Optimization analysis of dynamic characteristics of a certain car seat with rigid-flexible coupling

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Abstract. Aiming at the problem of the dynamic comfort of a certain car driver's seat, from the aspect of selecting the dynamic parameters of the seat cushion, a simulation idea for studying the dynamic comfort of the seat has been proposed. The rigid-flexible coupling dynamics model of the human body and the seat is established through the flexible processing of the seat cushion. ADAMS has been used to analyze the dynamics of the model and compare the changes in the human comfort level when the dynamic parameters of the seat cushion are changed. The optimal range for selecting its dynamic parameters has been obtained. ADAMS/Car has been used to establish a virtual model of the vehicle system, and the dynamic comfort of the model has been analyzed to obtain the human body acceleration power spectral density curve. The results indicate that the optimal selection ranges for seat cushion stiffness and damping are 14–20N/mm and 0.3–0.6Ns/mm, respectively. In this range, the resonance frequency of the car seat is lower than the most sensitive frequency of the human body. Use the human comfort evaluation method to verify that the result is reliable, it provides a direction for the subsequent design.

1. Introduction

The car seat is one of the safety components of the car, and its dynamic characteristics are the main influencing factors of ride comfort and occupant safety, so it is particularly important to study the dynamic characteristics of the seat [1]. At present, scholars at home and abroad have made many research results on the comfort of car seats, Zhang Z et al. used the finite element modeling method to change the local mass distribution of the car seat, which reflects the relationship between the local mass of the seat and its vibration characteristics [2]. Wang Y et al. proposed a quasi-zero stiffness (QZS) vibration isolator as a seat suspension, which can better improve the vibration isolation performance of the vehicle [3]. F. D'Amico et al. study proposes a theoretical model of qualitative relationships between differing stages and location of rutting, and the consequent effects on driving safety for different types of vehicles (passenger cars and powered two wheelers) [4]. It is worth to emphasize the relevance of this research for maintenance prioritization purposes at the road network level. Priority is based on the level of risk associated with the pavement degradations and with different types of vehicle. Wang Yong et al. used numerical methods to study the dynamic comfort of the human body-whole vehicle dynamic model under random excitation, the model has 8 degrees of freedom [5]. In the research of the above scholars, from the way of applying excitation to the seat entity structure to study its dynamic characteristics, to the mature development of computer technology, many research methods of seat vibration characteristics have appeared. For example, finite element method, multi-body system dynamics method, statistical energy analysis and transfer path analysis have achieved good results [6]. However, there are few studies on the dynamic comfort
of the human-seat system, and there is a lack of research on the influence of the flexibility of the seat cushion in the seat model.

In response to the above problems, taking the driver’s seat as the research object, make the seat cushion part of the seat flexible, establish a human-seat rigid-flexible coupling model and analyze the dynamic characteristics of the model in Adams. get the best range of cushion stiffness and damping. And by simulating the dynamic comfort of the vehicle system, the power spectrum density curve of the human body is obtained to verify whether the selected range of dynamic parameters is appropriate, and to provide an optimal direction for the design of the same type of car seat.

2. Build model

Traditional seat dynamics models are basically rigid components and do not deform during simulation analysis. In fact, the seat cushion is relatively soft and directly contacts the human body, which will cause greater deformation during the driving of the car [7]. Therefore, the cushion part of the seat is made flexible, establish a rigid-flexible coupling model of the human-seat system to improve the accuracy of the simulation. Build a model in Solidworks according to the actual seat, the solid model of the seat is shown in Figure 1.

![Seat solid model](image)

**Figure 1.** Seat solid model.

Finite element software is used to solve the modal to realize the softening of the seat cushion. The cushion sponge is made of polyurethane foam (PU), other materials are Q235 steel, the specific material parameters are shown in Table 1.

| Name | Density (kg/m$^3$) | Elastic modulus (GPa) | Poisson's ratio |
|------|--------------------|-----------------------|----------------|
| PU   | 520                | 0.85                  | 0.3            |
| Q235 | 7850               | 210                   | 0.3            |

Traditional seat dynamics models are basically rigid components and will not deform during simulation analysis. In fact, the seat cushion is relatively soft and directly contacts the human body, which will cause greater deformation during the driving of the car. Therefore, the cushion part of the seat is made flexible, and a rigid-flexible coupling model of the human body-seat is established to improve the accuracy of the simulation.

The meshing of the model is realized in Hypermesh, the foam adopts tetrahedral elements, the sheet metal adopts Shell elements, and the steel wire adopts beam elements. There are 10,919 nodes and 42021 units in total. Create marker points at the center of the connection between the seat cushion and the human body and the seat frame, replace the original rigid cushion with the cushion modal neutral file (MNF) generated by the solution. The rigid-flexible coupling model of the human-seat system is shown in Figure 2.
3. Dynamic simulation analysis

Consider model of human body as four parts (head, chest and shoulders, waist and abdomen, buttocks and thighs), and replace each part with a mass block. And use springs and damping elements to connect each mass block to form a human body vertical vibration model with four degrees of freedom [8], the seat is regarded as a mass block, connected to the human body in the same way, and has a degree of freedom.

The vibration differential equation of the human-seat system is

$$ [M]\ddot{z} + [C]\dot{z} + [K]z = [B]q $$

(1)

In the above formula, $[M]$ is the mass matrix; $[C]$ is the damping matrix; $[K]$ is the stiffness matrix; $[B]$ is the coefficient matrix; $\{q\}$ is the excitation vector, $\{z\}$ is the vertical component of the center of gravity displacement.

The Fourier transform of Formula (1) can be obtained,

$$ e^{j\omega \Xi} [M]\ddot{z}(\omega) + j\omega[C]\dot{z}(\omega) + [K]z(\omega) = [B]\{Q(\omega)\} $$

(2)

Among them,

$$ \{Q(\omega)\} = \frac{1}{j\omega} \{z_0(\omega)\} $$

(3)

which is substituted into Formula (2) to obtain,

$$ \{z(\omega)\} = (-\omega^2[M] + j\omega[C] + [K])^{-1}[B]\{Q(\omega)\} $$

(4)

The transfer function of the above model is

$$ H(\omega) = |H_1(\omega), H_2(\omega), H_3(\omega), H_4(\omega), H_5(\omega), |\n
= \left| -\omega^2[M] + j\omega[C] + [K] \right|^{-1} \left| \frac{1}{j\omega} \right| $$

(5)

In the above formula, $H_1(\omega), \cdots, H_5(\omega)$ are the displacement transfer functions between the various parts of the human body-seat and the car floor. The value of $H(\omega)$ is the ratio of the displacement of the center of gravity of each part to the input displacement of the body floor. The expression of the displacement transfer function $H_1(\omega)$ between the human head and the car floor is

$$ H_1(\omega) = \frac{z_1(\omega)}{x_0(\omega)} $$

(6)

The acceleration response transfer function of the human head is

$$ S[\omega] = \frac{z_1(\omega)}{x_0(\omega)} $$

(7)

The four mass blocks are connected in series in the above manner, and the structure diagram of the human body model is shown in Figure 3. According to GB/T 17245-2004 [9], the moment of inertia of each part of the human body has been set, the dynamic parameters such as the mass of each part of the human body are shown in Table 2.
After field measurement of the car seat, the weight of each part is: seat cushion sponge 1.32kg, backrest sponge 1.83kg, seat assembly 21.21kg. The original dynamic parameters of the cushion refer to the experimental data of Ye Fang et al. [10], the sponge stiffness is 18N/mm, and the damping is 0.3Ns/mm. The external excitation uses the sweep function to input the sine sweep excitation at the bottom of the cushion. Taking vertical as an example, the frequency domain curve of human head acceleration response is shown in Figure 4.

It can be seen from the above figure that the peak value of the acceleration response is 2.406mm/s², and the resonance frequency is 1.968Hz. When the stiffness is constant, choose different damping of the car seat cushion, and the vertical acceleration frequency domain curve of the head is shown in Figure 5.
Figure 5. The acceleration response curve when the damping changes.

The acceleration response peak value and resonance frequency obtained from the above figure are shown in Table 3.

Table 3. Simulation results of human chair system dynamics (1).

| Cushion stiffness (N/mm) | Cushion damping (Ns/mm) | Resonance frequency (Hz) | Peak head acceleration response (mm/s²) |
|-------------------------|-------------------------|--------------------------|----------------------------------------|
| 18                      | 0.1                     | 0.938                    | 3.323                                  |
| 18                      | 0.2                     | 1.883                    | 2.790                                  |
| 18                      | 0.3                     | 1.968                    | 2.406                                  |
| 18                      | 0.6                     | 2.041                    | 2.356                                  |
| 18                      | 0.7                     | 2.295                    | 2.026                                  |

The simulation results show that when the stiffness of the seat cushion remains unchanged, the greater the damping, the smaller the acceleration response of the human body, and the better the comfort of the seat. However, damping is related to material properties and manufacturing processes, and the actual damping cannot be increased indefinitely due to these limitations. The higher the damping, the closer the resonance frequency to the most sensitive frequency range of the human body (4–8Hz). Therefore, it is recommended that the best value range of cushion damping is 0.3–0.6Ns/mm.

When the damping is constant, choose different stiffness of the car seat cushion, and the vertical acceleration frequency domain curve of the head is shown in Figure 6.

Figure 6. Acceleration response curve when stiffness changes.
The acceleration response peak value and resonance frequency obtained from the above figure are shown in Table 4.

| Cushion stiffness (N/mm) | Cushion damping (Ns/mm) | Resonance frequency (Hz) | Peak head acceleration response (mm/s²) |
|--------------------------|-------------------------|--------------------------|-----------------------------------------|
| 10                       | 0.3                     | 3.672                    | 2.109                                   |
| 14                       | 0.3                     | 2.080                    | 2.379                                   |
| 18                       | 0.3                     | 1.968                    | 2.406                                   |
| 20                       | 0.3                     | 1.875                    | 2.596                                   |
| 24                       | 0.3                     | 1.497                    | 3.106                                   |

The simulation results show that when the damping of the seat cushion remains unchanged, the smaller the stiffness, the smaller the acceleration response of the human body, and the better the comfort of the seat. When the stiffness decreases, the corresponding elastic displacement of the human body in the vertical direction increases, which reduces the comfort of the human body. Therefore, the stiffness should have a minimum limit. It is recommended that the best value range of the seat cushion stiffness is 14~20N/mm.

4. Verification

Establish a vehicle system dynamic model including the front and rear suspension system, steering system, body, powertrain system, tires, and human body-seat system in the ADAMS/Car software. The human body-seat system model is added to the Other Subsystems option. Mount the entire car model on the FOUR POST four-column test bench, which is specially designed for vehicle ride comfort simulation. The established vehicle model is shown in Figure 7.

![Figure 7. Complete vehicle model.](image)

Select stiffness and damping from the range of values obtained from the above simulation results, choose 17N/mm for stiffness and 0.4Ns/mm for damping. ADAMS/Car software is used to establish a virtual model of the whole vehicle system. The Sayers digital model in the software Ride module is used to generate the road surface, which contains various types of road test parameters, which can better display the random unevenness of the road surface. The relationship between the spatial power spectral density of the road profile and the spatial frequency \( n \) in the road profile generator model is

\[
G_d(n) = G_e + \frac{\sigma_x}{(2\pi n)^2} + \frac{\sigma_a}{(2\pi n)^4}
\]  

(8)

In the above formula:

- \( G_e \) —White noise spatial power spectral density amplitude.
- \( G_a \) —The velocity power spectral density amplitude of white noise.
- \( \sigma_a \) —Amplitude of acceleration power spectral density of white noise.
The spatial power spectral density of the road profile is composed of three mutually independent white noises. An example of the parameters of the road profile in the Sayers model is shown in Table 5.

**Table 5.** Road roughness parameters.

| Type of Road   | IRI Road roughness | Spatial power spectral density ($G_e$) | Velocity power spectral density ($G_v$) | Acceleration power spectral density ($G_a$) |
|---------------|--------------------|---------------------------------------|----------------------------------------|-------------------------------------------|
| asphalt road  | 150 (in/m)        | $2.367 \times 10^{-6}$ cycle          | 0 (m cycle $\times 10^{-6}$)          | 0.17 (1 m cycle $\times 10^{-6}$)         |
| cement road   | 161 (m/km)        | $2.541 \times 10^{-6}$ cycle          | 0.1 (m cycle $\times 10^{-6}$)        | 0.25 (1 m cycle $\times 10^{-6}$)         |

Simulated driving at a speed of 60Km/h, and obtain the curve of human body acceleration power spectral density. Take the vertical direction as an example, the simulation results of simulated driving on asphalt pavement are shown in Figure 8.

![Figure 8. Simulation results of asphalt pavement.](image)

From the figure, the acceleration power spectral density reaches the peak value of $0.196 \text{m}^2/\text{s}^3$ at 2.61Hz. The simulation result of cement pavement is shown in Figure 9.

![Figure 9. Simulation results of cement pavement.](image)

From the figure, the acceleration power spectral density reaches the peak value of $0.309 \text{m}^2/\text{s}^3$ at 2.390Hz.

The simulation results are evaluated using ISO2631-1:1997(E) [11]. Perform frequency spectrum analysis on the acceleration time function $a(t)$ of the simulation result to obtain the power spectral density function $G_a(f)$. Substitute into the following formula to calculate.

$$a_w = \left[ \int_{0.5}^{80} W^2(f)G_a(f)df \right]^{\frac{1}{2}}$$  

(9)
In the above formula, $a_w$ is the root-mean-square value of acceleration, $W(f)$ is the frequency weighting function, and $G_d(f)$ is the power spectral density function. The frequency weighting function $W(f)$ (asymptote) is

$$W(f) =
\begin{cases}
0.5 & (0.5 < f < 2) \\
\frac{f}{4} & (2 < f < 4) \\
1 & (4 < f < 12.5) \\
\frac{12.5}{f} & (12.5 < f < 80)
\end{cases}
$$

(10)

Export the simulated human acceleration power spectrum curve to MATLAB. Write a calculation function of weighted acceleration root-mean-square in MATLAB according to Equation (8). The obtained weighted acceleration root mean square value is Table 6.

**Table 6.** Evaluation results of human comfort.

| Road          | $a_w$ (m/s²) | Comfort evaluation |
|---------------|--------------|--------------------|
| Asphalt road  | 0.251        | No discomfort      |
| Cement road   | 0.295        | No discomfort      |

It can be seen from the simulation results that the root-mean-square values of acceleration obtained on different roads are all within the range that the human body feels comfortable. The greater the roughness of the road surface, the faster the vehicle speed, the greater the root mean square value of the human body’s acceleration, and the lower the human body’s comfort. This is consistent with actual car driving and riding, so the simulation results are basically correct. It also shows that the optimal range of seat dynamics parameters obtained through simulation is correct.

5. Discussions
Through the principle of multi-body dynamics and simulation software, the rigid-flexible coupling model of the human body-seat system is analyzed, and the optimal selection range of cushion stiffness and damping is obtained in combination with the actual situation. Based on this value range, a virtual model of the vehicle system is established to analyze the vibration characteristics of the seat under different road conditions. The analysis results show that when the cushion damping of the seat is selected to be 0.3~0.6Ns/mm, the human body is in a comfortable state while riding and the acceleration response change value is not very large, so it is recommended to control the damping value within this range. When the cushion stiffness of the seat is selected to be 14~20N/mm, the human body is in a comfortable state and the acceleration response change value is not very large, so it is recommended to control the stiffness value within this range. Based on the optimal value range of the above dynamic parameters, a group was selected, and the dynamic comfort simulation analysis of the car seat was carried out on two roads at 60Km/h. Evaluation of simulation results using ISO2631-1:1997(E) human comfort evaluation method. The evaluation results show that both types of roads are within a comfortable range for the human body. The results verify the feasibility of the selection of car seat dynamics parameters.

Recommendations
In the next stage of research, the dynamic parameters of tires, suspension and other components can be analyzed, and the matching problem between the parameters can be analyzed to further optimize the dynamic characteristics of the seat.

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