A Novel Anti-skid Capability Testing Device for Port Rail-mounted Equipment: Mathematical Modeling and Experimental Investigation

Gongxian Wang¹, Qilin Tang¹, Zhihui Hu¹*, Chenzhang Hu², Yongzhi Li¹ and Yang Zhang¹

¹ School of Logistics Engineering, Wuhan University of Technology, Wuhan 430063, China.
² Guangdong Institute of Special Equipment Inspection and Research, Zhanjiang Inspection Institute, Zhanjiang 524022, China.

*Corresponding author: 13407101635@163.com

Abstract. Regarding to the lack of the effective method and equipment to test the anti-skid capability of port rail-mounted equipment along the rail. A novel anti-skid capability testing device (named as WACD) for port rail-mounted equipment is proposed in this paper. The mechanical model of the WACD is established to predict the maximum anti-skid capacity of the tested port rail-mounted equipment and analyze its working principle. After that, the experimental tests are carried out to verify the effectiveness and feasibility of the WACD. The test results confirm that the designed principle of the WACD is correct, and the testing device can be used to testing the anti-skid performance of the port rail-mounted equipment under the wind speed of 70 m/s.

Key words: port rail-mounted equipment, the anti-skid testing device, experiment test

1. introduction

The large port rail-mounted equipment like container crane and gantry crane are usually located in the coastal open-air areas. With huge structure and windward area, it is easy to be attacked by the extreme weather such as typhoons and hurricanes. In recent years, more and more port facilities are destroyed by catastrophic failures such as typhoons and sudden gust. Therefore, the higher safety requirements for large port rail-mounted equipment have been presented in the new standard of crane design (GB/T 3811-2008). However, many of working equipment are still designed by the old standard with the large investment and slow renewal of port equipment, which inevitably brought potential dangerous. Therefore, it is necessary to check whether anti-skid performance of the old port equipment can meet the latest design requirements.

In order to effectively test anti-skid capability, many researchers have been conducting much discussion and study in many fields. For example, in the literatures [1-3], the braking performance of working rail-mounted crane under wind load was analyzed, and they provides a basis for the study about the anti-skid capability of crane. Davico [4, 5] proposed a simple inertia dynamometer for testing anti-skid devices by analyzing the behavior of the controlled aircraft when braking, but it can be tested in
laboratory. Cheng [6, 7] designed a detection device to testing the wind resistance and anti-skid capability of gantry crane, but the testing capability is limited. Lu [8] presented a tension testing device to test the anti-skid characteristics of the resistant wind devices installed on the port equipment, but the safety of the operation is not enough. Kuo [9] designed presents a new scheme of four-phase control by accommodating all road conditions for an anti-skid brake system, but operation process is completed.

From the above, the testing capabilities of the above devices and methods are limited for the port equipment. What is more, they is hardly applied to the different types of port equipment with various anti-skid devices. Thus, they do not meet requirements of the effectively and flexibly in testing. Therefore, a novel wind resistance and anti-slip capability detection device (WACD) is proposed in this paper, and the correctness and effectiveness of the designed principle are verified by mechanical model and experiment test.

1.1. Composition and working principle

Fig. 1 shows schematic illustrate of the overall structure of the WACD. The composition of the device mainly consists of six parts: rods system, connecting rods, loading mechanism, locking mechanism, structural platform, sensors and counterweight. Two sets of structural platforms, locking mechanisms and rods systems are arranged symmetrically on both sides of the rail and connected by connecting rods. The column of tested port equipment and the structure platform are linked by the rods, and the sensors are installed on the end of rods system closed to the structural platform. The loading mechanism is installed on rib structure of the structural platform, and is used to simulate wind load. The counterweight is placed on the end beam of the structural platform and the locking mechanisms is placed on the middle of the structural platform and rail.

1. Tested port equipment 2. Rods system 3. Connecting rods 4. Loading mechanism 5. Locking mechanism 6. Structural platform 7. Counterweight

Fig. 1 The overall structure of the WACD

The locking mechanism is a vital part of the WACD, by which the structural platform is mounted on the rail as the fixed end of the testing system. The composition of locking mechanism are mainly composed of lifting mechanical, hydraulic cylinder, wedge, clamp, roller supporter, and lever shaft as Fig. 2 shown. The trapezoidal supporter is installed on the lower beam of the structural platform. The loading mechanism is placed on the top of the crossbeam which was connected with rollers supporter by lifting mechanical. The clamps are connected by spring. The wedge lies in top of the roller supporter. There is a certain clearance between the trapezoidal supporter and roller-wedge mechanism when the testing device is in non-working state.
1. Lifting mechanism 2. Hydraulic cylinder 3. Connecting shaft 4. Roller supporter 5. Trapezoidal supporter 6. Roller-wedge mechanism 7. Clamp mechanism

Fig. 2 The structure diagram of locking mechanism

When the structural platform is moving along the track, the rods are pulled taut by the hydraulic cylinder, which causes the roller supporter being lifted off the rail. But, once the testing device reaches the destination, the roller-wedge mechanism and clamp mechanism are put down to the track. At the beginning of the test, the rods are gradually tightened with the hydraulic jack loading. Then, the original clearance of the WACD about 20mm disappeared quickly and the locking mechanism started to work. Then, the force vertical to the inclined plane is produced on one of the rollers, in which the vertical component increases the frictional force between the roller supporter and the rail. In addition, the horizontal component of the force starts drive the wedge to move. As the contact surface is inclined plane, the clamps start to clamp the rail tightly with the roller moving. When the test end, the spring make the clamps resume its original form. The anti-skid force of the tested equipment is obtained by the sensors.

2. Mechanical model of the WACD

In order to derive the relation between the frictional force and all the parameters, the mechanical model of the WACD is simplified based on the following hypotheses: all the parts of the WACD are rigid bodies and the working process is static.

The force analysis of the WACD and its components is shown in Fig.3 to Fig.7

Fig. 3 Force diagram of the tested port equipment with the WACD

Fig. 4 Force diagram of structural platform
The friction pairs and dimension symbols of the components in the WACD are shown in the Table.1.

| Names                                                   | symbols | Names                                                   | symbols |
|---------------------------------------------------------|---------|---------------------------------------------------------|---------|
| Force of the rail to the structural platform            | \( N_c \) | Mass of the counterweight                              | \( G_1 \) |
| Force of the rail to the roller supporter               | \( N_1 \) | Pressure of the clamps to the rail                     | \( N_2 \) |
| Friction coefficient between the clamp and              | \( \mu_1 \) | Friction coefficient between the clamp and              | \( \mu_2 \) |
| the upper surface of the rail                          |         | the side surface of the rail                           |         |
| Force of the hydraulic cylinder                        | \( F_{f1} \) | Total anti-skid force                                  | \( F_F \) |
| Friction coefficient between the equipment              | \( f_c \) | Friction coefficient between the device components     | \( f \) |
| and the steel                                           |         |                                                         |         |
| Height of the clamp                                     | \( h \)  | Distance between the rail and the upper clamp block     | \( h_6 \) |
| Distance between the rail the lower clamp block         | \( h_7 \) | Ratio of the structural platform height to              | \( k_l \) |
| Leverage ratio for the clamp assembly                   | \( i \)  | counterweight                                           |         |
| Angle between the force \( T \) and \( y \) axes        | \( \theta \) | Angle of the trapezoidal frame                          | \( \alpha \) |
| Stability safety factor of port equipment               | \( k_w \) | Bevel angle of the roller wedge                         | \( \gamma \) |

The following relation can be obtained according to the above force analysis

\[
F_f = \mu_1 N_1 + \mu_2 N_2 + f_c N_c = (\mu_1 - f_c \cos \alpha) \frac{1 - k_w k_c f_c}{1 - f_c \cos \alpha + f} F_{f1} + \mu_2 C_1 C_2 (\cot \theta - C_2) + f_c G_1
\]

Where

\[
C_1 = f \left[ \frac{(h h_c + h h_i - 2 h h_i)(1 + i) - 2 h - h_c - h_i}{h (h_i - h_c - h_i - h_c - h_i)} \right]
\]

\[
C_2 = f \left[ \frac{2 h_c h_i (1 + i) - h_c + h_i}{h (h_i - h_c - h_i - h_c - h_i)} \right]
\]

\[
C_1 = \frac{f \cos \alpha + f + \sin \alpha}{\sin \alpha + f}
\]

\[
C_N = \cos \alpha \frac{1 - k_w k_c f_c}{1 - f_c \cos \alpha + f}
\]
Therefore, there are two possible working states of the WACD: (1) the friction force from the upper surface of rail reaches limit equilibrium state. (2) The friction force on the side surface of tail reaches limit equilibrium state.

In the case (1), the auto-lock condition can be expressed as

$$\mu_1 = \frac{1 - f_1 C_N}{C_i (i \cot \theta - C_i) + C_i (1 - f_1 C_N)} < f_2$$

In the case (2), the auto-lock condition can be expressed as

$$\mu_i = \frac{(1 - f_i C_z) - C_i f_z (i \cot \theta - C_i)}{C_N (1 - f_i C_z)} < f_i$$

3. Simulation analysis and experimental test

3.1. Simulation analysis

In order to discuss the performance of the WACD in principle, the MQ2538 portal crane is taken as the object of study, and a set of specific structural parameters about the WAAC is applied to the simulation analysis and experimental test. The main parameters of MQ2538 portal crane are listed in Table 2, and the related structural parameters of the WAAC are listed in Table 3.

| Tab. 2 Structural parameters of the locking mechanism |
|-----------------------------------------|------------------|
| parameters | value | parameters | value |
| Angle of trapezoidal frame $\alpha$ | $45^\circ$ | Angle of the wedge $\gamma$ | $25^\circ$ |
| Distance between shaft and jaw pad $h_2$ | $200$mm | Distance between shaft and top roller $h_3$ | $800$mm |
| Distance between upper contact and jaw pad $h_4$ | $650$mm | Distance between lower contact and jaw pad $h_5$ | $350$mm |

| Tab. 3 Parameters of the MQ2538 portal crane |
|-----------------------------------------|------------------|
| Parameters | Value | Parameters | Value |
| Mass of port equipment $G$ | $5.4$t | Gauge (m) $B$ | $16.5$m |
| Altitude of wind load $H_f$ | $23.3$m | Number of driving wheel $n_q$ | $16$ |
| Height of gravity center $a$ | $7.65$m | Total number of the wheel $n$ | $32$ |
| Windward area $A$ | $325$ m$^2$ | Wind coefficient $C$ | $1.1$ |
| Friction coefficient between driving wheel and track $f_c$ | $0.14$ | Variation coefficient of wind pressure height $K_h$ | $1.1$ |

The comparison between the theoretical and simulated results about the anti-slip force from the WACD is presented in Fig. 8. It is concluded that the friction force from the WACD is increasing with the increase of the simulated wind load. Its friction force is always greater than the simulated wind load, which confirms the effectiveness of the WACD.

![Fig. 8 Total friction force of the WACD](image-url)
3.2. Experimental test

In the test, four wind load measuring points were respectively arranged at both ends of the rods system, and three displacement measurement points are arranged on the crane, the rail clamps and the structural platform. The anti-slippering force was obtained when the equipment start to slip after the original clearance of the WAAC about 20mm disappeared quickly, then the experiment test ended. The measuring point arrangement is shown in Fig.9, and the test site is shown in Fig.10.

![Diagram of measuring points](image)

1. Counter weight 2. Structural platform 3.Rods system 4.Moving mechanism 5.Port equipment 6. WAAC 7>Loading mechanism 8.Connecting rods

**Fig. 9** Schematic diagram of the testing platform: (a) front view and (b) overhead view

![Scene picture of test devices](image)

**Fig. 10** Scene picture of test devices

The specific experimental data are listed in Table 4. It is shown that the gantry crane does not slip under the range of the simulated wind load from 483kN to 1204kN, and the anti-slippering force is recorded by the WACD with much accuracy. Moreover, the comparison between the theoretical and experimental results about the anti-slippering force is presented in Fig.11. It was shown that the results of the experiment and theoretical computation are coherent. Therefore, it can be concluded that the designed principle of the WACD is correct and the testing device is the effectiveness and reliability under the wind speed of 70m/s.

**Tab. 4** Experimental data

| No. | Force measuring point (kN) | Displacement measuring point (mm) |
|-----|---------------------------|-----------------------------------|
|     | Total                     | 1  | 2  | 3 |
| 1   | 31                        | 31 | 38 | 36 | 135 | 0 | 0 | 0 |
| 2   | 67                        | 63 | 55 | 39 | 224 | 10 | 0 | 0 |
| 3   | 120                       | 120| 102| 141| 483 | 20 | 0 | 0 |
| 4   | 222                       | 218| 198| 195| 829 | 20 | 0 | 0 |
| 5   | 255                       | 251| 227| 225| 956 | 20 | 0 | 0 |
| 6   | 268                       | 264| 244| 246| 1019| 20 | 0 | 0 |
| 7   | 279                       | 275| 253| 251| 1057| 20 | 0 | 0 |
| 8   | 283                       | 279| 263| 262| 1087| 20 | 0 | 0 |
| 9   | 312                       | 307| 291| 296| 1204| 20 | 0 | 0 |
4. Conclusion
A novel anti-skid capability testing device (WACD) for port rail-mounted equipment is proposed. The mechanism model is established to analyze working principle. Then, the simulation analysis and experimental test are conducted to verify the validity and correctness of the WACD. It is found that the WACD can test the anti-skid capability of the port equipment beyond the wind speed 70 m/s, which confirms that the designed criteria of the WACD is correct and the WACD is an effective testing device in the anti-slipping capability testing for port rail-mounted equipment.

References
[1] Tomczyk J, Cink J, Kosucki A. Dynamics of an overhead crane under a wind disturbance condition. Automation in Construction, 2014, 42(42):100-111.
[2] Gur S, Ray-Chaudhuri S. Vulnerability assessment of container cranes under stochastic wind loading. Structure & Infrastructure Engineering, 2014, 10(12):1511-1530.
[3] Hu J B, Chen D, Ding S Q, et al. Simulation of the Wind Field of Gantry Cranes Based on FLUENT. Applied Mechanics & Materials, 2012, 217-219:1530-1534.
[4] Davico L, Tanelli M., Savaresi S.M, Airoldi M., Rapicano G. A deceleration-based algorithm for anti-skid control of aircraft. IFAC-PapersOnLine, 2007, 31(1):65-70.
[5] Davico L, Tanelli M., Savaresi S.M, Airoldi M., Rapicano G. An anti-skid braking system for aircraft via Mixed-Slip-Deceleration control and Sliding Mode Observer. 2017 IEEE 56th Annual Conference on Decision and Control, CDC 2017, pp: 4503-4508.
[6] Cheng Mingqi, Zhu Jiankang, Ji Yucheng, Yang Xiaouu, CaiFuhai. Design of Wind-resistant and Anti-skid Detecting Device for Portal Crane. China Special Equipment Safety, 2013, 29(03):16-18.
[7] Zhu Jiankang, ChengMinqi, LuXianpiao, JiYucheng, HuangLiangbin. Design of Wind Resistance Simulated Detection Device for Portal Crane. HOISTING AND CONVERTING MACHINERY, 2013(01):9-11.
[8] Lu Yunlin, YuXinguo. A Study on Testing Method of Wind-proof Device of Door Machine. PORT OPERATION, 2003(02):18-19.
[9] Kuo C.Y, Yeh, E.C. Four-phase control scheme of an anti-skid brake system for all road conditions. Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering, 1992, 206(4):275-283.