

Lateral Stability Analysis of Telehandlers Based on Multibody Dynamics

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Abstract: At the beginning, this article analyzed the lateral stability of telehandlers, and reached the following results: the critical overturning angle, the critical sliding angle, and the conditions of sliding happen before overturning. Then, the ADAM virtual prototype of telehandlers was built based on the multibody dynamics model, and the dynamic simulation of the lateral stability of telehandlers was carried out, and then we got the rule of that the right tire reacting force change with the critical overturning angle with frame leveling or not. Base on the 'UA' model of tire, we studied the influence of vertical stiffness and lateral stiffness on the lateral stability of telehandlers. The result of virtual simulation method was compared with that of the theoretical calculation and platform experiment. It can be seen that the result of the virtual simulation method is closer to the actual situation, and can shorten the development process and reduce the cost, which can guide the structure design of telehandlers more scientifically. This article can also provide reference for the design of the lateral stability of the rear axle articulated vehicles.

Key-Words: Telehandlers, Lateral Stability, ADAMS, Overturning Angle, Multibody Dynamics

1 Introduction

Telehandlers is mainly used in the fields of military and civilian logistics, architectural engineering, agriculture, etc. Vehicle integrates the functions of cranes, forklifts, and loaders, becomes the important logistics and engineering equipment. A variety of works can be implemented, such as obstacle-surmounting operations, pulling in and out operations, loading and unloading operations without operation platform, as well as the integrated high raising operations with large span.

Telehandlers stability can maintain the normal performance under all possible conditions without sliding and overturning. Sliding angle and overturning angle are usually used to evaluate the stability, and should be preferentially considered in the structure layout and design of telehandlers[1]. A wealth of statistical data show that majority forklifts rollover accidents happened are caused by the lateral instability[2]. Therefore, the lateral stability of telehandlers study is extremely necessary.

Currently, there are three methods to evaluate the lateral stability of telehandlers: theoretical calculation, virtual simulation and platform experiment. They are distinguished from each other,

as well as connected with each other. Platform experiment is a traditional method to verify the lateral stability of telehandlers, commonly used in the performance simulation of virtual prototype. Theoretical calculation method is often used in the vehicle structure design, especially in the barycenter position design, whose analysis result has some differences with the actual situation. Virtual simulation method is often used in the performance simulation of virtual prototype, which largely overcomes errors of the theoretical calculation to the actual, but also replaces the process of "physical prototype design verification" in traditional design, which has large resource consumption. This method can avoid the phenomenon of rebuilding prototype due to parametric design unreasonable in platform experiment [3, 4].

This paper studied the vehicle leveling system and the influence of tire vertical stiffness, lateral stiffness on lateral stability of telehandlers by using ADAMS, and compared its result with those of theoretical calculation and platform experiment.

2 The lateral stability analysis of telehandlers

For safety reasons, sliding and overturning are the

sign of instability, and overturning is a bigger danger. So, it must be ensured that there is no sliding and overturning happen, at least that the sliding could happen before overturning, which is the precondition to stability analysis and calculation[1, 5]. Telehandlers with a rigid suspension weighs G , its static force diagram on the slope with α angle is as shown in the figure 1.

The barycenter is marked as F , the support force from slope to two wheels is Y_1 and Y_2 , and the static friction is Z_1 and Z_2 as wheels sliding down. No-load lateral overturning moment and stability moment can be got at P , which is an intersection point of slope and the tire bottom. [6, 7].

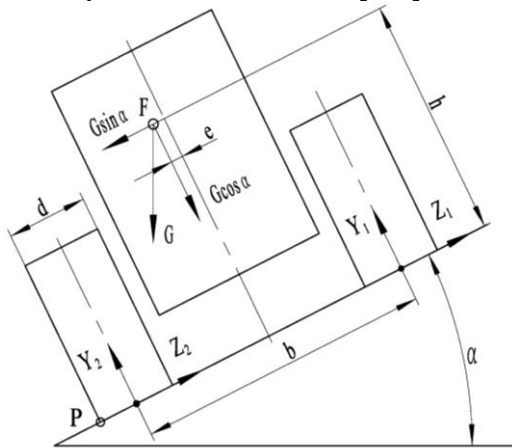


Fig. 1 Force diagram of telehandlers when laterally driving on the slope

No-load lateral overturning moment is given by:

$$T_w = mgh \sin \alpha \quad (1)$$

Where m is the no-load mass of the vehicle, α is the gradient, h is the perpendicular distance from barycenter to slope with none-load.

No-load lateral stability moment is given by:

$$T_z = mg \left(\frac{b+d}{2} - e \right) \cos \alpha \quad (2)$$

Where b is the wheelbase, d is the wheel width; e is the offset distance from barycenter to the longitudinal symmetry plane.

The stability coefficient is defined as: (normally, the value should be greater than 1.5)

$$n = \frac{T_w}{T_z} \quad (3)$$

State of critical overturning: make n be 1, get that:

$$\tan \alpha = \frac{b+d-2e}{2h} \quad (4)$$

So, we can get that:

$$\alpha_i = \arctan \left(\frac{b+d-2e}{2h} \right) \quad (5)$$

Where α_i is the critical overturning angle.

It follows that the critical overturning angle is the

angle between the barycenter line and vehicle longitudinal line when the barycenter line go through the point P . So, it relates to the barycenter position of telehandlers, not the mass, and the critical overturning angle increases with the ratio of horizontal and vertical component of barycenter position.

The maximum static friction is given by:

$$Z = Z_1 + Z_2 = \mu_1 Y_1 + \mu_2 Y_2 \quad (6)$$

Where μ_1 and μ_2 are coefficients of static friction of the two wheels (that is adhesion coefficient), normally, $\mu_1 = \mu_2 = \mu$.

Critical sliding state, make that:

$$Z = mg \sin \alpha_s = \mu (Y_1 + Y_2) = \mu mg \cos \alpha_s \quad (7)$$

The Critical sliding angle is given by:

$$\alpha_s = \arctan(\mu) \quad (8)$$

It follows that, when the coefficients of static friction of the two wheels is equal, the critical sliding angle is proportion to the coefficient of static friction.

So, the condition to ensure sliding happen before overturning is that: $\alpha_s < \alpha_i$, which means that the ratio of horizontal and vertical component of barycenter position is bigger than the coefficient of static friction:

$$\frac{b+d-2e}{2h} > \mu \quad (9)$$

3 Multibody dynamics model of telehandlers

The dynamic system of telehandlers is made up of several parts, it has many kinematic characteristics, such as inertia, elasticity, damping, etc. Because telehandlers can be influenced by the steering wheel rotation, aerodynamic (such as lateral wind) and uneven road, its kinestate can be changed easily, which may cause overturning happen. Because the influence factors are dynamic, it is difficult to guide the vehicle barycenter position inspection and structure parameter adjustment according to usual static criteria of lateral stability. Therefore, to establish a dynamic model and test the stability of telehandlers by ADAMS kinematics simulation is necessary [6, 8].

Telehandlers has the four-wheel drive system and three-section telescopic boom structure, and three steering ways, such as two-wheel steering, four-wheel steering and crab steering. Front axle and rear axle are connected by rigid suspension. The frame hinges with front axle and rear axle through the cylindrical joint, and can swing with some degree opposite to the both sides of axle. The front axle installs the leveling cylinder, which makes the front

axle could be locked and makes the frame can level within 10 degree more or less. Therefore, telehandlers can handle the uneven placed materials, or drive on the slope full-loaded.

Based on the frame structure and the multibody dynamics theory, we established the vehicle multibody dynamics model. The mass of the vehicle can be divided into three parts, the mass of frame and front axle marked as M_1 , rear axle mass marked as M_2 , the combined mass of telescopic boom and fork marked as M_3 , as shown in figure 2. Simplify the part between the telescopic boom and the frame to a piecewise linear spring with viscous damping. Spring is located between the two hinge point marked as F and F' of the hydraulic cylinder, spring stiffness is set as K_b , and damping is set as C_b . Simplify the tires to a three-dimensional piecewise linear springs with viscous damping.

Take the right front wheel for example, vertical spring is located between the point A_0 and the wheel center point A , and it's vertical stiffness is set as K_{f1} , vertical damping is set as C_{f1} . Lengthways spring is connected with point A_0 at one end, and the other end is suspended along the lengthways direction, and it's lengthways stiffness is set as K_{f2} , lengthways damping is set as C_{f2} . Driving force P_A and running resistance F_A act on point A' along the lengthways direction, which on the suspended end of lengthways spring. Lateral spring is connected with the point A_0 at one end, and on the other end of lateral spring is suspended along the lateral direction, and it's lateral stiffness is set as K_{f3} , lateral damping is set as C_{f3} . Lateral force S_A (lateral adhesion force or sliding friction force) laterally act on point A'' , which on the suspended end of lateral spring.

Similarly, the other three wheels are simplified in the same way with the right front wheel. So, the dynamic system has complete six degrees of freedom [9-11].

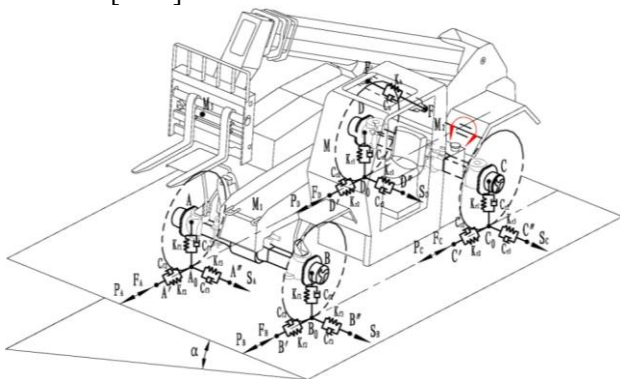


Fig. 2 Multibody dynamics model of telehandlers

Related simulation parameters of telehandlers as following:

Tab 1. Related simulation parameters of telehandlers

Parameters	Signs	Values	Units
Overall Length	L	6590	mm
Overall Width	W	2340	mm
Overall Height	H	2390	mm
Maximum Loads	G	2500	kg
Total Mass	M	7990	kg
Front Axle Mass	M_1	2560	kg
Rear Axle Mass	M_2	3707	kg
Telescopic Boom and Fork	M_3	1723	kg
Load Center Distance	h_1	600	mm
Maximum Speed	V	45	km/h
Minimum Turning Radius	R	7200	mm
Minimum Ground Clearance	h_2	400	mm
Vertical Stiffness	K_{f1}	1000	N/mm
Vertical Damping Coefficient	C_{f1}	3.1	
Lengthways Stiffness	K_{f2}	40000	N
Lateral Stiffness	K_{f3}	30000	N/rad
Lateral Damping Coefficient	C_{f3}	2.3	
Static Friction Coefficient	UMA X	1.1	
Rolling Resistance Coefficient	f	4.0	
Tire Radius	R_T	650	mm
Tire Width	W_T	350	mm

4 Dynamics simulation for lateral stability

4.1 The multi-body dynamics simulation model design

Based on the above multibody dynamics model of telehandlers, the ADAMS virtual prototype model with rigid suspension system is established, avoiding the complex mathematical formula derivation process. Import the UG model with the X_T format into ADAMS to simulate. Before simulation, the environment of simulation is set, and then the required constraints is added after summing several parts of model, not only because that can make it easier to add constraints, but also can reduce the calculation amount during simulation and improve the accuracy of the simulation results[12].

Whether the frame of telehandlers level or not can directly affect the barycenter position, and also directly affect its lateral stability. Therefore, different conditions must be studied respectively.

The UA tire model used in the virtual prototype simulation model belongs to physical model, which

takes the unstable condition into account, and the effective frequency could be set to 8 Hz. It has good accuracy considering limited parameters. To prevent sliding happen before overturning, the coefficient of static friction should be set as 0.9.

As shown in figure 3, the ADAMS virtual prototype model of telehandlers with leveling system move on a 2D slope at no-load, and its telescopic boom was drawn back.

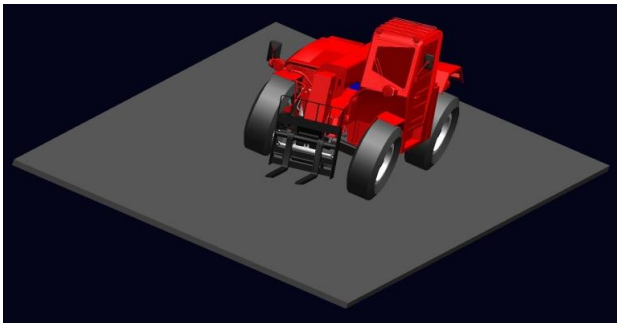


Fig. 3 The ADAMS virtual prototype model of telehandlers with leveling system move on a slope

4.2 The effect of leveling system on the lateral stability of telehandlers

In the lateral stability dynamics simulation, the slope angle can be modified by STEP function. And the reacting forces of the right front tire and the right rear tire change with the slope angle was studied. The simulation results as seen in figure 4 and figure 5, the reacting force decreases with the increase of slope angle. When the reacting force approximate to zero, telehandlers becomes instable, and its critical overturning angle of right front tire can be obtained to be 35 degree if with leveling system, and 30.9 degree if without leveling system. The critical overturning angle of right rear tire can be obtained to be 38.5 degree if with leveling system, and 34.9 degree if without leveling system.

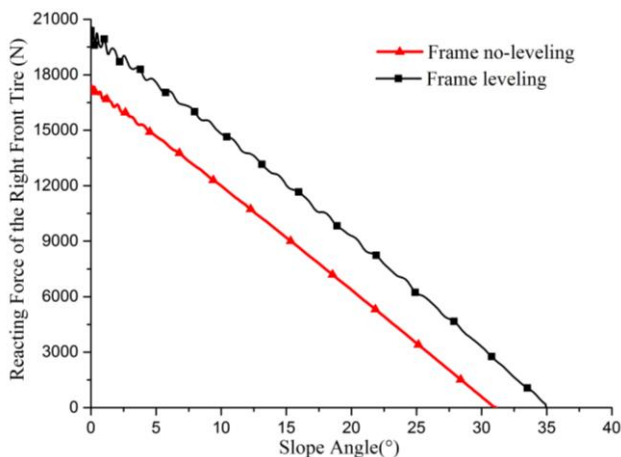


Fig. 4 Curve of the reacting force of the right front tire changed with the slope angle

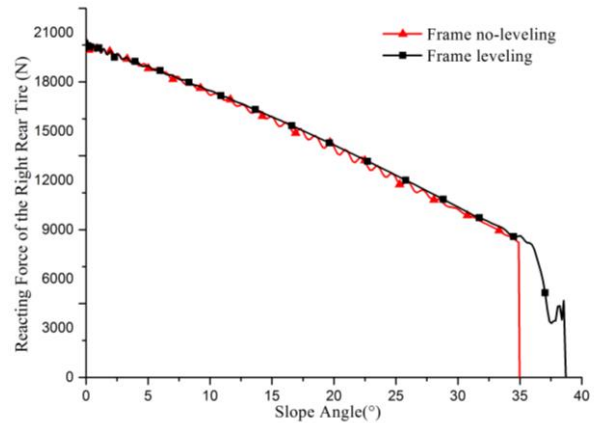


Fig. 5 Curve of the reacting force of the right rear tire changed with the slope angle

By comparing Figure 4 and Figure 5, it is found that with the leveling system, the critical overturning angle of right rear tire slightly larger than the right front tire, which is caused by the center of gravity of the vehicle close to the rear tires. So, when lateral instability of telehandlers occurred, it tended to occur at the right front tire first. Because the rear axle of telehandler articulated, only the front axle has leveling oil cylinder, that frame leveling system has little effect on the reacting force of the right front tire, but has greater impact on the critical overturning angle of the right rear tire.

4.3 The effect of vertical stiffness of tires on lateral stability of telehandlers

Vertical stiffness of the tire determines its vertical deformation, related to the tire load and pressure, which increases with the increase of tire pressure, and then growth slows down, which appears logarithmical increase. In order to make the results more comparable, study the state without leveling system only.

In UA tire model, the vertical stiffness values were set to be 600, 800, 1000, 1200, 1400 respectively, other parameters could be found in Table 1. We got curves of the reacting force of the right front tire and right rear tire, changing with the slope angle at different vertical stiffness, shown in Figure 6, 7.

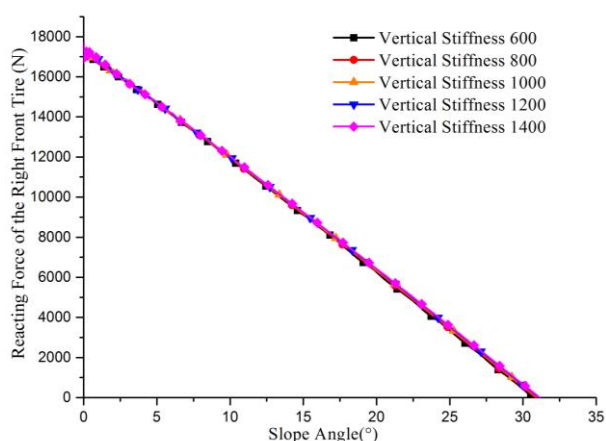


Fig. 6 Curves of the reacting force of the right front tire

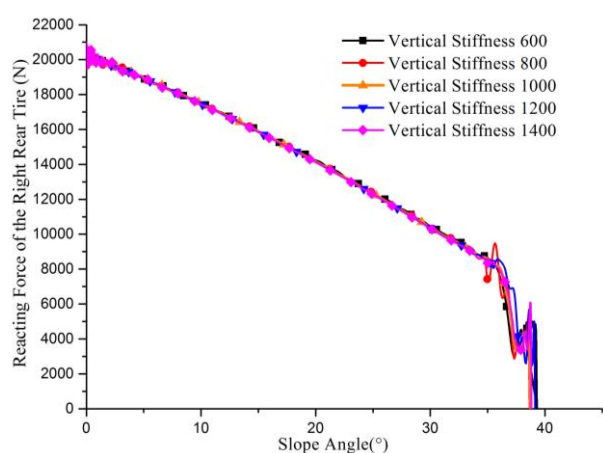


Fig. 7 Curves of the reacting force of the right rear tire

Figure 6&7 shows that the reacting force of the right front tire or the right rear tire are very nearly at different vertical stiffness. So, we can draw a conclusion that the vertical stiffness of the tire has little effect on tire reacting force, and little effect on the critical overturning angles of telehandler. The critical overturning angle at the right front tire is about 31° , and that at the right rear tire is about 38° . Therefore, the tire vertical stiffness has little effect on lateral stability of telehandler.

4.4 The effect of lateral stiffness of tires on lateral stability of telehandlers

Lateral stiffness of the tire determines its lateral deformation. We still only study the state of the frame without leveling system. In UA tire model, the lateral stiffness values were set to be 20000, 25000, 30000, 35000, and 40000 respectively, other parameters could be found in Table 1. We got curves of the reacting force of the right front tire and right rear tire, changing with the slope angle at different

lateral stiffness, shown in Figure 8, 9.

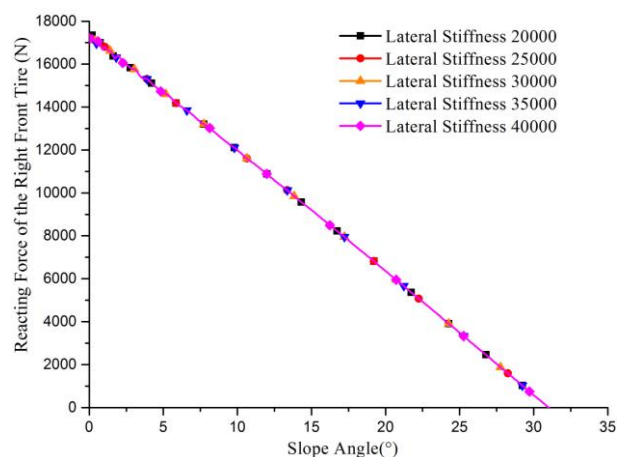


Fig. 8 Curves of the reacting force of the right front tire

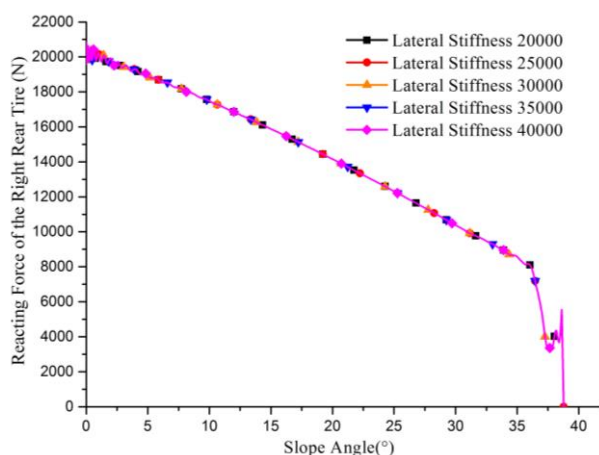


Fig. 9 Curves of the reacting force of the right rear tire

As shown in Figures 8&9, the curves almost completely overlap, so we can see that the tire lateral stiffness has no effect on lateral stability, owing to the lateral stiffness of the tire determines its lateral deformation only.

5 Statics calculation for lateral stability of telehandlers

Because the rear axle of telehandlers is articulated with the frame, the supporting plane turns to ABE plane from ABCD plane. Its front fulcrum A and B are the ground points of left and right wheels, respectively, and the rear fulcrum E is the hinge center of rear axle and frame, as shown in figure 10. The point J is the projection of the barycenter on the ABE plane. Line JK parallel to line AB, and meet in point K with line BE. When telehandlers laterally overturn, its overturning axis is line BE or AE[13].

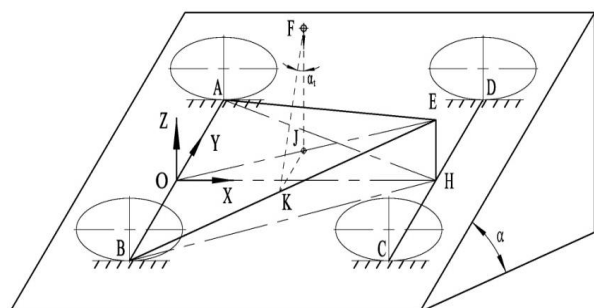


Fig. 10 The overturning angle of telehandlers analysis

By the formula (5), when $e = 0$, the overturning angle of telehandlers is $\alpha_t = \arctan(JK / FJ)$.

5.1 Frame without leveling

Using traditional method to analyze the stability of telehandlers, the position of the barycenter must be known at first. Normally, the position of the barycenter could be measured on prototype using platform experiment method, and then prototype's stability can be checked[3]. In this paper, we build the global coordinate system for ADAMS virtual prototype model as shown in figure 10. We can get the barycenter position exactly in ADAMS by the command of Aggregate Mass, and the barycenter coordinates is $(XF, YF, ZF) = (1604, 0.28, 1178)$, $BO = 930\text{mm}$, and the coordinates of point E is $(XE, YE, ZE) = (3300, 0, 590)$, then:

$$FJ = Z_F - X_F \times Z_E / X_E \approx 891.22 \quad (10)$$

$$JK = (1 - X_F / X_E)BO + |Y_F| \approx 478.24 \quad (11)$$

$$\alpha_t = \arctan(JK / FJ) \approx 28.2^\circ \quad (12)$$

5.2 Frame leveling

After the frame leveling on the slope, the barycenter position is changed, that can improve the lateral reliability of telehandlers. The coordinates of point E is $(XE, YE, ZE) = (3300, 0, 590)$, the barycenter coordinates is $(XF, YF, ZF) = (1604, 90, 1168)$, and $BO = 930\text{mm}$, then:

$$FJ = Z_F - X_F \times Z_E / X_E \approx 881.22 \quad (13)$$

$$JK = (1 - X_F / X_E)BO + |Y_F| \approx 567.96 \quad (14)$$

$$\alpha_t = \arctan(JK / FJ) \approx 32.8^\circ \quad (15)$$

6 Platform experiment for lateral stability of telehandlers

Through early structural design and virtual simulation, we produced the prototype. And then, we finished the lateral stability experiment using platform method in China National Construction Machinery Quality Supervision Testing Center. As seen in Figure 11.



Fig. 11 Platform experiment for lateral stability of telehandlers

The critical overturning angle was been gotten at the Testing Center. The critical overturning angle of telehandlers with frame without leveling is 30.1 degree. The critical overturning angle of telehandlers with frame leveling is 34.6 degree. The angles gotten by three methods of theoretical calculation, virtual simulation and platform experiment were compared, as shown in table 2.

Tab 2. Lateral overturning angles by statics and dynamics method with leveling or not

Overturning Angles	Without Leveling	Leveling
Dynamic Simulation	30.9°	35.0°
Statics Calculation	28.2°	32.8°
Platform Experiment	30.1°	34.6°

As seen in the table 2, whether the frame have leveling or not, can easily affect the position of the barycenter, the critical overturning angle of telehandlers with frame leveling is bigger than that without leveling. It can obviously improve the lateral stability that telehandlers is leveled when driving or operating on the slope.

The dynamic simulation result is closer to the platform experiment result compared to the statics calculation result. The main reason is that the tire is seen as a totally rigid part in statics calculation, and the overturning point is the intersection point of slope and the bottom of the left tire. However, in the dynamical simulation, the vertical stiffness and damping coefficient of the tire is being considered, so that the result of dynamical simulation seems to be closer to the actual situation. Therefore, the dynamics simulation can guide the structure design of telehandlers more scientifically compared with the statics calculation.

6 Conclusion

By studying the lateral reliability of telehandlers, it can be found that to ensure sliding happen before overturning must make sure that the ratio of

horizontal and vertical component of barycenter position is bigger than the coefficient of static friction. And it is found that the effect of frame leveling on the lateral stability of telehandlers is significant; during ramp movement security can be improved if with frame leveling. For rear axle articulated vehicle, when front axle is fixed or with frame leveling system the critical overturning angle occur in the right front tire. By using UA tire model simulation, it is shown that the tire vertical stiffness has little effect on the lateral stability, and lateral stiffness almost no effect on lateral stability.

It can be seen from the example in this article that the virtual simulation method could drive product development by using simulation technology, which can avoid complex mathematical formula derivation process, and can make it come true to simulating lateral stability with high precision simulation in design phase, and its result is more close to actual situation comparing with the theoretical calculation method, that can improve the lateral reliability analysis and forecasting abilities. Comparing with prototype testing it can greatly optimize the development cycle, shorten the process and reduce costs.

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