STUDY ON ACTIVE ANTI ROLLOVER CONTROL AND MODEL TEST OF TRACTOR MOMENTUM FLYWHEEL

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拖拉机动量飞轮主动防侧翻控制与模型试验研究

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ABSTRACT

The tractor working environment is complex and changeable, and the dynamic variation range of the center of gravity position of the tractor body is large. In order to avoid rollover accident, an active anti rollover control method of tractor momentum flywheel and its model test are proposed in this paper. The tractor dynamic system model and control strategy are verified by a 1:16 scale tractor model. The research results show that when the model tractor crosses the trapezoidal obstacle B, the roll angle of the whole machine is temporarily stable near 35°, indicating that at this time, the tires on one side of the whole machine are in actual contact with the obstacle, showing a short stable state of the whole machine. When the pavement roughness reaches F-H level, without any active anti rollover control, the evaluation index EP shows a divergence trend when it is greater than 1, and the simulation calculation is terminated due to the occurrence of rollover of the whole machine. The test data and simulation results under two different driving speeds are in good agreement, which verifies the effectiveness and reliability of the tractor rollover dynamic system model and the momentum flywheel active stabilization system.

摘要

拖拉机作业环境复杂多变，拖拉机机体重心位置动态变化范围较大，为避免发生侧翻事故，本文提出拖拉机动量飞轮主动防侧翻控制方法及其模型试验。通过 1:16 比例模型拖拉机对拖拉机动力学系统模型及控制策略进行验证。研究结果当模型拖拉机翻越梯形障碍 B 时，整机侧倾角短暂稳定在 35° 附近，说明此时整机一侧轮胎均与障碍物实际接触，表现为短暂的整机稳定状态。当路面粗糙度进入 F-H 级时，在没有任何主动防侧翻控制的条件下，评价指标 EP 大于 1 后呈发散趋势，仿真计算均因整机侧翻的发生而终止。两种不同行驶速度工况下的测试数据和仿真结果吻合度较高，验证了拖拉机侧翻动力学系统模型及动量飞轮主动回稳系统的有效性和可靠性。

INTRODUCTION

With the development of economy, the application scope of agricultural machinery is more and more extensive, but its accident rate is also on the rise. Especially, tractor rollover accidents frequently occur *(Vahdanjoo M. et al., 2020)*. The causes of rollover accidents are mainly due to design defects and quality problems of tractors, and also due to improper operation of users. Whether the tractor is working in the field or on the road, once a rollover accident occurs, it is inevitable to cause casualties and economic losses *(Karakulak S. S. et al., 2020)*. Therefore, the detection of tractor's maximum stable inclination angle is a very important project. Tractor rollover test is a test to exam the stable angle and maximum stable inclination angle of tractor rollover. It is a necessary item for tractor supervision, inspection and popularization appraisal *(Song H. S. et al., 2020)*. Passing the tractor rollover test is of great significance for controlling the height of the tractor's center of gravity, driving safely or operating safely in the field, which can not only improve the stability and safety of the tractor, but also reduce the incalculable accidents of the tractor during operation. Tractor itself is a complex system with large delay, high nonlinearity, time-varying and uncertainty. Moreover, it is difficult to establish an accurate mathematical model because of poor farmland conditions and complex interaction process between tires and ground. When the controlled object is affected by uncertain factors such as parameter perturbation and external interference, it will reduce the control quality of the system. Disadvantages such as increased oscillation and long transition time occur *(Elsayed A.T. et al., 2016)*.

Therefore, it is necessary to fully mine the vehicle state information contained in the vehicle model and select the appropriate control algorithm to improve the navigation system performance *(Shamsuddin P. et al., 2020)*. The necessary condition for tractor rollover is that the vertical line of the tractor's center of gravity crosses the fulcrum between the overturned tire and the ground. Therefore, the tractor can be prevented from turning over as long as the stable moment formed by the tractor's center of gravity on both sides of the tire and the ground fulcrum is greater than the dumping moment formed by other forces on the tire and the ground fulcrum, and the direction is opposite to the stable moment *(Hu Y. et al, 2016)*. When it's turning, the tractor speed should not be too fast, and the turning should not be too fast *(Stroganov Y N. et al., 2020)*. Because when it's turning, the tractor will produce an outward centrifugal force. The centrifugal force is directly proportional to the tractor's mass, directly proportional to the square of the tractor's traveling speed and inversely proportional to the turning radius. Therefore, when turning too fast, the centrifugal force of the tractor may be increased, and the centrifugal force will form a dumping moment on the fulcrum between the steering outer tire and the ground. When the dumping moment is greater than the stable moment formed by tractor gravity, the tractor will roll over. The center of gravity of loading should be low, and unbalanced loading should be prevented during loading. For example, the tractor is equipped with a bucket or combine, etc. *(Jang B. E. et al., 2021)*.

The centrifugal force acting on the center of gravity or the tilting force formed on the slope will increase the dumping moment due to the increase of the force arm (the height of the center of gravity is increased), which is easy to cause rollover. Due to the eccentric load, the center of gravity shifts to one side tire, which reduces the stabilizing moment formed by gravity against the side tire, and also easily causes the tractor or trailer to roll over *(Li S. et al., 2018)*. There are two reasons that cause the tractor to turn back. The first is the torque and traction resistance of the rear axle, and the second is that the tractor's center of gravity or the vertical line of the center of gravity moves backward, which causes the tractor's stable torque to decrease and causes it to turn over. When the clutch is engaged, the engine transmits the torque to the rear axle. If the rear wheels can't rotate for some reason, for example, the tires of the rear wheels are frozen on the ground or the tractor pulls too much, the driving torque will make the tractor rotate around the rear axle and make the front wheels leave the ground. If the engine has enough power, and the ground adhesion coefficient is good, it will cause the tractor to turn back, because the rear wheels cannot slip or roll forward in situ, and the torque of the rear wheels will make the tractor turn back. Tractor's center of gravity or vertical line of center of gravity moves backward, which causes the tractor's stabilizing moment to decrease and makes it turn backward. When a tractor climbs a hill, the front wheel should be weighted or the reverse gear should be hung. The method of retreating uphill, because when the tractor goes uphill, the action line of gravity leans towards the rear wheel, which increases the danger of the tractor turning backwards. Reduce the height of hitch point of trailer on tractor. Because the higher the towing point is, the greater the backward turning moment formed by the towing resistance of the trailer on the tractor, which is easy to cause the tractor to turn backward. The towing point of the trailer should be selected on the towing plate of the tractor. It can't be attached to other parts of the tractor, and the wrong attachment method may reduce the load of the front wheel of the tractor, make the operation fail, and even cause an accident of rollover. According to this research, *Bauer M. et al.* proposed that to prevent high-speed emergency braking, unilateral braking should be prohibited, speed should be reduced first when turning, and driving at low speed on snow, ice and muddy roads should make trailer braking precede tractor braking, etc. When the tractor skids during running, the skidding force will act on the center of gravity of the tractor, forming a dumping moment on the fulcrum between the tire and the ground, which will make the tractor slip into the ditch or roll over, turn on its side in the drain as shown in Figure 1 *(Rogov P. S. et al., 2020)*.

Fig. 1 - Tractor overturned in the gutter

Elsayed et al thought that tractor drivers should be extra careful when driving on a cross slope *(Elsayed A.T. et al., 2016)*. Because the action line of gravity of the tractor on the transverse slope leans towards the fulcrum between the tire and the ground on the inclined side, the stabilizing moment on this side becomes smaller, and the greater the slope of the ground, the smaller the stabilizing moment becomes. Therefore, when driving on a cross slope, the speed must be slow to prevent the ground from bumping and avoid turning on the slope *(Liao C. et al., 2018)*. *Zhang L*. et al. believe that when the tractor runs in dangerous areas such as ditch embankment and dam edge, the tractor should be a certain distance away from the ditch edge, and the driver must concentrate on driving the tractor *(Zhang L. et al., 2021)*.

On the basis of the current research, this paper puts forward the active anti-rollover control method of tractor momentum flywheel and its model test, and verifies the above tractor dynamic system model and control strategy by means of a 1:16 scale model tractor. The tractor dynamic system model established in this paper can accurately reflect the course of tractor obstacle crossing and rollover behavior, and the active stabilization system is effective and reliable. Tractor rollover dynamics system model and momentum flywheel active stabilization system are effective and reliable.

MATERIALS AND METHODS

System Modeling and Stability Evaluation

As shown in Figure 2, a mechanism independent of the main engine, the swingable front axle of tractor plays a role in improving the stability and obstacle-surmounting ability of the whole engine. In the modeling process, the front axle and the main engine have six degrees of freedom, namely, longitudinal, lateral, vertical, roll, pitch and yaw. The six-degree-of-freedom motion of the front axle is restricted by the motion of the engine body, except for the roll motion. Therefore, seven degrees-of-freedom can describe the dynamic behavior of tractors except tires *(Wu X. et al., 2017)*.

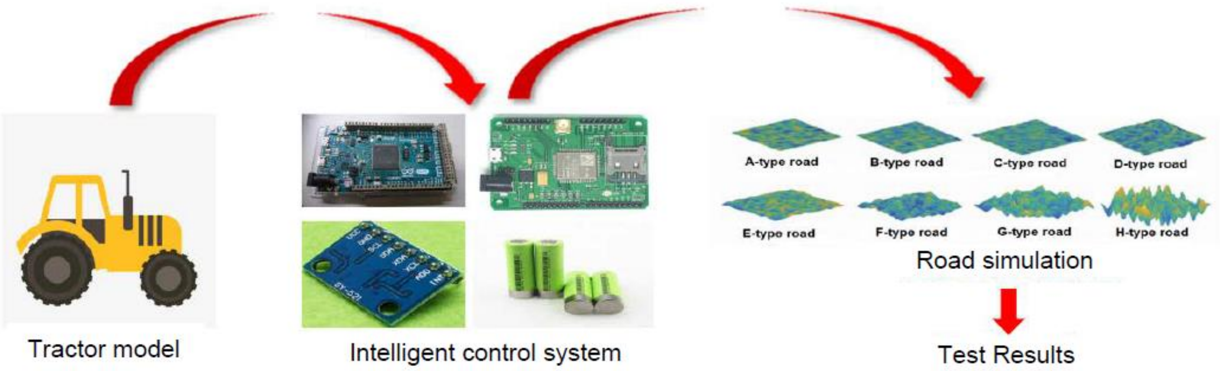

Fig. 2 - Schematic diagram of experimental simulation

The tractor runs at a constant speed along the X axis of the slope contour line, and the translational motion equations of its main engine along the Y and Z axes are shown in Formula (1).

$$\begin{aligned} m\ddot{y} &= mg\sin\alpha + F_{py} - F_{y3} - F_{y4} \\ m\ddot{z} &= F_{pz} + F_{z3} + F_{z4} - mg\cos\alpha \end{aligned} \tag{1}$$

The roll, pitch and yaw motion equations of the airframe around x, y and z axes are shown in formulas (2), (3) and (4) respectively.

$$I_{xr}\ddot{\varphi}_r = (F_{z3} - F_{z4})\frac{B_r}{2} + (F_{y3} + F_{y4})H_r - F_{py}e_{rz} \tag{2}$$

$$I_{yr}\ddot{\theta}_r = F_{pz}L_{r1} - (F_{z3} + F_{z4})L_{r2} \tag{3}$$

$$I_{zr}\ddot{\gamma}_r = (F_{y1} + F_{y2})L_f - (F_{y3} + F_{y4})L_r \tag{4}$$

The independent roll motion equation of the front axle around the X axis is shown in (5).

$$I_{xf} = \ddot{\theta}_f = M_{xf} \tag{5}$$

Formula (1)-(5) symbol description is shown in Table 1.

Table 1

Formula (1)-(5) symbol description

m	the mass of the whole machine
g	the acceleration of gravity
α	the lateral slope angle
F_{py}	the lateral force of the hinge point of the front axle
F_{pz}	the vertical stress of the hinge point of the front axle
F_{yi}	the wheel lateral force N, i=1-4
F_{zi}	the wheel vertical force N, i=1-4
I_{xr}	rotational inertia of the main body around the x axis
I_{yr}	rotational inertia of the main body around the y axis
I_{zr}	rotational inertia of the main body around the z axis
φ_r	represents the overall roll angle
B_r	the rear wheel track
H_r	height of center of gravity *(COG_r)* from the ground
e_{rz}	the vertical distance between the center of gravity of the machine body and the pivot of the front axle
L_{r1}	horizontal distance from COG_r to hinge point of front axle
L_{r2}	horizontal distance from COG_r to rear wheel
L_r	horizontal distance from COG_r to rear axle
L_f	horizontal distance from COG_r to front axle
γ_r	horizontal distance from COG_r to hinge point of front axle
I_{xf}	the moment of inertia of the front axle around the x axis
θ_f	front axle pitch angle
M_{xf}	surrounded by the front bridge

In the process of tractor running, all external forces (ignoring air resistance) on the machine body come from the contact between tires and the ground, so establishing a relatively accurate tire model is the basis for the whole machine dynamic model to reflect the real tractor state. In this paper, Fiala tire model 201 is selected, and the tire vertical force can be expressed as shown in formula (6).

$$F_{zi} = -k_{f/r}\Delta z_{f/r} - c_{f/r}\Delta \dot{z}_{f/r}(i = 1-4) \tag{6}$$

$c_{f/r}$ is the tire vertical damping, $k_{f/r}$ is the tire vertical stiffness, $\triangle z_{f/r}$ is the vertical deformation of the tire.

The lower corner mark f represents the front wheel and r represents the rear wheel. Considering the tractor-momentum flywheel system, ignoring the friction when the flywheel rotates around the motor shaft and the dissipation force in the process of tractor stabilization, the Lagrange method can be obtained as shown in Formula (7).

$$\left(I_x^* + I_w\right)\ddot{\varphi} - \frac{B}{2}(m + m_w)g\sin\varphi = -I_w\ddot{\zeta} \tag{7}$$

where I_w is the flywheel moment of inertia, I^*_x is moment of inertia of the whole machine around the x axis, and B is track coefficient, m_w is flywheel mass, ζ is flywheel angle, φ represents the overall roll angle.

The lateral stability evaluation index is an important symbol and control basis for reflecting the stability of the whole machine. The instability boundary exists in the tractor rollover process, which is determined by whether the projection of the center of gravity of the whole machine in the vertical direction crosses the roll axis. Therefore, this paper introduces the lateral stability evaluation index EP based on the extreme posture position in the rollover process, and its calculation formula is as follows (8).

$$EP = \frac{2H_{coc}mg\sin(|\varphi + \alpha|)}{Bmg\cos(|\varphi + \alpha|)} \tag{8}$$

H_{COC} is the height of gravity center of the whole machine. With 1 as the instability threshold, when the tractor is in a stable state, the lateral component of gravity is small, and at this time EP is less than 1. With the increase of the roll angle of the whole machine, EP continues to increase until EP reaches 1 when the center of gravity is directly above the roll axis, and the whole machine is in a critical unstable state. When the center of gravity of the whole machine crosses the roll axis, EP is greater than 1. If there is no outside intervention, a rollover accident will occur. This index is the basis for dynamic evaluation, monitoring and active control of lateral stability of the whole machine *(Zong, Z. et al., 2019)*.

Scale Model Test Platform to Build a Model Tractor

Considering the high risk of using real vehicles for rollover test, this paper verifies the above tractor dynamic system model and control strategy through a 1:16 scale model tractor. Considering the test function of the model tractor, the model tractor is mainly composed of control unit, drive unit, flywheel-motor unit, fuselage shell, chassis and front axle. The control unit consists of ArduinoDUE control module, HC-05 Bluetooth data transmission module, MPU6050 six-axis gyroscope and 12V lithium battery. The driving unit is composed of ZS-H1B double H-bridge DC motor driving module, permanent magnet DC driving motor, gear reducer and herringbone pattern model tire.

The flywheel-motor unit is composed of reaction torque flywheel, driving motor and Hall encoder, etc. The momentum flywheel is placed in the front of the tractor, which can replace the traditional static counterweight and actively provide anti-rollover torque, and build the completed 1:16 scale model. To further verify the effectiveness and universality of active rollover control of momentum flywheel system under complex road conditions, combining the relationship between displacement power spectral density (PSD) and spatial frequency in formula (9), the system excitation is provided for the simulation and verification of the active control system under the full-scale road surface.

$$G_q(n) = G_q(n_0)\left(\frac{n}{n_0}\right)^{-w} \tag{9}$$

where $G_q(n)$ is displacement power spectral density, $G_q(n_0)$ is road roughness coefficient, n is the spatial frequency, n_0 is the reference spatial frequency.

RESULTS

Determine the Test Verification of Active Stabilization System under Obstacles

Figure 3 and Figure 4 show the change trend of the whole machine's roll angle during the obstacle crossing process of the model tractor at different speeds. By using Matlab/Simulink software, the effectiveness of PID control is simulated and analyzed during the stabilization process of the reaction flywheel. According to the time domain definition of the two obstacle-crossing processes of the whole machine in Figure 3 and Figure 4, the lateral attitude of the whole machine fluctuates twice in different degrees during the process of the model tractor crossing the obstacle A. This is because the front axle can swing freely within a certain angle, so that the lateral attitude change of the whole machine caused by the obstacle crossing of the front wheel is less than the influence of the obstacle crossing of the rear wheel, which is in line with the actual working condition of the tractor. When the model tractor climbs over the trapezoidal obstacle B, the side inclination of the whole machine is temporarily stable near 35, which indicates that the tires on one side of the whole machine are actually in contact with the obstacle at this time. It shows a short stable state of the whole machine. The test data under two different driving speeds are in good agreement with the simulation results, which verifies the validity and reliability of the tractor rollover dynamic system model and the momentum flywheel active stabilization system.

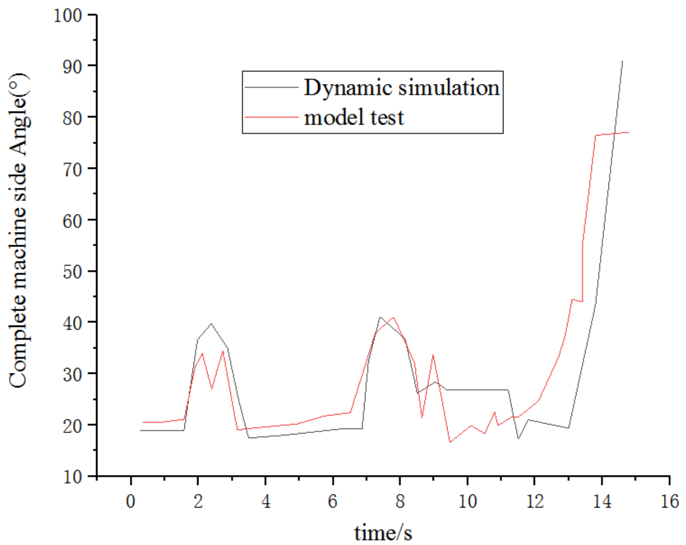

Fig. 3 - Change curve of roll angle of the whole machine at 0.1 m/s

The anti-rollover verification of momentum flywheel system is carried out by applying tractor dynamic system model verified above and full-scale random road surface, and the change rule of lateral stability evaluation index of the whole machine under F and H roads as shown in Figure 5 and Figure 6 is obtained.

When the tractor runs on a relatively flat road surface, the lateral stability evaluation index EP of the whole machine is always less than 1, and the whole machine does not show a rollover trend. This is consistent with the actual situation that the tractor has relatively good stability when running on the road surface with small fluctuation and low roughness.

When the roughness of pavement enters F-H level, under the condition of no active anti-rollover control, the evaluation index EP is greater than 1, and then it tends to diverge, and the simulation calculation is terminated due to the occurrence of the whole machine rollover. Under the condition of active control, despite the rollover tendency of tractors in different directions, the tractors are stabilized under the active intervention of momentum flywheel system, which can make the tractors run safely and smoothly on the road with large fluctuation and high roughness.

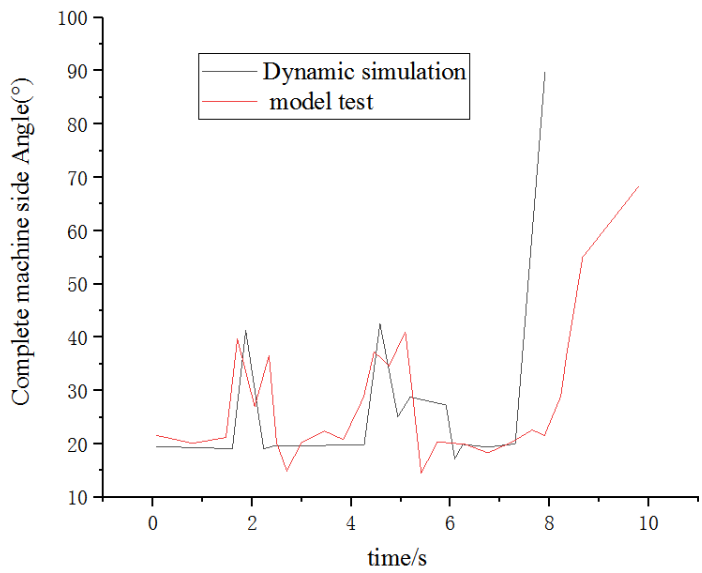

Fig. 4 - Change curve of roll angle of the whole machine at 0.2 m/s

Simulation and verification of effectiveness of momentum flywheel system under random road excitation.

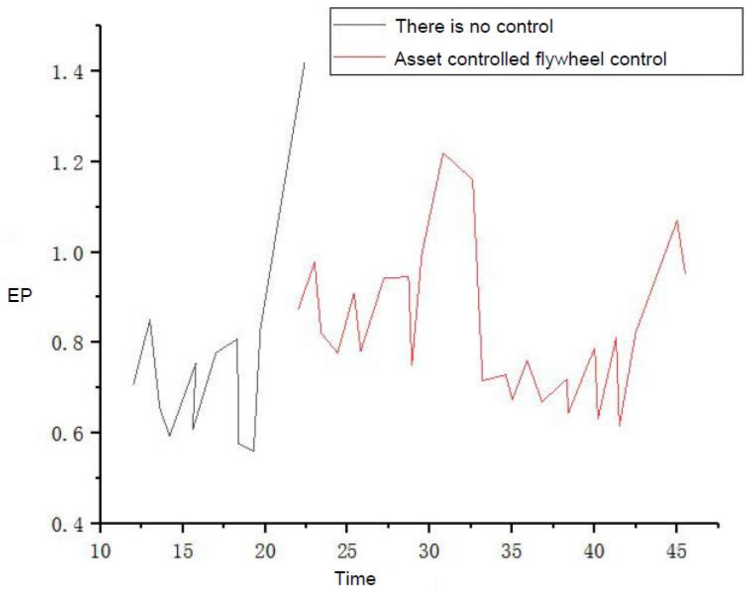

Fig. 5 - Variation law of lateral stability evaluation index of the whole machine under F level pavement

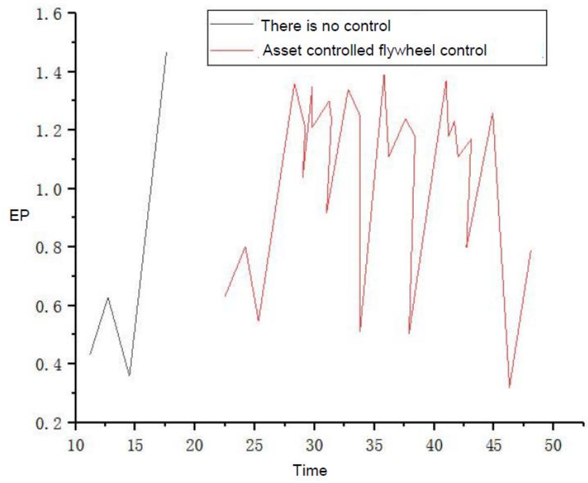

Fig. 6 - Variation law of lateral stability evaluation index of the whole machine under 4H grade pavement

The working state of the tractor momentum flywheel active anti-rollover control system is shown in Figure 7.

Fig. 7 - Anti-rollover control system for tractor

CONCLUSIONS

In this paper, the active anti-rollover control method of momentum flywheel is proposed, and the model and road test platform are built. The effectiveness of the active control system and dynamic model is verified by simulation. The tires on one side of the whole machine are actually in contact with obstacles, showing a short-term stable state of the whole machine. Test data and simulation results under two different driving speeds are in good agreement. The validity and reliability of tractor rollover dynamic system model and momentum flywheel active stabilization system are verified. The fact that the tractor has relatively good stability when running on the road with small undulation and low roughness coincides with the actual situation. The tractor rolls in different directions, but with the active intervention of the momentum flywheel system, they are stable, which enables it to drive safely and stably on the road with large fluctuation and high roughness. The method proposed in this paper can effectively suppress the rollover behavior of tractor under extreme working conditions.

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