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Establishing the physical model and solving the vehicle vertical dynamic equations

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ABSTRACT: *Proposal of this study is to establish the physical and mathematical models for a vehicle. A physical model of a wheel loader is established under excitation sine function of road surface. The mathematical equations are to describe the vertical dynamic motions of vehicle using the D'Alembert. Matlab/Simulink software is chosen to solve. The vertical acceleration responses of vehicle body are selected as the objective functions. The simulation results show the vehicle body vibrations represent the physical behaviors under the excitation sine function of road surface. In addition, the results of the study provide a theoretical basis for research on vehicle vibration and control.*

KEYWORDS: *Physical model, Mathematical equations, Simulation, Wheel loader*

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I. INTRODUCTION

Vehicle with a chassis connected to four wheels (usually). These four wheels contact with the road surface. The chassis isn't directly attached to the wheels-rather, it is connected to them by the suspension, which generally consists of coil springs and shock absorbers (dampers). In other words, the interface between the chassis and each wheel is a spring and damper. In the automotive world, the chassis is called the sprung mass, since it is the portion of the vehicle held up by springs. In contrast, each wheel is referred to as an unsprung mass [1]. Saurav Talukdar has been focused on mathematical modeling in vehicle ride dynamics to develop accurate models capturing dynamic behavior. It explores suspension systems, tire characteristics, and vehicle response to external forces. Various mathematical techniques are used, emphasizing the inclusion of real-world factors for improved control systems and design optimization, enhancing ride comfort, stability, and overall performance [2]. Tejas P., et al have been presented the mathematical modeling and simulation of a simple quarter car vibration model. The objective is to analyze the dynamic behavior and performance of the quarter car system. The model considers the interaction between the car body, suspension system, and road surface. Various parameters such as suspension stiffness, damping, and tire characteristics are incorporated into the mathematical model [3]. Tejas P., et al have been focused on the mathematical modeling and simulation of a simple half-car system. The objective is to analyze the dynamic behavior and performance of the half-car model, considering the interaction between the car body, suspension systems, and road surface. Various parameters such as suspension stiffness, damping, and tire characteristics are incorporated into the mathematical model [4]. Hui Zhou, et al have presented a simple mathematical model of a vehicle with a seat and occupant to investigate the impact of vehicle dynamic parameters on ride comfort. The model considers the interaction between the vehicle's suspension system, seat dynamics, and occupant. Various vehicle parameters such as suspension stiffness, damping, and seat characteristics are incorporated into the model. The study aims to analyze how changes in these parameters affect ride comfort and provide insights for optimizing vehicle design to enhance passenger comfort [5]. Radionova L.V et al have presented a mathematical model of a vehicle implemented in MATLAB Simulink. The model captures the dynamic behavior of the vehicle, including the suspension system, tire characteristics, and vehicle motion. Various vehicle parameters and inputs, such as road profile and driver actions, are incorporated into the model [6]. Manoj K, et al have been focused on the development of mathematical models for designing vehicles with optimal ride comfort. Various factors affecting ride comfort, such as vehicle dynamics, suspension systems, and road surface characteristics, are considered in the modeling process. The mathematical models are utilized to analyze and optimize vehicle parameters and design features to enhance ride comfort [7]. G.E. Prince, et al have been presented mathematical models for analyzing the motion of the rear ends of vehicles. The focus is on understanding and predicting the dynamic behavior of the rear suspension systems and tire characteristics. Various mathematical techniques, such as differential equations and state-space modeling, are employed to describe the motion of the rear ends. The developed models provide valuable insights for improving the stability, handling, and overall performance of vehicles [8]. Mukhtar

Kerimov, et al have been presented the methodological aspects of building a mathematical model to evaluate the efficiency of automated vehicle traffic control systems. The focus is on developing a comprehensive model that considers various factors such as traffic flow, signal timings, and control algorithms. Mathematical techniques, including optimization methods and simulation, are employed to assess the performance and effectiveness of the automated control systems. The findings contribute to the development and improvement of efficient traffic management strategies for automated vehicles [9]. R. Anbazhagan, et al have been focused on the mathematical modeling and simulation of modern cars to analyze their stability. The objective is to develop accurate mathematical models that capture the dynamic behavior of cars under various driving conditions. Different aspects related to stability, such as vehicle dynamics, suspension systems, and control algorithms, are explored. Mathematical techniques, including differential equations and simulation methods, are employed to assess the stability performance of modern cars [10]. Ansul Kumar Sharma, et al have been presented a multi-physical model for the tire-road contact, specifically focusing on the effect of surface texture. The objective is to develop an accurate model that captures the interaction between the tire and the road surface, considering the influence of surface texture parameters. Various aspects of the tire-road contact, including tire deformation, friction, and contact mechanics, are integrated into the model [11]. A. Alexander et al have been presented a longitudinal vehicle dynamics model specifically tailored for construction machines. The objective is to accurately capture the dynamic behavior of these machines during longitudinal motion. The model incorporates various factors such as engine characteristics, transmission system, and tire dynamics. Experimental validation is conducted to assess the model's accuracy and reliability [9]. R. Anbazhagan, et al have been focused on the mathematical modeling and simulation of modern cars to analyze their stability. The objective is to develop accurate mathematical models that capture the dynamic behavior of cars under various driving conditions. Different aspects related to stability, such as vehicle dynamics, suspension systems, and control algorithms, are explored. Mathematical techniques, including differential equations and simulation methods, are employed to assess the stability performance of modern cars [10]. Ansul Kumar Sharma, et al have been presented a multi-physical model for the tire-road contact, specifically focusing on the effect of surface texture. The objective is to develop an accurate model that captures the interaction between the tire and the road surface, considering the influence of surface texture parameters. Various aspects of the tire-road contact, including tire deformation, friction, and contact mechanics, are integrated into the model [11]. A. Alexander, et al have been presented a longitudinal vehicle dynamics model specifically tailored for construction machines. The objective is to accurately capture the dynamic behavior of these machines during longitudinal motion. The model incorporates various factors such as engine characteristics, transmission system, and tire dynamics. Experimental validation is conducted to assess the model's accuracy and reliability. Liem N.V., Le, V., et al have been focused on parameter optimization and control of the cab's isolation systems of construction vehicles [12], [13], [14], [15], and [16]. The main idea of the paper is to develop a physical model for a wheel loader. The mathematical equations are derived using the D'Alembert's principle. The MATLAB/Simulink software is chosen for purposed simulation.

II. ESTABLISHING VEHICLE PHYSICAL MODEL

The starting point of the study is a real-life model. A physical model of a wheel loader is constructed as shown in Figure 1. The structure of the physical model of the wheel loader includes the vehicle body and axle masses, suspension systems and tires.

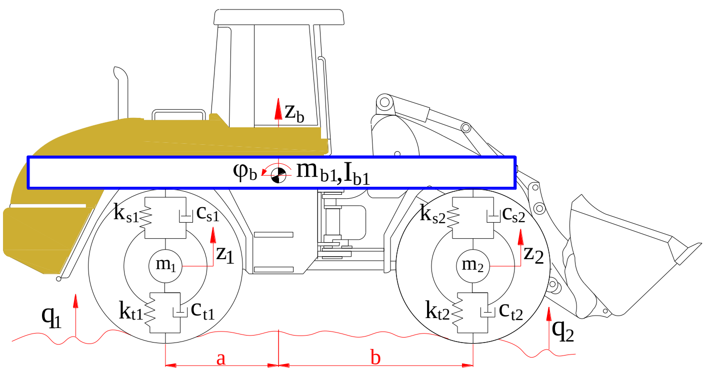


Fig. 1. Physical model of the wheel loader

Math equations: The equation of math for the dump truck is established using the D'Alembert's principle. From Figure 1, the equation of motion for the body of the wheel loader is written as follows:

The equations of math for vehicle body are written as follows

$$m_b\ddot{z}_b = -[[k_{s1}(z_b - a\varphi_b - z_1) + c_{s1}(\dot{z}_b - a\dot{\varphi}_b - \dot{z}_1] + [k_{s2}(z_b + b\varphi_b - z_2) + c_{s2}(\dot{z}_b + b\dot{\varphi}_b - \dot{z}_2]] \quad (1)$$

$$I_b \ddot{\varphi}_b = [k_{s1}(z_b - a\varphi_b - z_1) + c_{s1}(\dot{z}_b - a\dot{\varphi}_b - \dot{z}_1]\text{a-}[k_{s2}(z_b + b\varphi_b - z_2) + c_{s2}(\dot{z}_b + b\dot{\varphi}_b - \dot{z}_2]\text{b} \tag{2}$$

The equation of math for the rear axle mass is written as follows:

$$m_1\ddot{z}_1 = k_{t1}(z_1 - q_1) + c_{t1}(\dot{z}_1 - \dot{q}_1) \tag{3}$$

The equation of math for the front axle mass is written as follows:

$$m_2\ddot{z}_2 = k_{t2}(z_2 - q_2) + c_{t2}(\dot{z}_2 - \dot{q}_2) \tag{4}$$

From Eq. (1), (2), (3) and Eq. (4), the differential equations of vehicle motion are written as follow:

$$\begin{cases} m_b\ddot{z}_b = -[[k_{s1}(z_b - a\varphi_b - z_1) + c_{s1}(\dot{z}_b - a\dot{\varphi}_b - \dot{z}_1] + [k_{s2}(z_b + b\varphi_b - z_2) + c_{s2}(\dot{z}_b + b\dot{\varphi}_b - \dot{z}_2]] \\ I_b \ddot{\varphi}_b = [k_{s1}(z_b - a\varphi_b - z_1) + c_{s1}(\dot{z}_b - a\dot{\varphi}_b - \dot{z}_1]\text{a-}[k_{s2}(z_b + b\varphi_b - z_2) + c_{s2}(\dot{z}_b + b\dot{\varphi}_b - \dot{z}_2]\text{b} \\ m_1\ddot{z}_1 = k_{t1}(z_1 - q_1) + c_{t1}(\dot{z}_1 - \dot{q}_1) \\ m_2\ddot{z}_2 = k_{t2}(z_2 - q_2) + c_{t2}(\dot{z}_2 - \dot{q}_2) \end{cases} \tag{5}$$

III. SOLVING THE VEHICLE VERTICAL DYNAMIC EQUATIONS

To simulate and solve the mathematical equations, the Matlab/Simulink software is chosen. The simulated structure diagram is illustrated in Figure 2. The simulation results are depicted in Fig. 3 and Fig. 4 when vehicle moves at a speed of 9.72 m/s with the excitation sine function of road surface which it is described by the excitation sine function with frequency 5*pi (Hz), amplitude 0.25 (m).

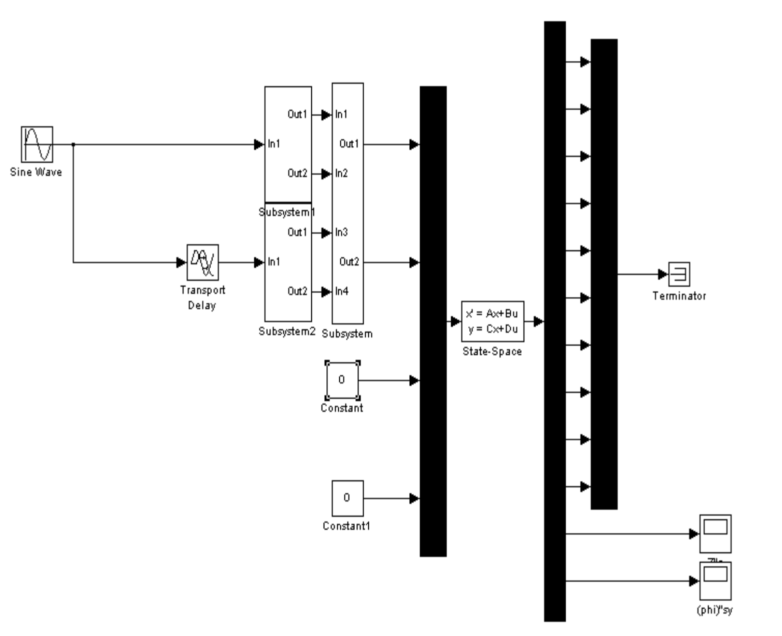


Fig. 2. Simulink simulation diagram

The simulation results of the vertical and pitch acceleration responses of the vehicle body were presented in Fig. 3 and Fig.4. From the results in Fig. 3 and Fig.4, we show that the vehicle body vibrations represent the physical behaviors under the excitation sine function of road surface.

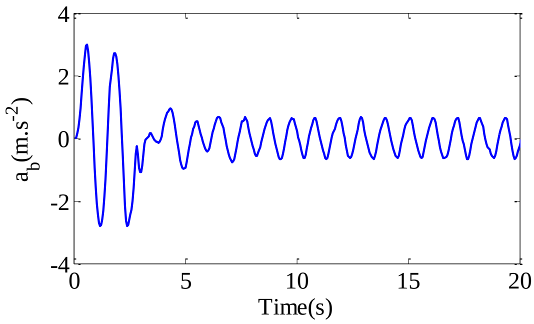


Fig.3. Time acceleration response of the vertical vehicle body

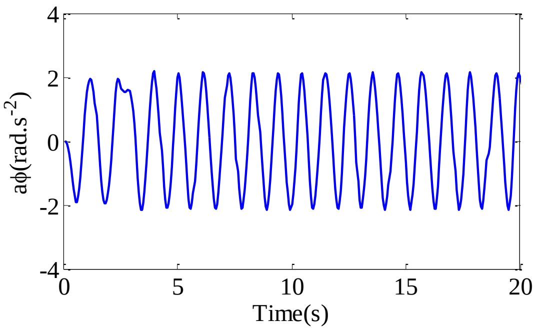
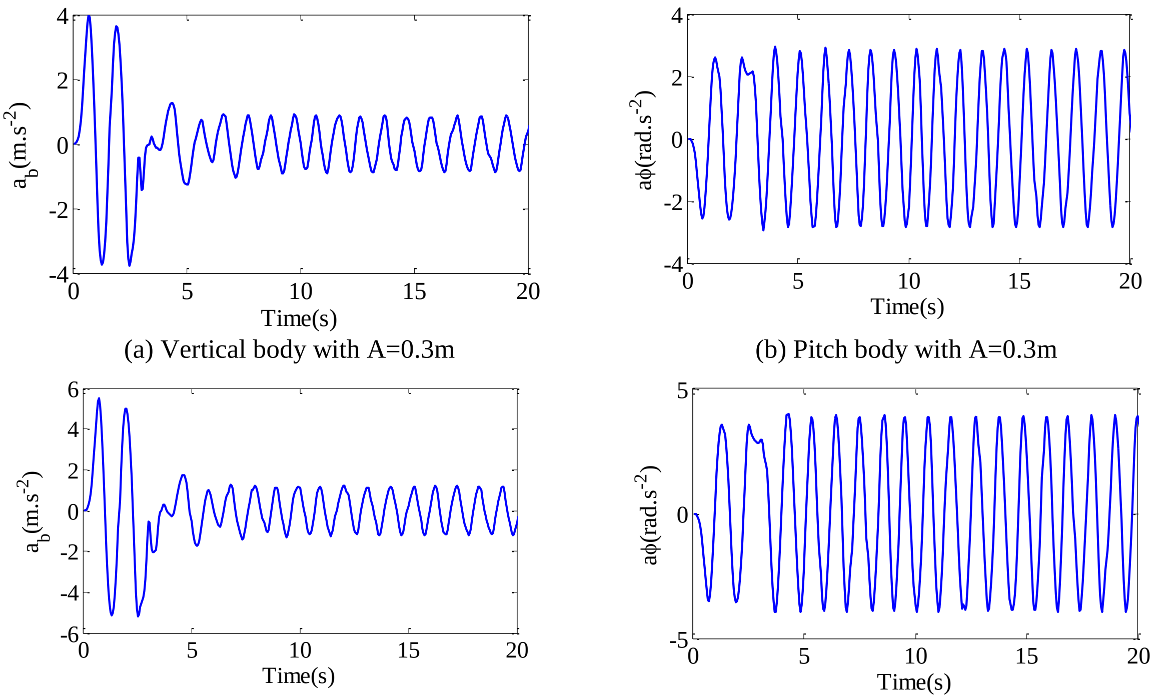


Fig.4. Time acceleration responses of the pitch vehicle body

Similarly, the amplitude values of the excitation sine function of road surface (A) change from 0.3m to 0.35m. The simulation results of the acceleration responses of the vertical and pitch vehicle bodies were presented in Fig. 5 when vehicle moves at the speed of 9.72 m/s.



(a) Vertical body with A=0.3m (b) Pitch body with A=0.3m

(c) Vertical body with A=0.3m (d) Pitch body with A=0.3m

Fig.4. Time acceleration responses of vehicle body

From the results in Fig. 5, the maximum amplitude values of the acceleration responses of the vertical and pitch vehicle bodies increase when the amplitude values of the excitation sine function of road surface increase. That recognizes that the excitation sine function of road surface has a great influence on the vehicle's vibration.

IV. CONCLUSION

The physical and mathematical models for a vehicle are proposed in this study. Some conclusions are drawn from the study results such as (1) The vehicle body vibrations represent the physical behaviors under the excitation sine function of road surface and (2) the excitation sine function of road surface has a great influence on the vehicle's vibration. The next research direction of the team will focus on analyzing and controlling the vehicle's suspension system as well as cab's isolation system of construction vehicles.

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