt{\frac{g}{(R + R' - 2r)}}
\]  

Then the natural frequency is

\[
f_n = \frac{\omega_n}{2\pi} = \frac{\sqrt{\frac{g}{(R + R' - 2r)}}}{2\pi}
\]  

3. Modeling of seat-human system dynamics

There is multiple natural frequency in human body. The dynamic characteristics of multiple degree of freedom of human body must be considered since human body can not be regarded as rigid during the design of seat suspension. As a result, the front and back seat-human system dynamics model is established in this paper, as shown is figure 3. The dynamic coupling characteristics between horizontal suspension and human body in the front and back directions are also be discussed. The human body model is quoted from literature [22], a 6 degree of freedom model. The parameters related to the human body model and the seat are shown in table 1. \( M_i \) is the mass of each mass block.
in the human body model. \(K_i\) is the stiffness of each linear spring; \(K_{ti}\) is the stiffness of each torsion spring. \(C_i\) is the damping of each linear damper; \(C_{ti}\) is the damping of each torsional damper.

**Figure 3.** Seat - human system dynamics model in front and back directions.

**Table 1.** Human body dynamics model and seat parameters in front and back directions.

| Related parameters of human body model | m1 (kg) | m2 (kg) | m3 (kg) | m4 (kg) | J1 (kgm²) | k1 (N/m) | k2 (N/m) | Kt1 (N/m) | c1 (Ns/m) | c2 (Ns/m) | c1 (Ns/m) | c2 (Ns/m) | h1 (m) |
|---------------------------------------|---------|---------|---------|---------|-----------|----------|----------|-----------|----------|----------|-----------|----------|-------|
|                                       | 20      | 35      | 10      | 8       | 5         | 39886    | 10924    | 10        | 359      | 542      | 112       | 112      | 0.35  |

| Related parameters of seat model      | m5 (kg) | m6 (kg) | J2 (kgm²) | k3 (N/m) | k4 (N/m) | Kt2 (N/m) | c3 (Ns/m) | c4 (Ns/m) | c5 (Ns/m) | c5 (Ns/m) | ct2 (Ns/m) | h2 (m)   |
|---------------------------------------|---------|---------|-----------|----------|----------|-----------|-----------|-----------|-----------|-----------|------------|---------|
|                                       | 6       | 2       | 1.0       | 26646    | 24610    | 10        | 0.0       | 0.0       | 100       | 1316      | 0.3        |         |

The dynamic model of the seat-human system in front and back directions is established based on the Lagrange equation.

\[
\frac{d}{dt} \left( \frac{\partial T}{\partial \dot{x}_i} \right) - \frac{\partial T}{\partial x_i} + \frac{\partial U}{\partial x_i} + \frac{\partial D}{\partial \dot{x}_i} = Q_i
\]  

(9)

Where, \(T\) is the kinetic energy of the system; \(U\) is the system potential energy; \(D\) is the dissipated energy of the system; \(X_i\) is the generalized degree of freedom of \(i\) item; \(Q_i\) is the generalized force corresponding to the generalized degree of freedom of \(i\) item.

**Kinetic energy** \(T\) of system is

\[
T = \sum_{i=1}^{6} \frac{1}{2} m_i \dot{x}_i^2 + \sum_{j=1}^{2} \frac{1}{2} I_j \dot{\theta}_j^2
\]  

(10)

Where, \(\dot{\theta}_1 = \frac{x_3 - x_4}{h_1}, \dot{\theta}_2 = \frac{x_6 - x_5}{h_2}\)

**System potential energy** is

\[
U = \sum_{i=1}^{4} \frac{1}{2} k_i \Delta x_i^2 + \sum_{j=1}^{2} \frac{1}{2} k_t j \dot{\theta}_j^2 + Mg y
\]  

(11)
Where, $\Delta x_1 = x_1 - x_1$, $\Delta x_2 = x_2 - x_6$, $\Delta x_3 = x_3 - x_5$, $\Delta x_4 = x_4 - x_6$, $\Delta x_5 = x_5 - z$, $M = \sum_{i=1}^6 m_i$.

(The human body is assumed as a mass block in the calculation since the dynamic characteristics of horizontal direction are considered, and the gravitational potential energy acts in the vertical direction), $y = 2(R-r) \left[ 1 - \sqrt{1 - \frac{(z-x_5)^2}{4(R-r)^2}} \right]$.

Dissipation energy of the system is

$$D = \sum_{i=1}^4 \frac{1}{2} c_i \Delta x_i^2 + \sum_{j=1}^2 \frac{1}{2} c_t \theta_j^2$$

(12)

The corresponding generalized forces for each generalized degree of freedom are respectively, $Q_1 = 0$, $Q_2 = 0$, $Q_3 = 0$, $Q_4 = 0$, $Q_5 = -\mu k y$, $Q_6 = 0$.

Substitute equations (10), (11) and (12) into equations (9). The 6 degree of freedom dynamics model of the front and back seat-human system with horizontal suspension can be obtained

$$m_1 x_1'' + k_1(x_1 - x_3) + c_1(x_1' - x_3') = 0$$

(13)

$$m_2 x_2'' + k_2(x_2 - x_4) + c_2(x_2' - x_4') = 0$$

(14)

$$m_3 x_3'' + \frac{f_1}{h_1^2}(x_3'' - x_4) + k_3(x_3 - x_1) + k_3(x_3 - x_5) + \frac{k_{t1}}{h_1^2}(x_3 - x_4) + c_1(x_3' - x_1') + c_3(x_3' - x_5')$$

$$+ \frac{c_{t1}}{h_1^2}(x_3' - x_4') = 0$$

(15)

$$m_4 x_4'' + \frac{f_1}{h_1^2}(x_4'' - x_5) + k_4(x_4 - x_2) + k_4(x_4 - x_6) + \frac{k_{t1}}{h_1^2}(x_4 - x_3) + c_2(x_4' - x_2') + c_4(x_4' - x_6')$$

$$+ \frac{c_{t1}}{h_1^2}(x_4' - x_3') = 0$$

(16)

$$m_5 x_5'' + \frac{f_2}{h_2^2}(x_5'' - x_6) + k_3(x_5 - x_3) + k_3(x_5 - x_3) + \frac{k_{t2}}{h_2^2}(x_5 - x_6) + \frac{1}{2(R-r)} \frac{Mg}{\sqrt{1 - \frac{(x_5 - z)^2}{4(R-r)^2}}} + c_3(x_5' - x_3')$$

$$+ \frac{c_{t2}}{h_2^2}(x_5' - x_6') = -\mu k \mp 2(R-r) \left[ 1 - \sqrt{1 - \frac{(z-x_5)^2}{4(R-r)^2}} \right]$$

(17)

$$m_6 x_6'' + \frac{f_2}{h_2^2}(x_6'' - x_5) + k_4(x_6 - x_4) + k_4(x_6 - x_5) + c_4(x_6' - x_4') + c_{t2}(x_6' - x_5') = 0$$

(18)

4. Model verification based on Adams

In order to verify this seat - human system dynamics model in this paper, the human body suspension system dynamic model with single degree of freedom is established based on the Adams software. As
shown in figure 4(a), model parameters are shown in table 2.

Table 2. Model parameters of Adams.

| M (kg) | R (m) | R’ (m) | r (m) |
|--------|-------|--------|-------|
| m1+m2+m3+m4+m5+m6 | 0.25  | 0.25   | 0.004 |

In addition, the spring stiffness parameters between the human body each mass in equations (13)-(18) increase to ten times the original parameters, which holds that the human body is a rigid body, then solve. human body displacement response in time domain can be achieved by two methods respectively, as shown in figures 4(b) and 4(c).

From figure 4, two models for human body response in time domain are consistent, which confirm the correctness of the seat-human system dynamics model. However, human body dynamic model quoted from literature [22] directly has never been verified in this paper. And researching on the dynamic characteristics of seat-human system dynamics model should be followed.

5. Results and discussion

5.1. Natural frequency characteristics

The horizontal natural frequency of the seat-human system is related to R, R’ and r, and has nothing to do with the human body quality when human body is regarded as a mass block from expression (8). When R = R’, the natural frequency of system horizontal directions (front and back, left and right) are the function of (R - r). Effect of (R - r) on the natural frequency of the system is shown in figure 5. It is similar to a hyperbola function. When it is close to 0, system natural frequency increases rapidly. When it is away from 0, with the increase of (R - r), the natural frequency of system declines slowly. The natural frequency is the key parameter in design of horizontal isolation suspension. To isolate the horizontal low-frequency excitation, the natural frequency of seat-human system in horizontal...
direction must be lower. Based on the frequency of isolation horizontal excitation, the natural frequency characteristics of seat-human system can be determined and further the following isolation system design parameters.

![Figure 5](image)

Figure 5. Effect of \((R-r)\) on the natural frequency of the system.

5.2. System dynamic characteristics

Effects of the key design parameters \((R, r, c_s)\) of horizontal vibration isolation suspension on the vibration transfer characteristics is studied on account of seat-human system dynamic model in front and back directions (equations (13)-(18)). Simple harmonic small amplitude sweep excitation is exerted on the floor. In a study of design parameters on the system vibration isolation characteristics, the other parameters are fixed parameter selection of each variable as shown in table 3.

| Table 3. Numerical value of \(R, r\) and \(c_s\). |
|-------------------------------|------------|-------------|
| \(R\)               | \(r\)      | \(c_s\)    |
| 1  0.13              | 0.016, 0.032, 0.064 | 100         |
| 2  0.065, 0.13, 0.26 | 0.032      | 100         |
| 3  0.13              | 0.032      | 10, 100, 1000 |

- Effect of \(r\) on seat-human system vibration isolation characteristics in front and back directions is shown is figure 6(a). with the decrease of \(r\), the natural frequency of system decreases, resonance peak moves to low frequency zone and vibration isolation performance is improved. But limited by structural design, too small value of \(r\) is not appropriate. The value of \(r\) can be determined by considering the value of \(R\) and structural design feasibility.

- Effect of \(R\) on seat-human system vibration isolation characteristics in front and back directions is shown is figure 6(b). with the increase of \(R\), the natural frequency of system decreases, resonance peak moves to low frequency zone and vibration isolation performance is improved. Combined with \(r\), the realization of structure (the structural limitation of machining pits on steel plates.) is also considered in design of \(R\). In addition, there must be enough clearance between the upper and the lower concave surfaces.

- Effect of \(c_s\) on seat-human system vibration isolation characteristics in front and back directions is shown is figure 6(c). With the increase of \(c_s\), basically resonance peak frequency remains unchanged, but the peak value decreases. The curve on the right side of the isolation zone increases, which means the decrease of vibration isolation performance. This effect and the influence of damping on the vibration isolation performance of the linear system is consistent. \(c_s\) must be a reasonable value in order to reduce the resonance peak values, even leading to a fall in vibration isolation performance of the isolation zone, since the horizontal excitation frequency may pass through the resonance zone.
6. Conclusion

Aiming at the problem of horizontal low-frequency vibration isolation of engineering vehicles, the design of horizontal suspension based on the principle of rolling vibration isolation is put forward in this paper. This suspension can realize the low frequency vibration in the horizontal plane (front and back, left and right). The natural frequency mathematical model of horizontal vibration isolation is established in the assumption that human body is a mass block. Considering complex dynamic characteristics of the human body, based on the Lagrange equation, the seat-human system dynamics model in front and back directions is deduced. The simulation verification has been done based on Adams software. The horizontal natural frequency of the vibration isolation suspension features and the effect of key design parameters on the vibration isolation characteristics in front and back directions are analyzed. Results show that the horizontal seat suspension based on rolling vibration isolation system can achieve very low natural frequency, and isolate the horizontal low frequency vibration in engineering vehicles. But there are still some problems, such as horizontal vibration limit problem or and the horizontal vibration isolation problems under complex conditions, etc. All the problems will be considered afterwards.

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