SimMechanics Simulation Analysis and Experiments Research on Orchard Vehicle Stability Control

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Keywords: Rollover and Pitch; Active Safety Control; Vehicle Dynamics; SimMechanics Model

Abstract. This paper presents a dynamic orchard vehicle model in the SimMechanics simulation environment of Matlab. The model's function is to replace physical vehicles during different experiments in rollover and pitch research. Two simplified linear dynamic models are developed to analyze the force situation in rollover and pitch. A size-reduced physical model of the orchard vehicle is constructed, it's a front-wheel-drive, differential steering car, and can realize the rollover prevention control by active-steering. In SimMechanics, a vehicle model based on physical model is designed. Both two models are used to simulate actual steering conditions in experiments. By analyzing the test results of the two models, we can find that they correspond with each other. So the SimMechanics model can be used as a substitute to simulate the vehicle's motion and can be applied to analyze the vehicle stability properties.

Introduction

In recent years, with the continuous development of orchard industry, orchard vehicles are extensively used in orchard work. However, due to the variety of fruit trees and the complexity of field conditions in forest, it's not easy to ensure stability of vehicles [1-4], which may have a tendency to rollover or pitch. Rollover is a lateral movement that vehicle rotates 90 or more degrees about the longitudinal axis, causing the car body crash the ground, while pitch is a movement rotates about the lateral axis. They usually occur in the process of fruits picking and transportation, in addition, for having a larger work space, orchard vehicles don't have a closed cab to protect the driver, so once the rollover or pitch accident occurs, it will lead to serious economic losses and heavy casualties.

For the above circumstances, considerable researches have therefore been devoted to detecting and preventing rollover through active control. Numerous approaches attempted to detect or predict roll angle are applied, such as onboard sensing and a combination of automatic steering and braking to keep balance. B. Chen and H. Peng study on differential-braking-based rollover prevention for sport utility vehicles with human-in-the-loop evaluations [5]; Bo Liu and A. Bulent Koc develop a mobile application for tractor rollover detection and emergency reporting [6]; H.Yua, L. Güvençb and Ü. Özgünera have a research on an active control system using active suspension mechanism to improve heavy-duty trucks' roll stability both in the static cornering and in emergency maneuver [7]; Jiang et al. developed a detailed tractor semi-trailer plus tanker model considering liquid sloshing effects [8].

In this paper, we focus on constructing a dynamic orchard vehicle model in the SimMechanics simulation environment of Matlab. First, a size-reduced physical model of the orchard vehicle is constructed, it's a front-wheel-drive, differential steering car with 11-degree-of-freedom (11DOF), and can realize the rollover prevention control based on active-steering. Then, a vehicle model is developed in SimMechanics which is in line with the physical model. After series of experiments under different steering conditions, we finally draw a conclusion that the simulated results demonstrate the behavior of the physical vehicle.

Orchard vehicle dynamic model

While orchard vehicle are driven on the irregular roads, the body's center of gravity position, pitching Angle and pitching Angle acceleration, roll Angle and roll Angle acceleration change with the pavement fluctuation. Studying these parameters helps control the stability of the orchard vehicle. Assume the vehicle body is a rigid body, we establish a model with seven degrees of freedom, which is shown in figure 1.

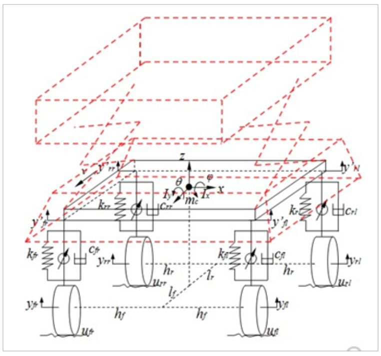


Fig. 1 vehicle model with seven degrees of freedom

According to Newton's law, we can get vehicle vertical motion equation:

$$m_c(a_c - L\ddot{\varphi}) = F_{1fr} + F_{1fl} + F_{1rr} + F_{1rl} \quad (1)$$

In the type: m_c is the body quality; a_c is the body centroid acceleration; L is the suspension longitudinal distance between the mass center of the suspension and whole vehicle; φ is the body pitching Angle; F_1 is the suspension force of car body; *fl, fr, rl, rr* is is the left front, right front wheel, left rear, right rear wheel; *f, r* is the front and rear wheels.

Suspension of body forces are:

$$F_{1fr} = k_{fr}(y_{fr} - y'_{fr}) + c_{fr}(\dot{y}_{fr} - \dot{y}'_{fr}) \quad (2)$$

$$F_{1fl} = k_{fl}(y_{fl} - y'_{fl}) + c_{fl}(\dot{y}_{fl} - \dot{y}'_{fl}) \quad (3)$$

$$F_{1rr} = k_{rr}(y_{rr} - y'_{rr}) + c_{rr}(\dot{y}_{rr} - \dot{y}'_{rr}) \quad (4)$$

$$F_{1rl} = k_{rl}(y_{rl} - y'_{rl}) + c_{rl}(\dot{y}_{rl} - \dot{y}'_{rl}) \quad (5)$$

In the type: k is the suspension stiffness; c is the suspension damper; y_{fr}, y_{fl}, y_{rr}, y_{rl} is the vertical displacement of front and rear axle without suspension quality; y'_{fr}, y'_{fl}, y'_{rr}, y'_{rl} is the vertical vibration displacement of front and rear suspension.

Pitching motion equation:

$$I_y\ddot{\theta} = l_f\left(F_{1fr} + F_{1fl}\right) - l_r\left(F_{1rr} + F_{1rl}\right) \quad (6)$$

In the type: I_v is the moment of Inertia of body around the y axis; l_f is the distance between front axle and center of mass; l_r is the distance between rear axle and center of mass.

Body roll motion equation:

$$I_x\ddot{\theta} + h_f\left(F_{1fl} - F_{1fr}\right) + h_r\left(F_{1rl} - F_{1rr}\right) = 0 \quad (7)$$

In the type: I_x is the moment of Inertia of body around the x axis; θ is the body roll Angle; h_f is the distance between front wheel and center of mass; h_r is the distance between rear wheel and center of mass.

Design of SimMechanics Model

Conducting rollover experiments is dangerous and costly in reality, and it is difficult to guarantee the experiment environment, so creating a vehicle model which can simulate actual conditions is necessary. For reasons such as noted above, a model of the orchard vehicle is developed in

SimMechanics. During the constructing process, in order to ensure the stability of simulation effects, we make such simplifications as following:

i. The vehicle's center of gravity is set at symmetry position referring to all the four wheels.

ii. In order to keep wheels driving on ground, the upward supports are added at the axle of each wheel.

iii. Vehicle steering is actuated by exerting forces on wheels' x and y axis.

Module of vehicle body

Before building orchard vehicle model, gravity vector is set as [0 0 -9.81] m/s2 under the location [x y z] field in machine environment block so as to simulate gravity in reality. And then a ground block connecting to machine environment should be configured, the ground coordinate system (CS) axes are fixed to be parallel to the World CS axes. The vehicle is modeled as a rigid body with three translational and three rotational DOFs located at the vehicle center of gravity (CG), and it is connected to ground by a bushing block, which constrains DoFs of vehicle body. After that, CS of vehicle model should be defined: set CG of vehicle body at the origin of World CS, and four wheels position can be fixed translated from origin of car body CS according to the size of physical model. The last step is to specify the body's mass properties and inertia tensor.

Module of wheels

Each wheel has a rotational DoF about y axis to actuate moving forward along x axis. In addition, a rotational DoF about z axis is added to each front wheel to complete steering action. Then, connect the vehicle body with two front wheels and two back wheels by universal and revolute blocks, which represent two and one rotational DoFs respectively.

Subsystems of motor and contact force

Create two subsystems, one is about wheel contact forces which according to vehicle body condition, and the other is a motor containing four body actuator blocks to provide driving torque. By setting the parameters in these two subsystems, it is sufficiently realistic to simulate vehicle motion and allow for a linearized analysis for the vehicle stability properties.

Simulation model

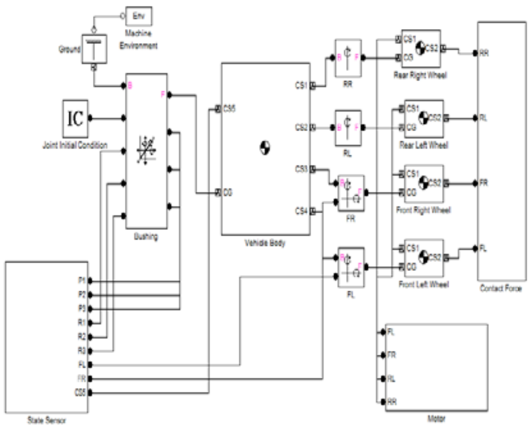


Fig. 2 The orchard vehicle model in SimMechanics

To detect the stability of vehicle body, a sensor is added at CG to measure posture of vehicle during simulation, and displacement-time graph can be output through a scope block. Besides, other sensors used to detect velocity, acceleration, angular acceleration can be connected to bushing block. Similarly, to measure the rotational angle of wheels, a sensor is added to each front wheel, and the scope block can output an angular displacement-time graph. Fig. 2 shows the definition of the whole orchard vehicle model in SimMechanics and Fig. 3 is a screenshot on plan X-Y during simulation.

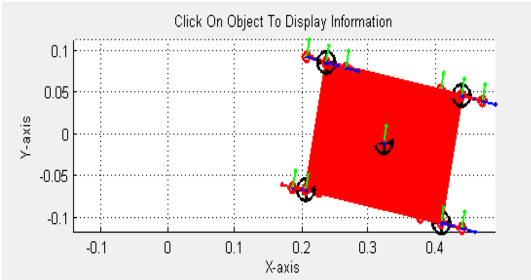


Fig. 3 Simulation screenshot on plane X-Y

Control model

As shown in figure 7, control module contains the input state variable Velocity (v) and output state variable Angle (φ) and Angle Velocity ($\dot{\varphi}$), parameter v controlled by coefficient KP, Kd, φ and $\dot{\varphi}$. And tilting control model is shown in figure 7. The working process of the active control model can be described as follows: orchard vehicle driven forward with velocity v at 0 time, then encounter ups and downs road at t time. The new input variable $v(t+1)$

$$v(t+1) = v + \Delta v \quad (8)$$

By controlling v with time, we can prevent orchard vehicle from tilting and control the stability of the system.

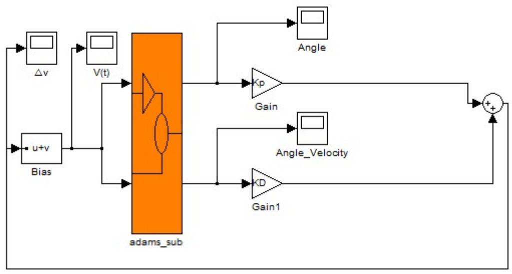


Fig.4 Simulink control model

Experiments and Results Analysis

Experiment 1

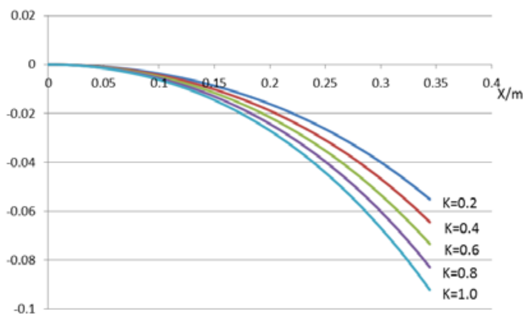


Fig. 5 Relationship between force ratios and the locus of CG

In this experiment, forces are exerted on the axes of front wheels serving as the frictions from ground. An independent variable is defined as "*K*", which represents the ratio of forces on front left wheel (F_{FL}) to front right wheel (F_{FR}). We set $F_{FRx} = F_{FRy} = 0.05N$, then a certain force exerted on the front left wheel is calculated according to a force ratio. The vehicle model can steer at different angles during moving forward in two seconds. Under the premise of ensuring the stability in the whole process, a sequence of data about force ratios and the locus of CG can be obtained (Fig.5) of CG and force ratio "*K*" and force ratio. Make a tangent line at the last point of the curves above, these slopes indicate the steering angles in two seconds. (Fig. 6)

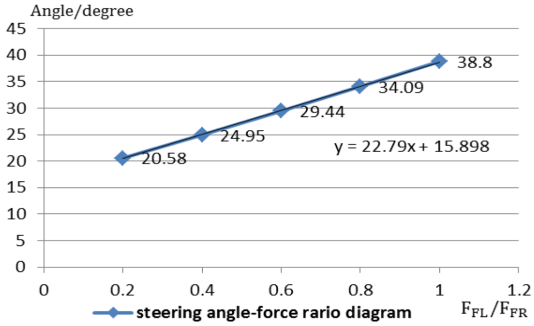
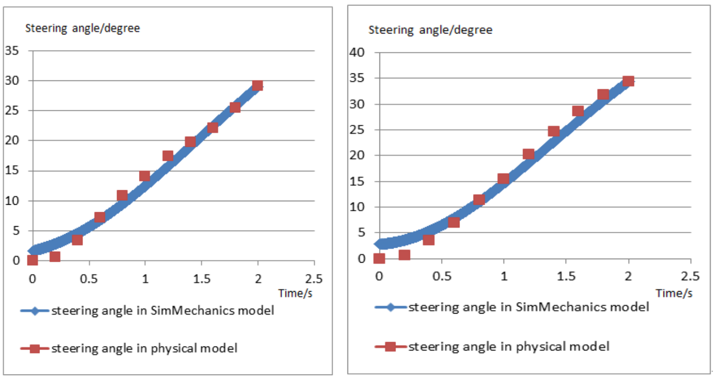


Fig. 6 Relationship of steering angle

Experiment 2

In this experiment, we conduct a steering test on the physical vehicle model, the steering angle increases by time. Set a time period of two seconds from the beginning of steering, then a series of steering angles can be obtained at various points within the period, and a curve of steering angler to time ($\phi - t$) is generated. Read the steering angle at the last time point in the diagram, and match it to the steering angle – force ratio diagram in Diagram 2, then a corresponding force ratio can be got. We still set $F_{FRx} = F_{FRy} = 0.05N$ and work out the force exerting on front left wheel in SimMechanics model. After simulating and date processing, it is feasible to generate a locus of CG on plane X-Y. By differentiating it, the steering angle ϕ at each time point is accessible, thus a $\phi - t$ curve in simulating environment is obtained.

In order to ensure the reliability of the results, we conduct two experiments under different initial steering conditions on the physical model. We randomly set 2 different PWM (Pulse Width Modulation) values on front wheels in each experiment to realize the differential, and then corresponding steering angles in two seconds can be got(29.13°, 34.40°).



(a) (b)

Fig. 7 Comparison steering angles in SimMechanics model and physical model

In each experiment, we can get two $\phi - t$ curves on physical model and SimMechanics model, compare the two curves in one diagram, it is easily to observe that their locus coincide with each other, which means the model in SimMechanics can effectively substitute the physical model to carry out an experiment.

CONCLUSIONS

Aiming at the high frequency of vehicle rollover accident and the serious consequence it may bring about, this paper puts forward a way to prevent rollover through active steering based on existing rollover-prevention technology. In dynamic model, the forces in vehicle rollover are analyzed.

Then the vehicle is modeled as a multibody system with 11DoFs and simulated using SimMechamics package of Matlab. In experiments, the SimMechanics model and physical model are used to simulate actual steering conditions. Comparing the data getting from the two models, we can find that they correspond with each other. That means the SimMechanics model is sufficiently realistic to simulate the vehicle's motion and can be applied to analyze the vehicle stability properties. So using the SimMechanics model to substitute physical vehicle in experiments can help save hardware cost, which is of great importance in the research of orchard vehicle rollover prevention. However, there are still some deficiencies in our experiments, we merely realize steering by simulating the fictions from ground, rather than by differentiating, so there may be some deviations from real situation. Aiming to this problem, we will make a progress in future works.

Acknowledgements

Program for The National Natural Science Fund (Grant No. 51405492), Beijing Municipal Science and Technology Commission project (Grant No. D151100003715001) and Chang jiang Scholars and Innovative Research Team in University of China (Grant No. IRT13039).

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