

Study on Load and Pitching Fluctuations in Scale Car Suspension Systems on a Shaker Rig Considering Weight Distribution

by

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Abstract

Automotive suspension systems play a crucial role as a vehicle's key components, serving multiple functions. Their primary purpose is to respond to road surface irregularities and vehicle body movements while maintaining optimal ride height. The advancement of aerodynamics has significantly enhanced the kinematic performance of competitive vehicles. Concurrently, suspensions have become stiffer to uphold a consistent distance between the vehicle body and the road, thereby improving aerodynamic efficiency. However, increased suspension stiffness reduces static spring displacement in response to aerodynamic forces while amplifying ground load fluctuations. Hence, to develop an active suspension system that enhances aerodynamic performance, minimizes load fluctuations, and improves vehicle dynamics, we conducted a foundational study using two methods: simulation and a vibration test system to assess scale car dynamics under vibrations. The analysis reveals that road surface inputs induce fluctuations in pitch angle and ground load due to variations in weight distribution.

Keywords: Vehicle, Dynamics, Mechanical engineering, Control, Shaker rig

1. Introduction

A race track features both straight and corner sections, necessitating race cars to optimize performance not only on straights but also through corners to reduce lap times. Thus, minimizing speed reduction in corners becomes crucial. Typically, when a vehicle maintains a constant speed on a course with a fixed radius, such as during steady circle turns, it must generate lateral force directed toward the corner's center to turn effectively. Since cornering force increases with the square of the driving speed, higher speeds demand greater cornering force. The lateral force produced by tires, crucial for generating cornering force, depends on the tires lateral slip angle and the ground load. For this reason, recent race cars are equipped with aerodynamic devices that generate force vertically downward by utilizing the airflow near the vehicle.

This increases the ground load on the tires without increasing the mass of the vehicle, and the lateral force on the tires also increases in proportion to the ground load, thereby increasing the vehicle's speed while turning and improving its dynamic performance^{1,2)}. However, airflow-induced downforce is notably diminished by changes in attitude caused by acceleration/deceleration and cornering. Therefore, to optimize aerodynamic device utilization, spring constants and damping coefficients of springs and dampers are typically set high to minimize vehicle body displacement³⁾. Conversely, increasing the spring constant or damping coefficient of springs or dampers tends to elevate tire ground load and vehicle height fluctuations due to road surface irregularities.

Fluctuations in tire contact load result in lateral force fluctuations. Because the relationship between tire ground load and lateral force is nonlinear, lateral force fluctuation is also nonlinear and intricately impacts cornering. As mentioned, tire ground contact load significantly influences vehicle dynamic performance, yet directly measuring it while a vehicle is on the track is impractical. Consequently, a post rig, a device simulating vehicle running conditions, is commonly employed to measure various parameters related to vehicle motion, including tire ground load^{4,5)}.

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The post rig recreates vehicle running conditions by utilizing vibrating actuators placed beneath each tire, enabling the measurement of nonlinear tire ground loads and vehicle vibration characteristics during road surface inputs. To achieve this goal, by employing a scale car for the rig, the actuators' output under the tires can be maintained at lower levels, enabling experiments at higher frequencies compared to traditional post rigs and testing machines. The use of scale cars also allows for experimentation with various vehicle parameters. The front-rear weight distribution of a vehicle is a crucial factor in assessing driving performance^{6,7)}. However, this distribution can vary depending on the engine and transmission mounting positions. Moreover, road surface inputs can alter vehicle vibration characteristics, potentially impacting dynamic performance.

To investigate these effects, this study utilizes a 1/5-scale vehicle. Accordingly, a post rig system corresponding to a 1/5 scale car was developed. As a fundamental analysis using this setup, this paper examines changes in tire ground load and pitch angle as the vehicle's weight distribution is altered.

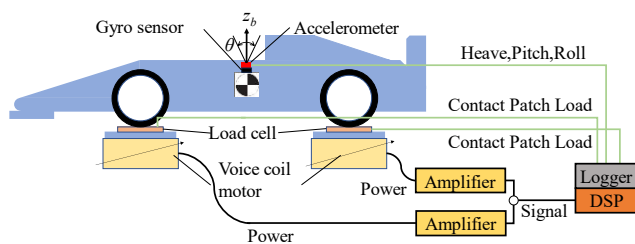


Fig. 1 Schematic diagram of the shaker rig illustrating its key components and their arrangement

2. Experimental Apparatus

Our proposed post rig is a 1/5 scale car system equipped with a voice coil motor mounted under each tire. Fig. 1 illustrates a schematic of the proposed system. The DSP depicted in the figure processes the input signal using an amplifier and then amplifies it using a bipolar power supply to drive the voice coil motor. During this process, a displacement sensor and load cell installed in the vehicle measure the ground load and vehicle height, enabling the determination of the vehicle's response to the input, assuming road surface irregularities. Fig. 2 showcases a 1/5 scale car, while Fig. 3 displays the suspension mounted on the scale car. Additionally, Fig. 4 depicts a voice coil motor installed under the tires, and Fig. 5 illustrates the bipolar power supply responsible for supplying power to drive the voice coil motor.



Fig. 2 Photograph of the experimental apparatus featuring a 1/5 scale car

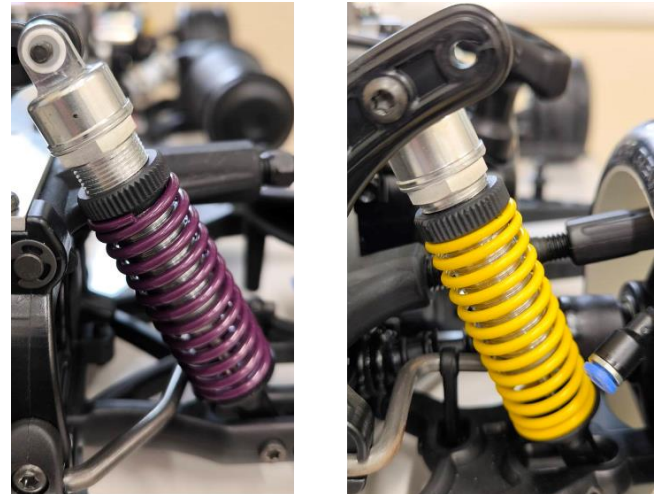


Fig. 3 Photograph of the suspension system for the 1/5 scale car



Fig. 4 Photograph of the voice coil motor



Fig. 5 Photograph of the bipolar power supply

3. Model of Experimental Vehicle

The equations governing the motion of both the sprung body and unsprung bodies, along with the rotational motion equation of the sprung body, are provided below. This simulation utilizes a two-wheel model, representing the front and rear wheels of the vehicle as individual units, as depicted in Fig. 5. Key parameters—comprising the tire spring parameter, suspension spring parameter, damper damping ratio, and lower spring weight—are assigned to both the front and rear wheels. In this study, the center of gravity is varied in the front-rear direction, and the vehicle's response is examined. This change in the center of gravity alters the forces applied to the front and rear wheels, thereby affecting the critical damping coefficients of the sprung front and rear wheels, as well as the distance from the center of gravity to the front and rear axles.

$$m\ddot{x} + k_f(z_{bf} - z_{tf}) + c_f(\dot{z}_{bf} - \dot{z}_{tf}) + k_r(z_{br} - z_{tr}) + c_r(\dot{z}_{br} - \dot{z}_{tr}) = 0, \quad (1)$$

$$m_{usf}\ddot{z}_{tf} + k_{tf}(z_{tf} - z_0) - (k_f(z_{bf} - z_{tf}) + c_f(\dot{z}_{bf} - \dot{z}_{tf})) = 0, \quad (2)$$

$$m_{usr}\ddot{z}_{tr} + k_{tr}(z_{tr} - z_0) - (k_r(z_{br} - z_{tr}) + c_r(\dot{z}_{br} - \dot{z}_{tr})) = 0, \quad (3)$$

$$i\ddot{\theta} + (k_f(z_{bf} - z_{tf}) + c_f(\dot{z}_{bf} - \dot{z}_{tf}))l_f - (k_r(z_{br} - z_{tr}) + c_r(\dot{z}_{br} - \dot{z}_{tr}))l_r = 0, \quad (4)$$

where m is body mass [kg], k_f represents the front spring rate [N/m], c_f denotes the front damping rate [Ns/m], k_r is the rear spring rate [N/m], c_r is the rear damping rate [Ns/m], m_{usf} is the front unsprung mass [Kg], k_{tf} is the front tire spring rate [N/m], m_{usr} is the rear unsprung mass [Kg], k_{tr} is the rear tire spring rate [N/m], i is the pitch inertia [kgm²], l_f is the distance from the center of gravity to the front wheel axle [m]. l_r is the

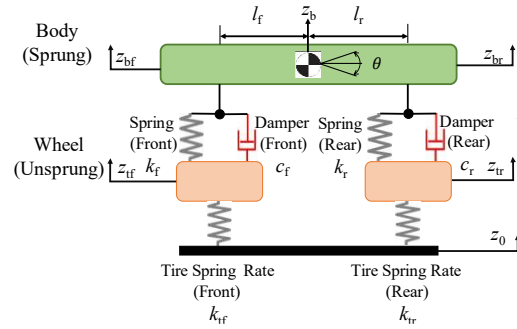


Fig. 6 Schematic diagram of the suspension system

distance from the center of gravity to the rear-wheel axle [m]. And l (sum of l_f and l_r) represents the wheelbase of the vehicle

4. Analysis Conditions

Dynamic simulations were conducted to understand the pitching response by subjecting the vehicle to vibration. The parameters detailed in Table 1, were sourced from a Formula SAE vehicle specifically designed for small race cars [8]. Within this simulation, the ground displacement z_0 in contact with the front and rear wheels underwent variation. z_0 was modulated as a chirp signal, as shown in Fig. 7, featuring a 5.0 mm amplitude and a frequency range of 0–30 Hz over a 300 s duration, applied simultaneously to both front and rear wheels in synchronization. Experimental conditions are detailed in Table 2. This study explored varying weight distributions, including front-to-rear ratios of 50:50, 55:45, 60:40, 65:35, 70:30, 75:25, and 80:20. To assess pitching behavior, the ratio of pitch angle θ to displacement z_0 was computed.

Table 1 Analysis parameters

Parameters	Values
m	236 kg
k_f, k_r	40 kN/m
c_f, c_r	0.7
m_{usf}, m_{usr}	16 kg
k_{tf}, k_{tr}	90 kN/m
i	100 kgm ²
$l_f + l_r$	1.53 m

Table 2 Road input parameters

Parameters	Values
displacement	5.0×10^{-3} m
starting frequency	0 Hz
maximum frequency	30 Hz
experimental time	300 sec

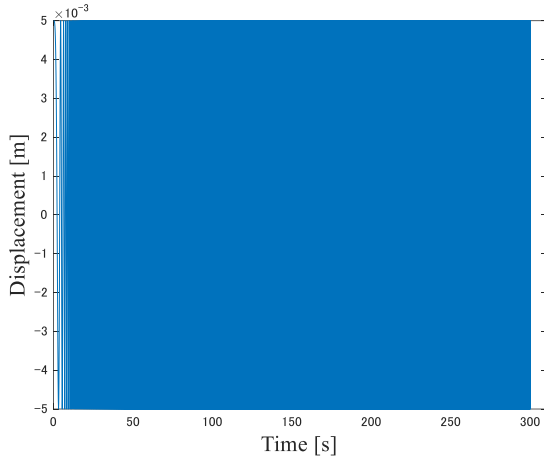


Fig. 7 Road input plot

5. Analysis Result

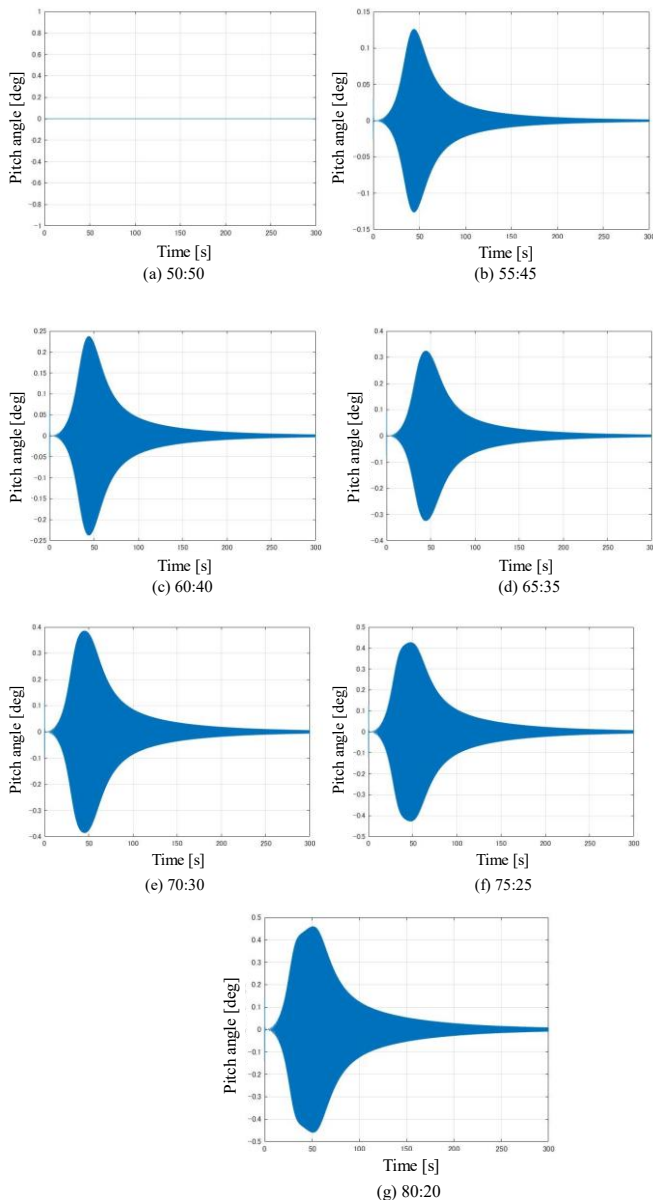


Fig. 8 Variations in analyzed pitch angle θ over time

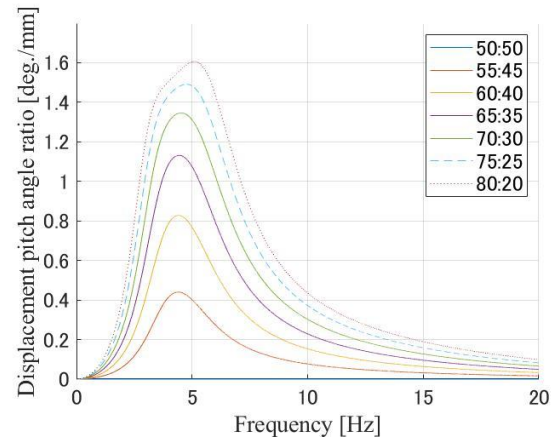


Fig. 9 Analysis of the relationship between oscillation frequency and displacement pitch angle ratio

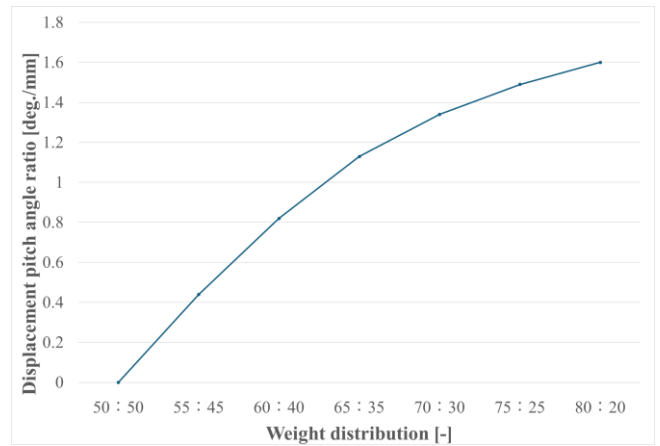


Fig. 10 Displacement pitch angle ratio versus weight distribution

Fig. 8 depicts the time history of the analyzed pitch angle θ . The horizontal axis represents time, while the vertical axis represents pitch angle. Here, weight distribution varied from 50:50 to 80:20. The peak of the pitch angle was reached around 50 seconds for all weight distributions. However, as the weight distribution shifted toward the front or rear, the peak of the pitch angle became larger, and the convergence before and after the peak slowed down, resulting in changes in the waveform. Fig. 9 illustrates simulation outcomes regarding the frequency response of the pitch angle, considering a shift in vehicle weight distribution from 50:50 to 80:20. The horizontal axis represents frequency, while the vertical axis illustrates the rate of variation of the pitch angle, which is the pitch angle divided by the road input. Fig. 9 demonstrates that the peak occurs around 4 Hz, but the peak frequency changes as the weight distribution shifts toward the front or rear. This simulation ensured synchronized oscillation of the front and rear wheels. With identical front and rear parameters set the same, no pitching occurred when the weight distribution was 50:50. This suggests that concentrating the vehicle mass closer

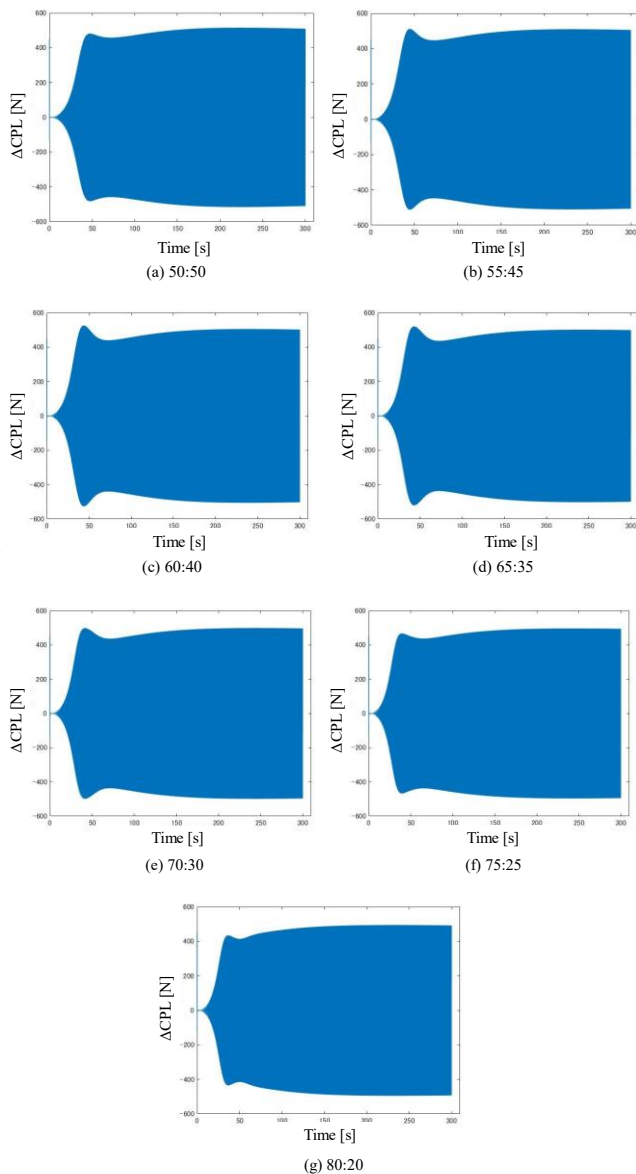


Fig. 11 Variations in contact patch load over time

5. Conclusion

to the center of gravity can mitigate pitching vibrations without altering the natural frequency of the pitch angle. Fig. 10 displays the pitch angle peaks from a weight distribution of 50:50 to 80:20. The horizontal axis shows the weight distribution, and the vertical axis shows the peak of the rate of variation of the pitch angle. Fig. 10 illustrates that the peak of the pitch angle increases as the weight distribution is shifted toward the front or rear but does not increase linearly with the change in weight distribution. Fig. 11 shows the time history of contact patch load. The horizontal axis represents time, and

the vertical axis represents the contact patch load of the front wheels. The weight distribution was varied from 50:50 to 80:20. As in Fig. 8, a peak occurred around 50 seconds, but the change in weight distribution had little effect on the contact patch load.

This study aimed to explore the dynamic behavior of a scaled model under oscillation. A two-wheel vehicle model was developed, incorporating the motion of both front and rear wheels, as well as vertical and pitch rotational movements of the sprung body. By adjusting weight distribution ratios between the front and rear sections, the model changed the pitch angle and CPL. The results highlight the potential of concentrating the vehicle mass around its center of gravity to dampen pitching vibrations effectively. Specifically, when the front-to-rear mass ratio was 50:50, pitching motion was completely eliminated. Additionally, the use of a dynamic mass damper proved effective in mitigating pitching even with dispersed vehicle mass. Future investigations will include post-rig testing of pitch angle and CPL experiments on an actual 1/5 scale car, as well as exploring the implications of dynamic behavior while driving the vehicle on a circuit.

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