Investigation of PID Control Model Performance in Off-Road Working Vehicle Motion Stability Control System

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***Abstract*—This paper focuses on tip-over problem of orchard vehicle, establishes vehicle dynamic model with 7 degrees of freedom (DOF), and proposes a vehicle motion stability control method based on real-time adjustment of vehicle posture parameters, relies on ADAMS and MATLAB to set up co-simulation control model, and conducts vehicle scale model motion stability control simulation and test. Analysis of simulation result shows that vehicle motion stability control model mentioned above can effectively prevent orchard vehicle tip-over accidents. To verify simulation result, vehicle state parameter collection system is established to acquire information on vehicle velocity and posture in real time. It is found in the same environment, including road conditions and parameter adjustment, vehicle scale model test and co-simulation result have a basically consistent variation tendency. When vehicle encounters tip-over accident, angles such as pitching angle vary rapidly. In anti-tip-over control process, pitching and rolling angle have greater influence on vehicle motion stability. If K_p and K_d are adjusted properly, good vehicle motion stability control effect is acquired.**

***Index Terms*—ADAMS; co-simulation; MATLAB; motion stability control; orchard vehicle.**

I. INTRODUCTION

With development of domestic orchard industry, orchard production scale and mechanization level are increasing, as well as farmers' demands for orchard machinery. Because of application to pruning, plucking, transportation and other aspects in particular environment, orchard vehicle is used more extensively in orchard production. However, orchard vehicle encounters tip-over accidents frequently in operation process, threatening security of operator and assets [1], [2]. These accidents are caused mainly by two reasons. On one hand, orchard operation environment is relatively complex and orchard vehicle often moves on uneven and fluctuating road [3]. On the other hand, centroid of orchard vehicle is too high, increasing tip-over risk. Hence, study on prevention of orchard vehicle tip-over problem has great importance on efficiency and security of orchard operation.

Manuscript received 7 November, 2016; accepted 2 February, 2017.
This research was funded by grant (No. 51405492) program for The National Natural Science Fund of China, grant (No. D151100003715001) Beijing Municipal Science and Technology Commission project of China and grant (No. IRT13039) Chang Jiang Scholars and Innovative Research Team in University of China.

At present, domestic and foreign studies on prevention of vehicle tip-over problem are mainly located on heavy vehicle and early warning mechanism. Wang Wei proposes an anti-tip-over detection method for variable amplitude cylinder vehicles [4]. Yang Liu [5] does some research on orchard vehicle anti-tip-over system based on ZigBee. Preston Thomas [6] develops a stability control and early warning system installed on heavy vehicle. What need to point out is that orchard vehicle has particular structure characteristic and faces relatively complex road conditions, making its tip-over accidents different from heavy vehicles'. Based on previous researches, this paper puts forward study on orchard vehicle active anti-tip-over control [7]–[9].

Specifically speaking, this paper establishes orchard vehicle dynamic model, sets up virtual vehicle simulation model with ADAMS, conducts co-simulation in association with MATLAB, proposes an orchard vehicle motion stability control method to exert active anti-tip-over control over vehicle, and builds an entity vehicle model to verify above research results.

II. MODEL CREATION

A. Dynamic Model

When moving on uneven road, orchard vehicle parameters (including centroid, pitching angle, pitching angular acceleration, rolling angle and rolling angle acceleration) vary as road fluctuates. Research on these parameters has great importance on orchard vehicle motion stability control [10], [11]. Based on the assumption that target vehicle is a rigid body, when moving on slope, vehicle has 7 DOF [12], that is, vehicle body centroid has 3 DOF on pitching, longitudinal and vertical movement, wheel dynamic model has 4 single DOF, shown in Fig. 1.

According to the Newton law, vehicle vertical movement equation is expressed as

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

where m_c is mass, a_c is vehicle body centroid acceleration, L is vertical distance between suspension centroid and vehicle centroid, φ is pitching angle of vehicle body, F_{1i} is acting force exerted by suspension on vehicle body, $i = fl$, $i = fr$, $i = rl$ and $i = rr$ represent left front wheel, right front wheel, left rear wheel and right rear wheel respectively.

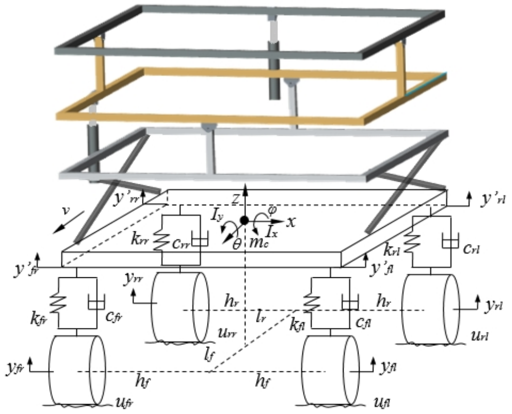


Fig. 1. 7 DOF whole vehicle model.

Equations of acting force exerted by suspension on vehicle body are expressed as:

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

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

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

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

where k is suspension stiffness, c is damping of suspension damper, y_{fr}, y_{fl}, y_{rr} and y_{rl} are vertical displacement of unsuspended mass at front and rear axle, y'_{fr}, y'_{fl}, y'_{rr} and y'_{rl} are vertical vibration displacement of front and rear suspension.

Equation of vehicle body pitching movement is expressed as

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

where I_y is rotary inertia of vehicle body along y axis, l_f is distance between front axle and centroid, l_r is distance between rear axle and centroid.

Equation of vehicle body rolling movement is expressed as

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

where I_x is rotary inertia of vehicle body along x axis, θ is rolling angle of vehicle body, h_f is distance between front wheel and centroid, h_r is distance between rear wheel and centroid.

B. Motion Stability Control Method

When orchard vehicle crosses barriers, the most direct reflection of tip-over is that wheels don't have contract force on ground. It means that in extreme state, contract force on ground exerted by tires should meet the following need

$$|u| \geq 0. \tag{8}$$

When vehicle nears critical point of instability, inertia force is exerted on vehicle body to make tires meet needs of (8) at some extent.

Vehicle tip-over problem is mainly depicted with vehicle body pitching angle, which can be taken as control target to determine acceleration. Specifically speaking, pitching angle of vehicle body is measured by sensors in real time. Moreover, to transmit brake signal to wheels, other parameters of vehicle body are also required, including pitching angular acceleration, pitching angular velocity and theirs directions. According to vehicle coordinate system, symbol of pitching angle is determined. In this paper, clockwise direction is assumed to be positive direction of pitching angle. Based on brake signal outputted by above equations, equation of wheel velocity is expressed as

$$v = K_p \varphi + K_d \dot{\varphi}, \tag{9}$$

where v is wheel velocity, K_p and K_d are adjustment coefficients.

In consideration of simplification, orchard vehicle tip-over accident, which takes place when vehicle crosses barriers, can be regarded as an uphill and downhill process. When orchard vehicle moves uphill, pitching angle increases gradually, pitching angular velocity varies, as well as contract force on ground exerted by front and rear wheel. When pitching angle reaches a certain value, front wheel doesn't meet needs of (8) any longer and vehicle tips over backward. When orchard vehicle moves downhill, pitching angle decreases gradually. When pitching angle reaches a certain value, rear wheel doesn't meet needs of (8) any longer and vehicle tips over frontward. In case control of (9) is exerted, when vehicle moves uphill and downhill, brake force of vehicle changes as pitching angle and pitching angular velocity vary. By adjustment of vehicle velocity, adhesive ability of tire on surface is enhanced to increase motion stability and prevent tip-over accident.

III. VIRTUAL VEHICLE SIMULATION MODEL

A. Scale Model

To reduce risk and cost, this paper establishes orchard vehicle model on the scale of 1:5 in laboratory environment to conduct tip-over test, shown in Fig. 2.

Fig. 2. Vehicle scale model.

Specifically speaking, authors use ADAMS to set up virtual prototype of scale model, conduct vehicle motion stability analysis in orchard road conditions, rely on

MATLAB/Simulink module to make control algorithm co-simulation [13]–[15] based on dynamic characteristics of virtual prototype model, adjust parameters of control model to optimize control method, and finally verify practicability and availability of control algorithm by solid vehicle test of scale model, whose main parameters are shown in Fig. 1.

Vehicle body of scale vehicle model consists of vehicle chassis and lifting platform. Two engines are connected with axial wheels and rear wheels are installed on vehicle body by axle. Lifting platform can load heavy goods to change centroid of vehicle body. Moreover, lifting platform is connected with vehicle chassis by hinge joint and its height can be adjusted in linear way. Mpu6050 gyroscope is installed on vehicle centroid to collect 3-axis angular acceleration and velocity. After Kalman filtering process and analysis with MC9S12XS128 central processing unit, vehicle location information (including pitching angle and sideslip angle) is calculated based on vehicle location signal and regarded as input signal of vehicle body control. With control model of (9), velocity control signal is outputted by TB6612 DC Motor to make scale model move smoothly.

B. Simulation Model

ADAMS is virtual prototype analysis software developed by MDI of America and used extensively [16]. In this paper, ADAMS is adopted to conduct statics, kinematics and dynamics analysis of virtual prototype.

According to 7 DOF dynamic model and scale model, virtual prototype simulation model is established [15], [16], whose main components are vehicle body, tire and power system. Scale model parameters are shown in Table I, and modeling process is depicted as follows:

1. Establish basic components of scale model with ADAMS/VIEWS.
2. Confirm each component's structure, assembly components and determine components' parameters, including mass, centroid and rotary inertia of 3 axes, based on parameters in Table I.
3. Determine constraint relation of each component's connection positions and add various kinds of constraint relation in turn according to component movement.
4. Make a parametric definition for parameters which need to be measured, add braking function and conduct test.

Accuracy of simulation model design has great influence on effect of control model. Hence, after establishment, model needs to be analysed, checked and modified further to guarantee accuracy of virtual prototype model.

Selection of tire model is mainly determined by working conditions. In practice, effectiveness and accuracy of calculation is affected by selection of tire in different environment, which means that appropriate selection of tire is very important. UA model built with ADAMS is mostly used to control vehicle motion stability. UA tire model is established based on magic formula, whose general expression is

$$Y\left(x\right) D sin\left\{C tan^{-1}\left[Bx-E\left(Bx-tan^{-1}\left(Bx\right)\right)\right]\right\}, \quad (10)$$

where *Y(x)* is lateral force, self-aligning torque or longitudinal force, *x* is sideslip angle or longitudinal slip rate of tire in different conditions, *B*, *D* and *E* are coefficients and determined by vertical load of wheels and camber angle, *C* is curve shape factor.

TABLE I. SCALE MODEL PARAMETERS.

Item	Value	Item	Value
Gravity acceleration	9.81m/s^2	Rotary inertia of vehicle body along z axis	0.0132 kg·m^2
Mass of vehicle body	2.04kg	Mass of a wheel	32.3 6g
Length of vehicle body	0.206m	Wheel radius	32.5mm
Width of vehicle body	0.156m	Wheel width	25.0mm
Height of vehicle body	0.152m	Wheel axial rotary inertia	2.5×10^{-5}kgm^2
Rotary inertia of vehicle body along x axis	0.0081 kg·m^2	Wheel yaw rotary inertia	1.5×10^{-5} kgm^2
Rotary inertia of vehicle body along y axis	0.0100 kg·m^2	Total mass of vehicle	2.17 kg

UA tire has good robustness [17], [18]. By taking non-steady state effect into consideration, analysing interaction between friction circle and side slip as well as interaction between friction circle and longitudinal slip, and regarding extroversion, relaxation length and tire radius as calculation factors, mathematical model of UA tire is concise and has relatively high accuracy. Hence, this paper selects UA model as tire model of virtual prototype. Input and output variables of UA model are shown in Fig. 3.

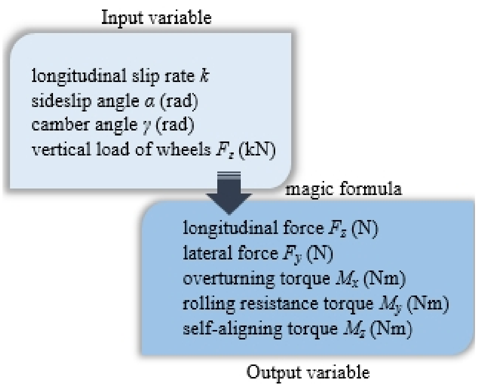


Fig. 3. Main parameters of tire model.

C. Model Simulation and Result Analysis

Orchard vehicle motion is impacted by road conditions. This paper selects sinusoidal road to conduct simulation tests. In consideration that setting road parameters has great influence on verification of feasibility of orchard vehicle tip-over control model, it is necessary to conduct simple simulation to compare with motion styles of vehicle model in different road conditions, which is helpful to set appropriate road parameters to conduct co-simulation with ADAMS and MATLAB.

Specifically speaking, scale vehicle model built with ADAMS is used to conduct motion simulation, which is aimed to find out vehicle motion state in different road conditions and estimate vehicle tip-over risk. Meanwhile, vehicle parameters (including velocity, pitching angle, pitching angular velocity and so on) are measured and analyzed with ADAMS/PostProssecor module. When vehicle moves, pitching angle variation can directly reflect vehicle tip-over process. Therefore, following part of paper is concentrated on comparative analysis of vehicle pitching angle variation.

Because irregular orchard road surface can be regarded as a superposition of uniform and small regular waves, simulation of vehicle motion in irregular fluctuating road is equal to simulation of vehicle motion in fixed fluctuation frequency and amplitude. This paper uses sinusoidal 2D road surface built with ADAMS to conduct simulation, where amplitude is 30 mm and wavelengths are 1200 mm, 800 mm and 400 mm respectively. Figure 4 shows pitching angle-time curve of vehicle uniform motion.

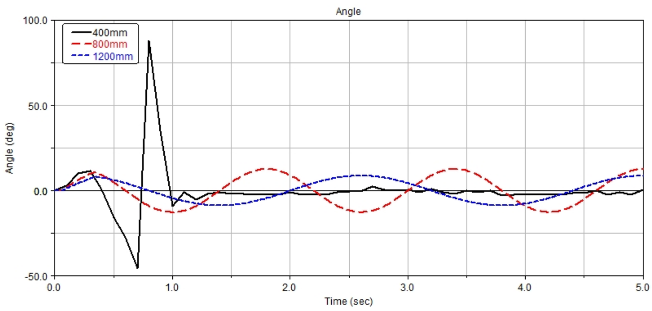


Fig. 4. Model simulation.

As shown in Fig. 4, when road fluctuation is relatively small, for example, wavelength is 1200 mm or 800 mm, vehicle motion state is relatively smooth, pitching angle presents sinusoidal variation according to road surface. When road fluctuation is relatively big, that is, wavelength is 400 mm, vehicle encounters tip-over accident and pitching angle varies irregularly. Therefore, when simulation model is used to conduct vehicle anti-tip-over active control test, road surface model with 400 mm wavelength can be used for comparative test to analyses vehicle motion stability without and with stability control algorithm and improve control model.

IV. CONTROL SYSTEM DESIGN

A. Hybrid Modelling with ADAMS and MATLAB

For realize an active control of anti-tip-over a control module with MATLAB/Simulink is needed to implant control algorithm and conduct co-simulation [19], [20]. Then you should take the following steps:

1) Selection and adjustment of road surface model

A superposition of the vehicle responds to uniform and small regular waves can depict orchard vehicle motion on irregular road surface. Therefore, the vehicle performance under fixed fluctuation frequency and amplitude can be used for study of the complex vehicle motion performance on the road. As a result, a sinusoidal road has been selected under testing.

2) Setting of state variables

To stabilize the vehicle, motion a control of wheels braking must be performed. The respective value of the braking signal is derived from (4) and it needs to be regarded as an input variable. The state variable should be inputted as a vehicle velocity under control process. If this measure is adopted, the value of this input variable is calculated by Simulink controller model and implemented further to ADAMS vehicle model under co-simulation. The pitching angle and pitching angular velocity are therefore, the output state variables, whereas, velocity v is input variable φ and $\dot{\varphi}$ are output variables respectively.

3) Importing of MATLAB/Simulink module

Virtual prototype model is exported by ADAMS/Control module and imported by MATLAB respectively. The model parameters have been set in Simulink model, and co-simulation with ADAMS and MATLAB is completed. (Simulink control model is shown in Fig. 5).

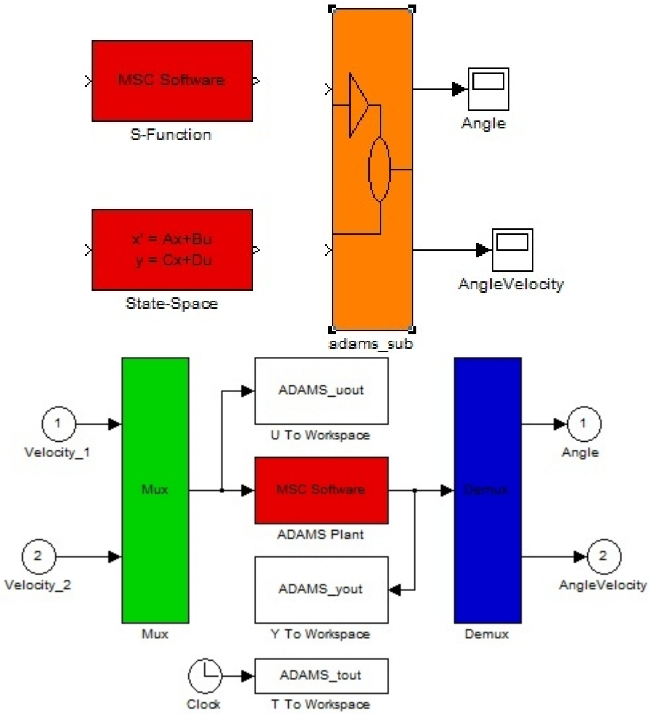


Fig. 5. Simulink model.

B. Control Model

The input state variable v as well as output state variables K_i, φ and $\dot{\varphi}$ are involved in ADAMS_sub- module as shown in Fig. 5. Equation (9) indicates that v is determined by K_p, K_d, φ and $\dot{\varphi}$ parameters as it can be seen from Fig. 6. Therefore, the tip-over control model is established basing on such values.

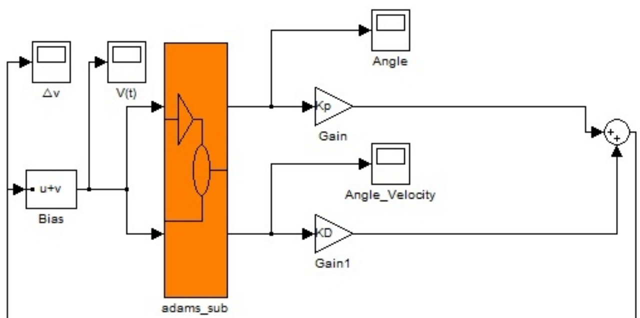


Fig. 6. Simulink control model.

The process of the active control model proceeds as follows: orchard vehicle moves at time 0 and encounters fluctuating road at time t, where, v is input variable, $\varphi(t)$ and $\dot{\varphi}(t)$ are output variables, and $v(t+1)$ is input velocity at time t + 1. According to (9), $v(t+1)$ is given as

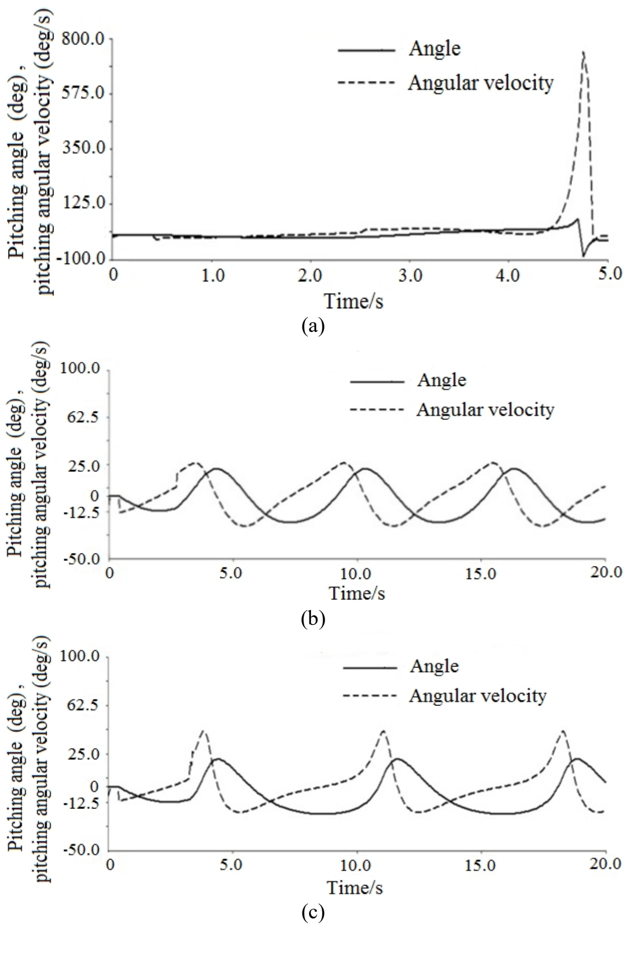
$$v(t+1) = v + \Delta v. \tag{11}$$

Meanwhile, the output variables $\varphi(t+1)$ and $\dot{\varphi}(t+1)$ emerge. By respective adjustment of increment Δv value, the orchard vehicle motion stability is maintained to prevent the vehicle tip-over.

V. CO-SIMULATION

It is learned from analysis of (9) and control model shown in Fig. 6 that on assumption of orchard vehicle motion on sinusoidal road, if φ varies, $\dot{\varphi}$ varies accordingly. Because angles vary quickly in tip-over process, $\dot{\varphi}$ has greater influence on vehicle motion stability in anti-tip-over control. Meanwhile, in practice, velocity increment can be controlled by adjustment of K_p and K_d. Value selection of K_p and K_d has great influence on control effectiveness [21]. Simulation result mentioned above shows that scale model vehicle will tip over when moving on sinusoidal road with 30 mm amplitude and 400 mm wavelength. What follows is to exert control over model by co-simulation, shown in Fig. 8, and to analyse simulation model motion state.

This paper selects different K_p and K_d value to conduct co-simulation and gets representative velocity, pitching angle and pitching angular velocity curve shown in Fig. 7.



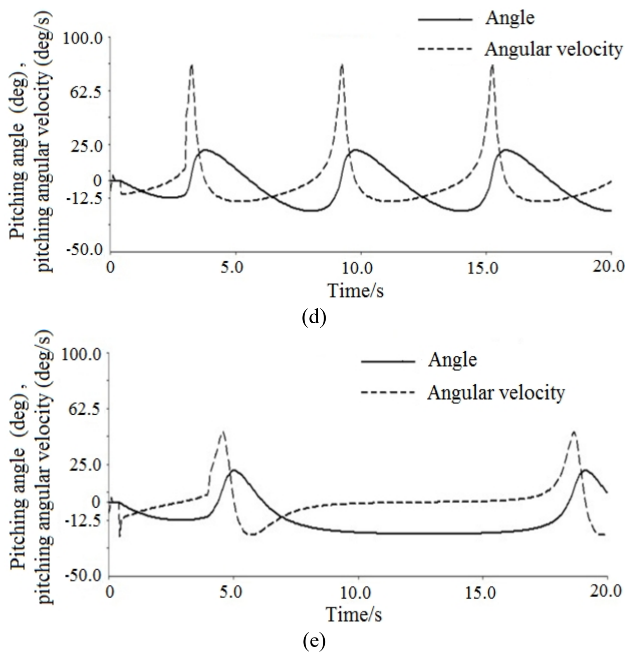


Fig. 7. Control algorithm simulation test: a) K_p = 0.25, K_d = 0; b) K_p = 0, K_d = 0.25; c) K_p = 1, K_d = 0.25; d) K_p = 1, K_d = 0.5; e) K_p = 1, K_d = 1.

Figure 7 shows that after realization of control, scale model can move on sinusoidal road smoothly, that is, control model shown in Fig. 6 can effectively reduce orchard vehicle tip-over risk. Tip-over accident rate varies according to road conditions and does not represent stable sine curve.

It is learned from analysis of test results that value selection of K_p and K_d in control model has great influence on orchard vehicle motion stability. As shown in Fig. 7(a), in case K_p = 0.25 and K_d = 0, adjustment of vehicle angles has little effect on vehicle control. Tip-over accident occurs when vehicle moves on test road.

As shown in Fig. 7(b), in case K_p = 0 and K_d = 0.25, control of vehicle motion stability and prevention of vehicle tip-over are realized by adjustment of vehicle pitching angular velocity. However, vehicle pitching angle variation is relatively big and ride comfort is relatively bad.

As shown in Fig. 7(c), in case K_p = 1 and K_d = 0.25, pitching angle variation has greater influence on vehicle stability control compared to Fig. 7(b). It means that when K_d remains unchanged and K_p varies only, control effect in angular velocity is bigger and pitching angle variation is more stable.

As shown in Fig.7(d), in case K_p = 1 and K_d = 0.5, when vehicle crosses barriers, uphill and downhill velocity variation is bigger than that in Fig. 7(c) and angular velocity is up to 80 deg/s. Thus, vehicle motion stability is impacted.

As shown in Fig. 7(e), in case K_p = 1 and K_d = 1, vehicle uphill velocity decreases to about 10mm/s so that vehicle is hard to go uphill.

Above analysis shows, that appropriate value selection of orchard vehicle control parameters can not only effectively avoid vehicle tip-over, but also increase motion stability.

VI. SCALE MODEL TEST

Orchard vehicle scale model shown in Fig. 2 consists of wheels, battery, single chip, sensors and so on. Considering vehicle motion stability control is realized by adjustment of velocity in test, two DC motors controlled by microcontroller

MC9S12XS128 are installed on the inside of rear hubs, stability control program is downloaded to microcontroller MC9S12XS128, rear wheel speed is measured by optical encoder and speed signal is transmitted accordingly.

In test, vehicle body posture information (including pitching angle) is collected by chip MPU6050. After Kalman filtering process, data is transmitted to two nodes. On one hand, data is transmitted to master computer through serial input ZigBee module in wireless way and saved in master computer. On the other hand, data is transmitted to microcontroller MC9S12XS128 and transformed into control signal by microcontroller's internal control program. Then control signal is sent to ECU and motors to realize real-time control.

To ensure consistency of scale model test and simulation, sinusoidal road with 30 mm amplitude and 400 mm wavelength is established.

Measurement deviation of pitching angular velocity may be caused by potholes on road surface during vehicle motion and can be eliminated as gross error through data process. To verify effectiveness of co-simulation model in practical application, this paper conducts comparative test with scale model shown in Fig. 8.

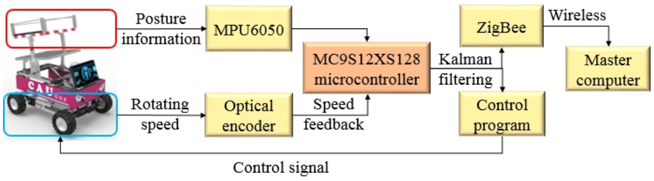


Fig. 8. Scale model control process.

First test is concentrated on entity vehicle motion state without control. When vehicle moves at a speed of 70 mm/s on sinusoidal road, pitching angle varies, shown in Fig. 9, and vehicle tips over.

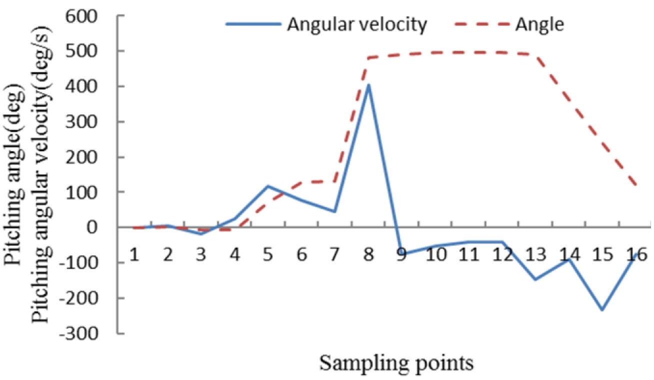


Fig. 9. Solid vehicle without control.

Second and third tests are concentrated on entity vehicle motion state with control. In case K_p = 0.25 and K_d = 0.25, pitching angle varies, shown in Fig. 10(a). In case K_p = 1 and K_d = 0.25, pitching angle varies, shown in Fig. 10(b). Results of both tests show that scale vehicle crosses sinusoidal road and does not tip over. Moreover, with increase of K_p, vehicle angular velocity variation is bigger and pitching angle variation is more stable. After comparison of simulation test results, we find that if control is exerted over vehicle, vehicle stability can be maintained and tip-over can be prevented.

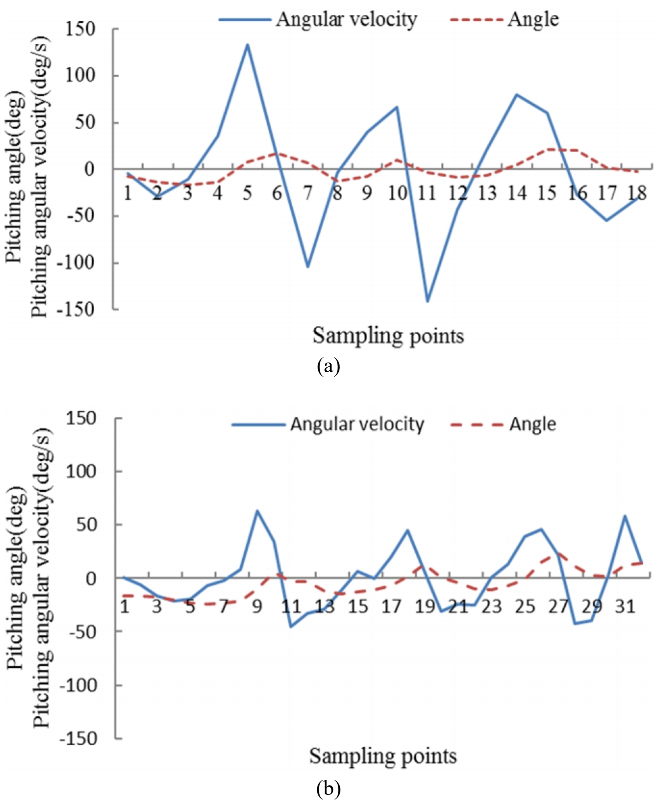


Fig. 10. Solid vehicle with control: a) K_p = 1, K_d = 0.25; b) K_p = 0.25, K_d = 0.25.

Following co-simulation tests are conducted as adjustment parameters vary [22]. As shown in Fig. 11, when K_d is zero or relatively small, that is, control is not exerted over vehicle or obvious, vehicle tip-over may occur. In case K_p = 0.25 and K_d = 0, only vehicle pitching angel variation is involved in speed control. In case K_p = 0 and K_d = 0.25, by control based on angular velocity variation, vehicle can cross sinusoidal road at relatively low average speed of 22 mm/s and motion process is relatively stable. In case K_p = 1 and K_d increases from 0.25 to 1 gradually, vehicle can cross sinusoidal road. However, as K_d increases, vehicle pitching angle variation is bigger in uphill and downhill motion. Although vehicle doesn't tip over, motion process is relatively unstable.

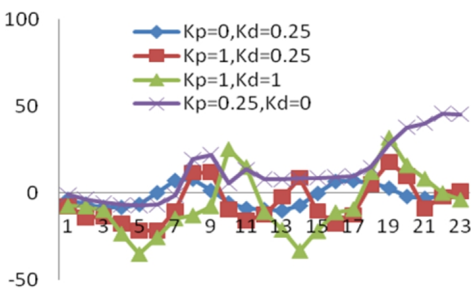


Fig. 11. Scale model and solid vehicle test data.

Above analysis shows that test and co-simulation results are consistent in variation trend. When vehicle encounters tip-over accident, angles such as pitching angle vary rapidly. In anti-tip-over control process, pitching and rolling angle have greater influence on vehicle motion stability. If K_p and K_d are adjusted properly, good vehicle motion stability control effect is acquired. Considering road conditions simulated in scale vehicle test and simplification of vehicle dynamic model, there is some difference between scale vehicle test and simulation. Although simulation has clearer periodicity and regularity, comparison of control results attained by adjustment of main control parameters, such as pitching angle and pitching angular velocity, shows that change trend of simulation is close to that of scale vehicle test. Therefore, further analysis and test on control model parameters can be conducted based on co-simulation analysis method.

VII. CONCLUSIONS

1. To improve orchard vehicle motion stability and solve its tip-over problem, this paper proposes an anti-tip-over control method. Authors establish orchard vehicle dynamic model with 7 DOF as well as orchard vehicle model on the scale of 1:5 for reducing risk and cost. Virtual simulation model is built with ADAMS and simple simulation is conducted concluding with a suitable road surface model of 400mm wavelength for tests next.
2. Control algorithm is designed in MATLAB on the basis of control model and cooperates with simulation model in ADAMS to conduct co-simulation. In co-simulation, orchard vehicle moves on sinusoidal road with 30 mm amplitude and 400 mm wavelength. Control is exerted over model by adjustment of coefficients K_p and K_d, which respectively related to pitching angle and pitching angular velocity. The effect changes with different K_p and K_d value and prevention of vehicle tip-over can be realized such as in case $K_p = 1$ and $K_d = 0.25$.
3. Scale vehicle model test is carried out on the same road condition to keep consistent with co-simulation and also concentrates on vehicle motion state as parameters vary. Test result shows that change trend of control is close to co-simulation, that is, scale model tips over without control and can move on smoothly with control of $K_p = 1$ and $K_d = 0.25$.
4. It is learned from analysis and comparison of co-simulation and scale vehicle test that orchard vehicle tip-over accident can be prevented effectively and vehicle motion stability in complex road conditions can be attained by appropriate adjustment of model control parameters.

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