Structure design and parameters calculate of suspension system test bench

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Abstract. In order to research the vibration property of different dampers in different road conditions and different control strategies, a type of electro-hydraulic road excitation test bench is designed in allusion to a quarter of vehicle suspension system of a single wheel. Firstly, the structure and components of the test bench is designed, then the design requirements and targets are ascertained for the three types of normally used excitation through theoretical analysis, they are sine excitation, random excitation, and bump excitation. After that, the parameters of the test bench are calculated according to the requirements and targets. Finally, a prototype of the test bench is manufactured and the performances of the test bench are tested under the three types of excitation respectively, the results of the test show that, the errors between the actual displacements and the target displacements are tiny, and the test bench could make the objective road excitation reappear well.

1. Introduction

Bench test is an effective method to test the performance of vehicle suspension system with less manpower and material resources consumption. There are several types of commonly used suspension system test bench, for example, the MTS 320 four channel tire coupled road simulator [1-2]; MTS 871 single channel electro-hydraulic servo system, which can simulate the wheel by sine, impulse and random excitation [3-4]; INSTRON produced 8800 series hydraulic servo vibration test bench can also simulate random excitation of different road level [5-7]. On the domestic front, literature[8] designed a suspension test device based on cam mechanism, but its function is limited in sinusoidal excitation; the suspension system test bench produced by Beijing FOLI System Company also realize sinusoidal excitation only[9-10]. It can be found that the suspension test bench is mainly produced by the companies and the design method is not supplied, and some literatures which discussed the design method is mainly based on the cam mechanism, and can only realize sinusoidal excitation however. According to the research requirements in the suspension system tests, the structure of a single wheel suspension system test bench system is designed, the system parameters are calculated, and a set of test bench system which can realize sinusoidal, random and impulse excitation is developed. Finally, performance tests are carried out to verify whether the test bench system reach the design object.
2. Structure design and system constitute of the test bench

The suspension system test bench adopts electro-hydraulic excitation control system; the overall structure of the system is shown in figure 1, reference to the suspension system of a quarter of vehicle. The components of the suspension test bench mainly including control unit, suspension model unit, excitation unit, hydraulic pump, and sensors group.

![Figure 1. Structure of the suspension system test bench.](image-url)

(1) Control unit
The control unit is mainly composed of vibration control device, sensor, data acquisition system and the corresponding control software, its main function is to have a feedback control on the electro-hydraulic servo valve and the hydraulic pump.

(2) Suspension model unit and sensor group
The suspension model unit is mainly composed of mass blocks (several), upper platforms, two suspension springs, damper, lower platforms, and analog tyre spring, etc. Different types of vehicle suspension systems are simulated by dynamic similarity principle. When the analog tyre spring is removed and connecting the working platform directly to the lower platform, the suspension system can be simplified as a single degree of freedom system (as shown in figure 1). The sensor group includes platform displacement sensor, suspension deflection sensor, servo cylinder displacement sensor, upper platform acceleration sensor, lower platform acceleration sensor and lower platform force sensor.

(3) Excitation unit and the hydraulic pump
The excitation unit is composed of electro-hydraulic servo valve, servo amplifier, vibrating head and working table, etc. The hydraulic pump mainly includes hydraulic pump station, oil cooler and corresponding control box. The hydraulic pump is the power source, and the oil cooler and its control box make up the heat dissipation system. In order to ensure that the resonance of the system does not affect the safety of the building, it requires the total weight of the foundation to exceed 20 times of the maximum output force, and achieving vibration isolation from the laboratory building.
3. Excitation signal generation
The feature of the excitation signal directly affects the parameters of the test bench. There are mainly three kinds of excitation modes: sinusoidal excitation, random excitation and impulse excitation.

3.1. Sinusoidal excitation
Sinusoidal excitation is mainly used to investigate the response characteristics of suspension system at specific excitation frequency, and can also be used to test the static mechanical properties of the damper. The expressions of displacement, velocity and acceleration are as follows: \( x_{r}(t) = A \sin \omega t \), \( \dot{x}_{r}(t) = -A \omega^{2} \sin \omega t \). In the formula, \( A \) is the amplitude of the displacement of sinusoidal excitation, \( \omega \) is the angular frequency of the sinusoidal excitation, \( \omega = 2 \pi f \); \( f \) is time frequency; \( t \) is time.

When testing the frequency response of the suspension system using sinusoidal excitation, the excitation frequency needs to cover the inherent frequency of spring mass (1~2Hz) and the un-spring mass (10~15Hz), therefore the frequency range should be not smaller than 1~15Hz. When using sinusoidal excitation to test the static mechanical properties of the damper, the maximum excitation speed should generally be greater than 0.52m/s, so \( A \omega > 0.52 \) m/s. Considering the requirements above, the upper limit design target for the sinusoidal excitation can be set to \( A = 0.005 \) m and \( f = 16.55 \) Hz.

3.2. Random excitation
Random excitation uses the road power spectral density to describe the statistical characteristics of road roughness, and divides it into 8 grades from A to H [11], the formula is:

\[
G_{x_{r}}(n) = G_{x_{r}}(n_{0})(\frac{n}{n_{0}})^{-W}, \quad (n_{1} \leq n \leq n_{u})
\]  

(1)

In the formula: \( n \) is spatial frequency; \( n_{0} \) is the reference spatial frequency; \( n_{0} = 0.1 \) m\(^{-1}\); \( x_{r} \) is vertical displacement of the road; \( G_{x_{r}} \) is road roughness coefficient; \( W \) is frequency index; \( n_{u} \) and \( n_{1} \) represent the upper and lower spatial frequency, usually takes 2.83m\(^{-1}\) and 0.011m\(^{-1}\) respectively, in the usual speed \( v = 30~70 \) km/h, the frequency range is \( f = 0.214~23.58 \) Hz, which can cover the resonant frequency of the spring mass and the un-spring mass effectively.

According to the sampling theorem, the spatial sampling frequency should be more than two times of the cut-off frequency of the simulated road, then it can be obtained \((1/\Delta l) \geq 2n_{u}\) and \(\Delta l \leq 0.177m\). In order to ensure the accuracy of the lower limit frequency, there is \( n_{1} \geq \Delta n \), and the total sampling distance \( L \geq 1/n_{1} \), \( L \geq 91m \) can be obtained. Using harmonic method to generate a random road excitation [12], dividing the spatial frequency range into \( m \) cells, if the speed of the vehicle is \( v \), the vertical displacement of the road at moment \( t \) is as follows:

\[
x_{r}(t) = \sum_{i=1}^{m} \sqrt{2G_{x_{r}}(n_{mid,i})} \Delta n_{i} \cdot \sin \left(2\pi n_{mid,i}vt + \theta_{i}\right)
\]  

(2)

In the formula, \( \Delta n_{i} \) is spatial frequency interval, \( \Delta n_{i} = (n_{u} - n_{1})/m \); \( \theta_{i} \epsilon [0, 2\pi] \).

Generally, the testing speed under random excitation is 30~70 km/h, according to literature [11], the road level of China is mainly in B and C, considering the need of off-road vehicles and the cost at the same time, the upper target of the random excitation is set to road level D under the speed of 36km/h. If the sampling interval of the road is 0.125m, the sample frequency is \( f = 1/\Delta l = v/\Delta l = 80 \) Hz and the total sampling distance \( L \) takes 400m, the above requirements can be met.

3.3. Impulse excitation
Pulse excitation is mainly used to test the impact resistance performance of the suspension, pulse excitation can use triangle convex block or other convex shape according to needs. In this article selecting a common reducer 350mm in length and 50mm in height as the pulse source. In order to facilitate the observation and record the response of the suspension after impulse excitation, it can be
assumed that there is a plat road of 20m before and after the reducer, and the spatial domain signal of the road can be expressed as:

\[
x_{r}(l) = \begin{cases} 
0,0 \leq l < 20, & \text{20.35} \leq l \leq 40.35 \\
0.05 \sin \frac{20\pi}{7}(l-20), & 20 \leq l < 20.35 
\end{cases}
\]  

(3)

The test speed of the car under impulse excitation is generally 10~60 km/h. As impulse excitation requires larger excitation speed and acceleration of test bench, considering the cost of design, the upper limit of impulse excitation is only set to the speed of v=10km/h. According to the sampling theorem, the road sampling interval \( \Delta t \leq 0.35m \).

4. Parameter calculate of the test bench

The main parameters and the calculation method are as follows:

1. The maximum load \( m_r \): the maximum load of the test-bench is determined by the weight of the suspension system to be tested. Generally speaking, the weight of an ordinary family car is about 1.2 tons, and the weight of off-road vehicle is about 2.4 tons. The test platform's test is aimed at 1/4 vehicle suspension system, so the maximum load of the test platform can be set to 600kg;

2. The maximum excitation amplitude \( A_r \): the maximum amplitude of the test bench should be greater than the maximum value of the target excitation displacement signal to be achieved, that is, \( A_r \) should be greater than the maximum value of the objective excitation described in Section 3;

3. The maximum excitation speed \( v_r \) and the maximum excitation acceleration \( a_r \): the maximum excitation speed and acceleration of the test bench should be greater than the maximum value of the target excitation signal, and it can be achieved by the first and the second derivative of displacement.

4. The maximum excitation force \( F_r \): \( F_r \) should be greater than the maximum sum of all resistance to be overcome under the target excitation, including the inertia force \( F_m \), the gravitational force of the load \( G \) and the viscous damping force that the hydraulic cylinder \( f_r \), that is \( F_r > \max \{ F_m + G + f_r \} \).

5. The maximum excitation power \( P_r \): \( P_r \) should be greater than the maximum value of the objective excitation, \( P_r > \max \{ F_r v_r / \eta \} \); \( \eta \) is efficiency of the hydraulic system, generally takes 0.8~0.85.

6. The excitation frequency range: the excitation frequency range need to cover the resonance frequency of the car body and the tyre.

Using MATLAB/SIMULINK to calculate the parameters above under the three kinds of target excitation in time domain, we can get the parameters value respectively as shown in table 1:

| Table 1. Calculation of the parameters of the test bench under different excitation conditions. |
|---|---|---|---|---|---|
| excitation | \( x_r/m \) | \( v_r/m\cdot s^{-1} \) | \( a_r/m\cdot s^{-2} \) | \( F_r/kN \) | \( P_r/kW \) | Frequency range/Hz |
| Sinusoidal excitation | 0.005 | 0.484 | 46.870 | 34.00 | 20.57 | 1~15 |
| Random excitation | 0.0911 | 0.896 | 40.858 | 30.39 | 34.04 | 0.214~23.58 |
| Impulse excitation | 0.0495 | 1.094 | 33.608 | 26.04 | 35.62 | — |
| Maximum value | 0.0911 | 1.094 | 46.870 | 34.00 | 35.62 | 0.214~23.58 |

5. Manufacture and test of the test bench prototype

Considering the design margin and the calculation result above, the ultimate parameters of test bench are shown in table 2. Cooperating with Suzhou DONGLING vibration test instrument Co Ltd, a test bench prototype is manufactured as shown in figure 2, and three tests under the target excitation are carried out to verify whether the designed suspension system test bench reaches the design targets.
5.1. Sinusoidal excitation test and analysis
The amplitude and frequency of sine excitation are set as $A=0.005$ m and $f=16.55$ Hz. The target displacement curve, the actual displacement curve and the error between the two can be obtained as shown in figure 3. From the figure, we can see that the actual value curve matches the target value curve very well. After the calculation and analysis of the data we can get that the maximum error is $1.72e^{-4}$ m, the average error is $4.21e^{-5}$ m, and the accuracy is 96.36%.

![Figure 3](image)

**Figure 3.** Comparison between the actual and target displacement under sinusoidal excitation.

5.2. Random excitation test and analysis
Test the bench under the random excitation of road level D in 36 km/h, the target displacement, actual displacement and the error curve can be obtained as shown in figure 4, the fitting of the actual value curve to the target curve is relatively good; The frequency domain analysis of data is shown in figure 5, it can be seen that the error mainly produces in high frequency band of the vibration. After the processing and calculation of the data, it is found that the maximum error is $9.87e^{-3}$ m, the average error is $1.8e^{-3}$ m, and the control precision is 92.98%.

![Figure 4](image)
5.3. Impulse excitation test and analysis
Test the bench under impulse excitation in 10km/h, the target displacement, actual displacement and the error curve can be obtained as shown in figure 6. It can be seen that the actual displacement curve fits the target displacement curve well, the error mainly occurred in the process of recovering static after the impact of the shock. After the processing of the data, it is found that the maximum error is 1.43e-3m, the average error is 1.25e-4m, and the control precision is 99.02%.

6. Conclusions
Firstly the structure of the suspension system test bench is designed, and then the generation method of three typical kinds of excitation are introduced, including the sinusoidal excitation, random excitation and impulse excitation, the upper limit of the design targets for the three kinds of excitation are ascertained. After that, the main parameters of the test bench were calculated, including the maximum load, amplitude, speed, acceleration, force, power and the frequency range. Finally, a prototype of the test bench is manufactured; the performance of the bench is tested under the three target excitation conditions. The result shows that the control accuracy of the three excitation signals are 96.36%, 92.98% and 99.02% respectively. The error between the target excitation displacement and the actual displacement is small, and the control accuracy meets the design requirements.

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