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Dynamic Stability Analysis of High-level Order-picking Truck

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Abstract. More and more high-level order-picking trucks are used to pick and transport goods in warehouses. The dynamic stability of the truck has great effect on operation efficiency, quality and safety. It is instructive and meaningful for the optimization of structure and control strategy to analyze the dynamic stability of the truck. Firstly, the dynamic model of the order-picking truck is established using Alembert principle, and then the dynamic stability of the truck is analyzed. Secondly, the virtual prototype model of the truck is established and traveling process is simulated. The simulation further verifies the dynamic stability of the truck.

Introduction

High-level order-picking trucks have been widely used in order-picking operation of the warehouse due to their high working efficiency and low cost. However, the order-picking truck may tip over easily as a result of the shift of gravity center of the whole truck that is caused by high lifting height, accelerating and braking. Therefore, it is quite significant for improving dynamic performance of the truck to analyze the dynamic stability of order-picking trucks.

In order to ensure the high efficiency and safety of operation, the order-picking truck is supposed to have good maneuverability and stability. Maneuverability means the minimum turning radius and the required width of the aisle of warehouses. Stability means the capability of the truck to maintain its stability during travel and operation [1]. To ensure the order-picking truck being flexible enough under the premise of high stability, it is necessary to analyze the dynamic stability of the truck and optimize the structure and control strategy constantly. In this paper, the dynamic stability of the order-picking truck is analyzed using theoretic method and virtual prototype technology.

Establishment of Model

Basic Assumptions. Since the actual structure and movement of the order-picking truck is complicated, the following assumptions are made within reasonable range.

(1) The order-picking truck is assumed to be a rigid body.

(2) The order-picking truck travels on level and hard enough road and does not slip during the traveling process.

(3) The traveling process of accelerating and braking are considered to be uniformly accelerated motion, and the lifting and descending of operator platform are considered to be uniform motion.**Physical Model.** As Fig.1 shown, the high-level order-picking truck is mainly composed of chassis, mast system and operator platform. There is a big driving wheel under the chassis and two loaded wheels under two base arms. The three wheels compose the supported surface of the whole truck. During the traveling process, the operator platform and goods can lift or descend along the three-stage mast which is driven by hydraulic cylinder. The maximum lifting height of goods is up to ten meters. The whole truck can be simplified as a physical model shown in Fig. 2. The truck is supported by point A, point B and point C in the horizontal plane. The gravity center of the whole truck is focused on point D. The forces acting on order-picking truck under different traveling state will be analyzed separately, then their dynamic models will be established in the following.

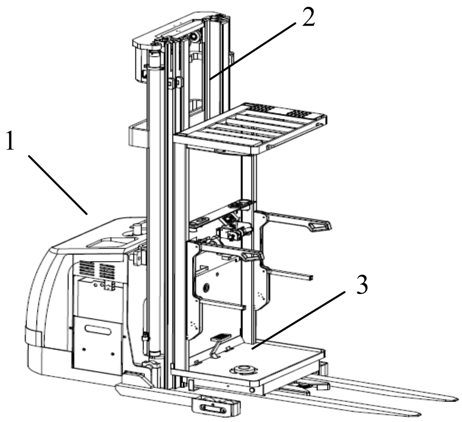
There are five traveling state during the process of traveling straight. The traveling state include uniform motion, accelerating forward, braking forward, accelerating backward and braking backward. Now we will take the state of accelerating forward for an example to analyze forces acting on the truck (see Fig. 2). Assuming that the truck can keep balance under the combined action of all forces during the process of accelerating forward, the dynamic equations can be established according to Alembert principle as follows.

$$\sum F_z = N_A + N_B + N_C - mg = 0 \tag{1}$$

$$\sum M_{BC} = N_A(x_1 + x_2) - mgx_2 + mah = 0 \tag{2}$$

$$\sum M_{AF} = N_B y_1 - N_C y_2 + mgy_3 = 0 \tag{3}$$

where m is the total mass of all components(including the driver); a is the acceleration of the truck; h is the distance from the location of gravity center to the ground; N_A, N_B, N_C are the normal action forces between the front wheel, left rear wheel, right rear wheel and ground; ΣF_z is resultant force of all the force in the vertical direction; ΣM_{BC} is the resultant torque of all the force relative to axis BC; ΣM_{AF} is the resultant torque of all the force relative to axis AF.



1.chassis 2.mast system 3.operater platform

Fig. 1 The structure of an order-picking truck

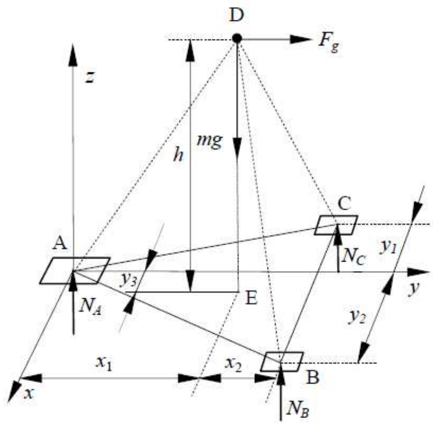


Fig. 2 Force analysis while accelerating forward

See Fig. 4 for the force analysis of truck during the process of turning left, the truck is acted upon by reaction force N_A, N_B, N_C, inertial force, centrifugal force and gravity. In the same way, assuming that the truck can keep balance under this traveling state, the dynamic equations are established according to the Alembert principle as follows.

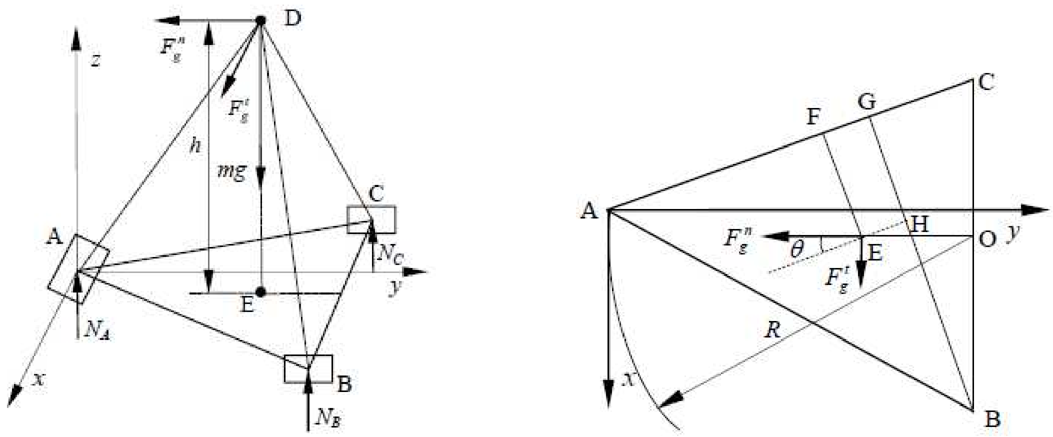


Fig. 4 The force analysis of the order-picking truck while turning left

$$\sum F_z = N_A + N_B + N_C - mg = 0 \tag{4}$$

$$\sum M_{AC} = N_B l_{BG} + F_g^n h \sin\theta - F_g^t h \cos\theta - mgl_{EF} = 0 \tag{5}$$

$$\sum M_{EF} = -N_A l_{AF} + N_B l_{EH} + N_C l_{CF} + F_g^n h \cos\theta + F_g^t h \sin\theta = 0 \tag{6}$$

where F_g^t is tangential inertial force during the process of turning left ; F_g^n is the centrifugal force; ΣM_{AC} is the resultant torque of all the force relative to the overturning axis AC; ΣM_{EF} is the resultant torque of all the force relative to axis EF.

Solution and Analysis of the Model

It can be seen from the dynamic equations that the stability of the truck is closely related to structure, acceleration, load and so on. The effect of these parameters on the dynamic stability can be obtained from the dynamic equations. In order to measure the stability of the truck, the normal forces of three wheels acting on ground during the traveling process can be got from dynamic equations. If the value of N_A, N_B, N_C is much greater than zero under all traveling state, the stability of the truck is good. Otherwise, the value of N_A, N_B, N_C is close to zero or smaller than zero under any one of the traveling state which demonstrates that the stability of the truck is poor under this state.

In order to verify the rationality of the dynamic model, a high-level order-picking truck is analyzed and discussed. The total mass m=5480kg, wheel base L=1537mm, maximum lifting height H_{max}=9m， load center distance c=600mm， maximum traveling speed of the truck varies with the lifting height as shown in the Fig. 5. After solving the dynamic equations, the value of N_A, N_B and N_C at different lifting height in the process of accelerating forward is shown in Fig. 6. The minimum value of N_A, N_B and N_C is 8102N. In the same way, the minimum value of N_A, N_B and N_C under other traveling state can be also obtained as shown in Table 1.

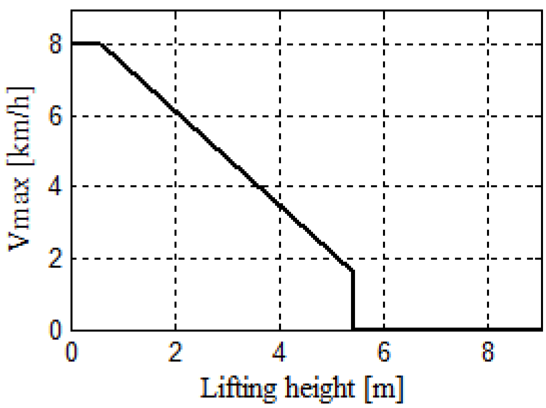


Fig. 5 The maximum traveling speed curve

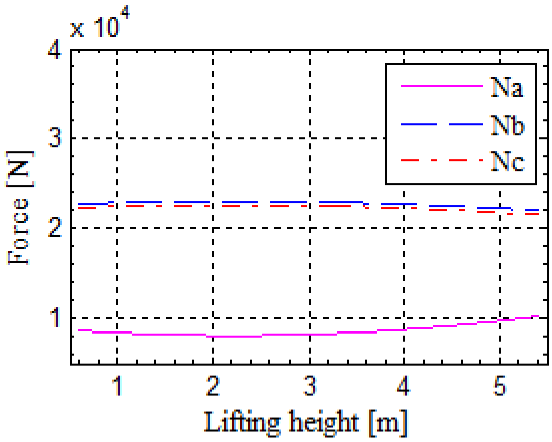


Fig. 6 The curve of N_A, N_B and N_C

Table 1 The minimum action force between wheels and ground under all traveling state

Contact force	Uniform motion	Brake forward	Accelerate backward	Brake backward	Turn left	Turn right
$N_{A\min}$ [N]	12099	12940	13991	4428	12089	12090
$N_{B\min}$ [N]	20527	16574	18467	20960	14520	23609
$N_{C\min}$ [N]	21079	17361	19142	21486	23731	17664

It can be seen from Table 1 that the minimum value of N_A, N_B and N_C under all the state are all much greater than zero, which indicates that the order-picking truck has good dynamic stability under these state.

Simulation of Virtual Prototype

The virtual prototype model of the high-level order-picking truck is established as shown in Fig. 7. After all the constraints and motion are defined, the traveling process of the truck is simulated. The traveling speed and lifting speed of the truck change according to the curve shown in Fig. 8.

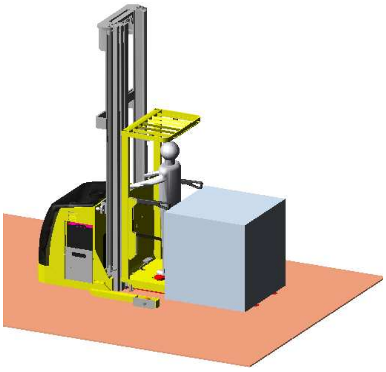


Fig. 7 Virtual prototype of the truck

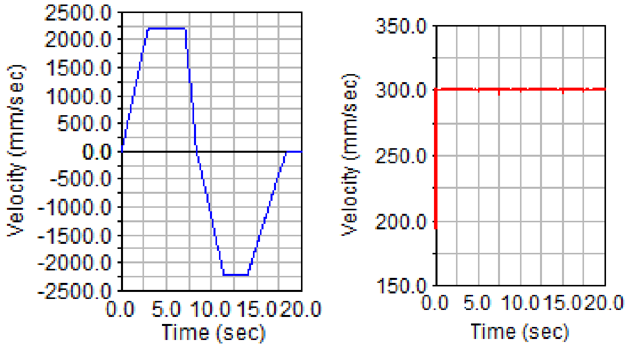


Fig. 8 Traveling speed and lifting speed of the truck

After finishing the simulation, contact forces between three wheels and ground are measured as shown in Fig. 9. The simulation results coincide with above-mentioned theoretic result. The maximum error of N_A, N_B and N_C between them is not more than 9.7%. The dynamic stability of the order-picking truck is confirmed to be good enough.

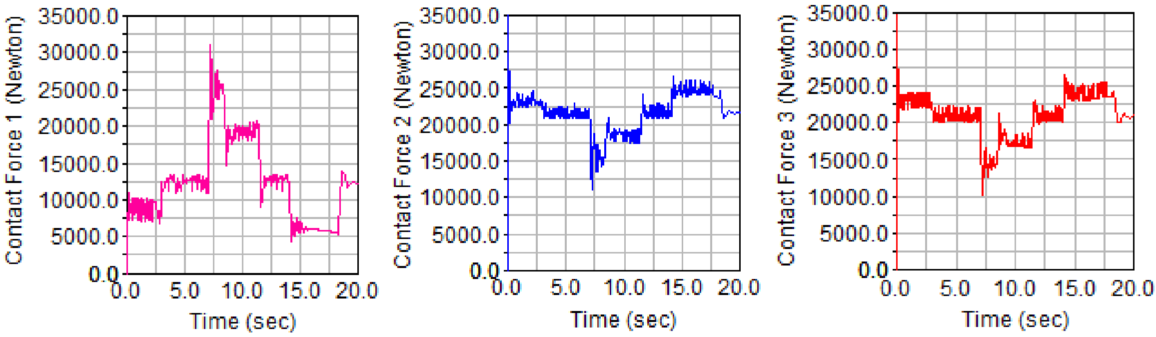


Fig.9 Normal contact forces between three wheels of the order-picking truck and ground

Conclusions

In this paper, the dynamic models of the order-picking truck under different traveling state are established using Alembert principle, then the stability of the truck is analyzed. In addition, the traveling process of the truck is simulated by virtual prototype technology. The simulation results show that the dynamic models of the truck are rational and effective. It is meaningful for the optimization of structure and control strategy to analyze the stability of the order-picking truck.

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