Dynamic stability analysis and Experiment of the Mobile Elevating Work Platforms

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Abstract. In order to calculate dynamic stability of the Mobile Elevating Work Platforms (MEWP) during driving across obstacles and operating on the slope, the analysis method based on mathematical models and simulation models of the MEWP was put forward, then the MEWP dynamic simulation models where the tires and booms were set as flexible bodies were made by ADAMS. Four kinds of the most dangerous working conditions were analyzed, and then the dynamic curves of tire loads and dynamic stability safety coefficient were obtained. Next, the dynamic stability of the MEWP during operating on the slope was verified by field experiments, and the results show that the minimum dynamic stability safety coefficient is 0.157. By comparison and analysis of dynamic stability safety coefficient between simulation analysis and field experiment, it can be seen that the deviations are all positive and less than 5%, therefore the results show that the dynamic stability of the MEWP during driving across obstacles are satisfied. At the same time, the analysis method combining dynamic simulation and some field experiments of the MEWP is proved reliability, accuracy and economy. In all, the dynamic stability of the MEWP can be calculated accurately by ADAMS, in the meantime, the overload operation test (1.5 times rated load) must be performed on the 5° cross slope before the MEWP are sold, and so long as the minimum dynamic stability safety coefficient is no less than 0.1, the MEWP are proved stability and safety.

1. Introduction
The Mobile Elevating Work Platforms (MEWP), also known as one of the aerial devices, are mechanical devices used to provide temporary access for people or equipment to inaccessible areas [1, 2], which are widely used in Aerospace, Shipbuilding, Construction and other industries [3, 4].

In RR961 research report of 2013, at least 82 overturning accidents happened and led to more than 20 people injury seriously even death [5]. Two kinds of typical overturning accidents are as shown in Figure 1. Thus, the most important performance of the MEWP is stability and safety in the process of driving or operating. Now, in the Europe standard EN 280 and the Chinese national standard GB 25849 illustrations can be clearly seen that “In the case of allowance by the manufacturer, the MEWP must be enough stability, at the same time, the MEWP can drive across the kerb or depression with a height of 0.1 m at the maximum permitted travel speed without overturning” [6, 7].
In recent years, a lot of research works about dynamic stability analysis of the MEWP have been carried out. The calculation method, such as the subjective and objective evaluation method, the torque balance method and the minimum tire load method were all put forward \[8\]. Based on the accident statistics, the dynamic stability boundary conditions with different types of the MEWP were analyzed \[9, 10\]. In the aspect of control strategy, the velocity and acceleration limitation were regarded as the key factor to keep the dynamic stability of the MEWP \[11, 12\]. With the help of simulation tools, the overturning relation between cross-obstacle collision and dynamic stability of the MEWP were also analyzed \[13\].

Based on the research results mentioned above, it can be seen that the dynamic stability of the MEWP is related to more factors such as ground conditions, operation velocity and acceleration, obstacles structure etc. However, at present the analysis methods based on dynamic simulation and field experiments of the MEWP haven’t been found yet. So in this study, a reliable and economical method combining simulation analysis with some field experiments was put forward and the effect of this method was discussed and verified.

2. Mathematic model

The MEWP are composed of chassis, turntable, booms, platform, power assembly, hydraulic actuators (including bumps, motors, hubs, valves and cylinders, etc.) and electric control units (including the controller, the junction boxes, the switches and lamps, etc.). When the MEWP driving or operating on level ground or the slope, the dynamic stability of the MEWP includes forwards stability and backwards stability, and the overturning load and force moment combination is as shown in Figure 2.

The anti-overturning force moment \(M\) is calculated as follows.

\[
M = \sum_{i=1}^{8} G_i \cdot L_i + \sum_{i=1}^{3} f_i \cdot l_i + 0.1 \cdot \sum_{i=2}^{8} G_i \cdot L_i
\]  

(1)

Where the parameters \(G_i\), \(f_i\), \(L_i\), and \(l_i\) are mean the gravity of different component assembly, wind loads with manual forces, level distance between the canter of mass of different component assembly and the tipping line and vertical distance from the point of wind loads with manual forces to the ground. Herein, the dynamic coefficient of the forces produced by acceleration or deceleration of structural moving components is 0.1 \[6, 7\].

If the force moment \(M\) is zero or negative, it means that the MEWP have overturned. On the contrary, even the \(M\) is positive, which must be greater than a certain value in order to ensure safety at work. Therefore, the tire reaction forces and dynamic stability safety coefficient of the MEWP were calculated as follows.
Where the parameters \( F \) and \( b \) are mean the minimum tire reaction forces (including two tires on the same side) and vertical distance from the point of the tire reaction forces \( F \) to the tipping line.

\[
\theta = \frac{F}{\sum G_i}
\]  

Where the parameter \( \theta \) means the minimum dynamic stability safety coefficient. While the MEWP are driven across obstacles (including the kerb or depression with a height of 0.1 m) by means of front side two tires or rear side two tires simultaneously or operated on the maximum 5° cross slope, the MEWP should be in the most dangerous working conditions. In this case, the dynamic stability and safety of the MEWP can be determined by the minimum \( \theta \).

3. Modeling and Simulation

3.1. Modeling
In order to improve assembly accuracy of the dynamic simulation analysis models, the 3D models of the MEWP were set up by Pro/E, then were converted *.x_t format into ADAMS [14]. In ADAMS, most of structural components including the chassis, turntable, platform and cylinders were set as rigid bodies, while booms using FEM and tires using Fiala module were set as flexible bodies. According to all of settings above, the elastic deformations of booms extension and tires loads were both taken into consideration, thus the simulation models of the MEWP would be closer to physical structures and the simulation calculation accuracy should be improved. Then the revolute pairs and sliding pairs with friction were set in different joints so that the simulation analysis models of the MEWP were in the same gravitational field [15, 16]. The simulation analysis models of the MEWP are as shown in Figure 3.

3.2. Working conditions
In According to structural calculation method stipulated in EN 280 and GB 25849, four kinds of the most dangerous working conditions were analyzed as shown in Table 1.
3.3. Simulation process

For driving across obstacles simulation analysis, the road spectrums were set up as shown in Figure 4.

![Diagram](image)

(a) Section of the kerb  (b) Section of the depression
(c) Combined road spectrums in ADAMS

In ADAMS, the MEWP were driven in turn across the kerb and depression as shown in Figure 5. For operating on the slope simulation analysis, the maximum 5° cross slope was used as shown in Figure 6. In ADAMS, the MEWP were operated on the cross slope (left padding 5°) as shown in Figure 7.

3.4. Simulation results and analysis

After driving across obstacles simulation analysis, the curves of dynamic tire loads were obtained as shown in Figure 8.
Figure 5. Driving across obstacles on the road spectrums

Figure 6. The maximum 5° cross slope

Figure 7. Operating on the cross slope

Figure 8. Simulation results of driving across obstacles
Where the parameters $LF$, $LR$, $RF$ and $RR$ mean left front tire, left rear tire, right front tire and right rear tire respectively, and the annotations $FAK$, $RAK$, $FAD$ and $RAD$ are mean the process of the front axle climbing over the kerb, the rear axle climbing over the kerb, the front axle climbing over the depression and the rear axle climbing over the depression respectively.

After operating on the cross slope simulation analysis, the curves of the dynamic tire loads were obtained as shown in Figure 9. The simulation results of tire loads were shown in Figure 8 and Figure 9, and were analyzed as follows.

(a) Tire loads of working conditions 3

(b) Tire loads of working conditions 4

**Figure 9.** Simulation results of operating on the cross slope

a) None of tire loads is zero during driving across obstacles and operating on the slope, which shows that the MEWP can keep dynamic stability and safety without overturning even in the most dangerous working conditions.

b) As shown in Figure 8(a), the minimum side tire loads are 20718 N (including $LF$=10736 N and $RF$=9982 N) in climbing over the kerb instantaneously. By contrast, as shown in Figure 8(b), the minimum side tire loads are only 3830 N (including $LR$=2020 N and $RR$=1810 N) in climbing over the depression instantaneously. Thus the minimum dynamic stability safety coefficient $\theta$ is 0.108 (20718/(19500*9.8)) and 0.020 (3830/(19500*9.8)) in driving across obstacles on working conditions 1 and 2 respectively (the design weight of the MEWP is 19500 kg and the gravitational acceleration g is 9.8 kg/m$^3$).

c) As shown in Figure 9(a), the minimum side tire loads are 60452 N (including $LR$=30198 N and $LF$=30254 N) when the booms rotate to 270°. By contrast, as shown in Figure 9(b), the minimum side tire loads are 21662 N (including $LR$=10765 N and $LF$=10897 N) when the booms rotate to 270°. Thus the minimum dynamic stability safety coefficient $\theta$ is 0.316 (60452/(19500*9.8)) and 0.113 (21662/(19500*9.8)) in operating on the cross slope respectively.

d) Comparing the change amplitude of tire loads in Figure 8(a) and 8(b), Figure 9(a) and 9(b), along with different dynamic stability safety coefficient, all of these show clearly the overturning backwards is more dangerous than the overturning forwards.

e) The curves of tire loads during driving across the kerb and the depression showed fluctuated, as shown in Figure 8(a) and 8(b). The fluctuation was caused by structure moving components (including turntable, booms, platform and sandbags, etc.) wagging during driving across obstacles. Even if the MEWP kept stability and safety when driving across obstacles, the great panic was brought to the operator. Thus, when the MEWP were driven across obstacles, the stability and safety of the MEWP belong to inherent design safety properties once the danger appeared suddenly. In fact, it is not allowed to drive across obstacles in any common operation, so irregular behaviour and habit must be all prohibited strictly.
4. Field experiments and analysis

4.1. Test method
In consideration of safety, feasibility and actual costs of field experiments, only the overload operation experiments were done. Like the same method used in simulation analysis, the wind loads, the manual forces and the dynamic structural loads were substituted by means of overload [6, 7], thus the sandbags of 345 kg in forward overturning test and the sandbags of 80 kg in backward overturning test were placed on the platform respectively. The MEWP were driven to four weighting sensors (the maximum measurement is 10000 kg and the error is ±5 kg), then two tires in left side were raised by use of the pads at the height of 0.3 m so that the MEWP inclined 5° as shown in Figure 10.

4.2. Test results and analysis
In field experiments, all of moving components (including booms, turntable, oil cylinders, bracket, platform and sandbags, etc.) were rotated together from 0° to 360 ° continuously, at the same time, the proportional flow valves were opened to the maximum flow in order to simulate the electric proportional control fails, then every tire loads were recorded. Each test was repeated at least 6 times (including the clockwise and the anticlockwise rotation three times respectively), then all the test data were processed by MATLAB and the curves of tire loads were as shown in Figure 11.

![Figure 10. Overturning experiments](image)

![Figure 11. Test results](image)

(a) Tire loads of working conditions 3 in the test (b) Tire loads of working conditions 4 in the test

The test results of the tire loads were as shown in Fig. 11 and were analyzed as follows. a) The change trend of test curves of tire loads is similar with simulation analysis results, which show the simulation models of the MEWP are satisfied and almost the same as the physical structures.
b) As shown in Figure 11(a), the minimum side tire loads are 62898 N (including $LR=31067$ N and $LF=31831$ N) when the booms rotate to $270^\circ$. By contrast, as shown in Figure 11(b), the minimum side tire loads are 29616 N (including $LR=15629$ N and $LF=13987$ N) when the booms rotate to $270^\circ$. Thus the minimum dynamic stability safety coefficient $\theta$ is 0.334 ($62898/(19216\times9.8)$) and 0.157 ($29616/(19216\times9.8)$) during operating on the cross slope respectively (the actual weight of the MEWP is 19216 kg and the gravitational acceleration $g$ is $9.8 \text{ kg/m}^2$).

c) The dynamic stability safety coefficient $\theta$ errors between test results and simulation results are $+1.8\%$ (0.334-0.316) and $+4.4\%$ (0.157-0.113), which is proved that simulation analysis can truly reflect the actual working status. Thus it can be seen that the flexible bodies (including booms using FEM and tires using Fiala module) used in simulation analysis are good for improving calculation accuracy.

d) By contrast, even the test of driving across obstacles were not carried out due to security risks and high costs, the simulation analysis results of driving across the kerb or depression and operating on the cross slope by using the same dynamic models, therefore the simulation results during driving across obstacles should be regarded as more accurate and effective evaluation and reference to dynamic stability of the MEWP in actual driving.

5. Conclusion
With the dynamic stability analysis of the MEWP above, the main conclusions can be drawn as follows.

a) By simulation analysis, the dynamic curves of tire loads and the minimum dynamic stability safety coefficient $\theta$ of the MEWP were obtained, and the results of which prove that the MEWP have enough stability and safety even in the most dangerous working conditions.

b) In operating field experiments, the dynamic stability safety coefficient errors between simulation results and test results are all positive deviation and less than 5%, which is proved that simulation analysis can truly reflect the actual working status. It also infers that the simulation analysis results of driving across the kerb and depression should be regarded as more effective and accurate evaluation and reference.

c) An accurate, simple and economical field experiments method for dynamic stability of the MEWP was put forward. So long as on the $5^\circ$ cross slope, the overload test (1.5 times rated load) was carried out and the tested minimum dynamic stability safety coefficient $\theta$ is no less than 0.1, which guarantee stability and safety of the MEWP sales to the customers.

d) Next, one new field experiment method based on small scale models of the MEWP in driving across obstacles would be considered and carried out.

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