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STUDY ON THE DESIGN OF CONTAINER HIGHWAY AND RAILWAY AUTOMATIC TRANSFER VEHICLE IN OCEAN PORT

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ABSTRACT

To realize "seamless" connection of ocean port container multimodal transport, efficiently carry out "door-to-door" transport of ocean port containers and overcome the shortcomings of existing highway and railway vehicles, this study takes the standard for heavy-duty container vehicles in TB1335-1996 Railway Vehicle Strength Design and Test Identification Code as the design basis and designs a new ocean port container transport vehicle in combination with automatic guidance technology. This study innovatively designs the automatic lifting system of the bogie and the docking part of the vehicle, introduces the automatic guidance technology and the remote-control technology to optimize the car body structure, and uses the SAP software to carry out the finite element analysis of the car body load capacity and Flexsim software to carry out the simulation analysis on the operation of vehicles. The designed transfer vehicle can improve the transfer efficiency of ocean port containers, reduce the transit time of field and station equipment and container transport links, and improve the level of multimodal transport and comprehensive economic benefits.

Keywords: Ocean port, Multimodal transport, highway and railway, unmanned automatic, seamless connection

INTRODUCTION

China is one of the major foreign traders, whose annual throughput of ocean port container has reached the top in the world in 2016. As an important transit point in multimodal transport, ocean ports often face problems such as the large-scale container turnover and rapid conversion of different transportation modes. As the economy and science and technology progress, the transformation and upgrading from traditional manpower to automation will certainly become its future development trend. At present, there are three major factors restricting the multimodal transport efficiency of an ocean port container. Firstly, the residence time is caused by the technical limitations of field and station equipment when changing the transport vehicle; secondly, all the departments fail to establish mature supporting information sharing service platforms and mechanisms in processing container-related business documents, which causes residence time. Thirdly, there is no information sharing platform established between transportation enterprises, leading to scattered transportation strength, decentralized businesses, and limited transportation efficiency. Therefore, it is of great significance to the development of modern port logistics to study and design a highway and railway ocean port container automatic transfer vehicle with diversified functions, intelligent operations, and complete service platform in accordance with the development trend of the ocean port and future market demand.

STUDY ON AND DESIGN OF VEHICLES

DESIGN IDEAS

This study introduces the automatic guidance technology into the design of the transfer vehicle, upgrades the automatic lifting system to replace the bogie of the existing highway and railway vehicle, and use automatic docking device to complete automatic docking between transfer vehicles, thus to design a new type of automatic transfer vehicle.

After the empty vehicle in the railway mode arrives at the dock, it enters the unloading area, and retracts the railway wheels with the automatic lifting system in the vehicle, which means it has been converted to the highway mode. Then the vehicle automatically breaks into individual transfer vehicles, which enter the ocean port along a given route under the control of the automatic guidance system (Figure 1).

Fig. 1. Operation effect of highway mode

Each automatic transfer vehicle in the ocean port carries containers along the established route, passing through the yard and security gates to the railway freight station. There is a transfer vehicle waiting area near the railway freight station. With the remote operation of the central control system, all the vehicles line up in a row, with each two of them in a pair, the tail of the front one connecting with head of another in an integrated manner and go above the railway track (Figure 2).

Fig. 2. Switching process between highway and railway modes

The automatic lifting system puts down the bogie and lifts the vehicle up, thus the vehicle is converted to the railway mode. The connection device of the automatic docking system of the first vehicle head is automatically connected with the train to complete the transhipment of the ocean port container. In actual operation, the vehicle switching between the highway and railway modes is performed simultaneously in the unloading area and the waiting area (Figure 3).

Fig. 3. Operation effect of railway mode

STUDIES OF TECHNIQUES

This research mainly involves five parts, including vehicle body design, force analysis, finite element analysis, three-dimensional model drawing of vehicle body, and model simulation [1]. The vehicle is designed to carry containers weighing 40ft, thus it belongs to heavy-duty vehicle. Technical parameters are designed according to *TB1335-1996 Railway Vehicle Strength Design and Test Identification Code* (Table 1) [2].

Tab. 1. Main technical parameters of automatic transfer vehicle

Items	Parameters
Vehicle weight (*t*)	18.2
Types of containers (*m*)	6.1 and12.2
Maximum payload (*t*)	60
Speed on highway (*km/h*)	10.8~21.6
Outline dimension (*m*)	15×3×1.5

DESIGN OF VEHICLE BODY FUNCTION UNIT

The vehicle body design includes the wheel design, the design of the automatic lifting system, the design of the automatic docking system, and the composition and functional design of other vehicle systems under both the highway and railway modes [3].

(1) Wheel design

According to the vehicle load, 8 highway wheels and 8 railway wheels are designed. Each highway wheel has a diameter of 1.1*m*, a width of 0.184*m* and a mass of 0.2*t*. Each railway wheel has a diameter of 840*mm* and mass of 0.9*t*.

(2) Design of automatic lifting system

The automatic lifting system consists of an automatic lifting device, a hydraulic lifter, a sleeve device and a railway wheel set. Different from conventional highway and railway bogie, the bogie is designed to be operated separately in a block with highway [4]. The discrete operation mode of bogie and highway blocks makes the lifting device with automatic control, easy operation, and the central control system of the vehicle responsible for the operation [5].

1) Driving device, whose function is to drive the hydraulic pump to discharge the hydraulic oil out of the hydraulic lift under the control of the central control system when the vehicle is switched from the railway mode to the highway mode;
2) Hydraulic cylinder whose function is to store hydraulic oil;
3) Hydraulic pump, whose function is to discharge the hydraulic oil from the hydraulic lift when the vehicle is switched from the railway mode to the highway mode;

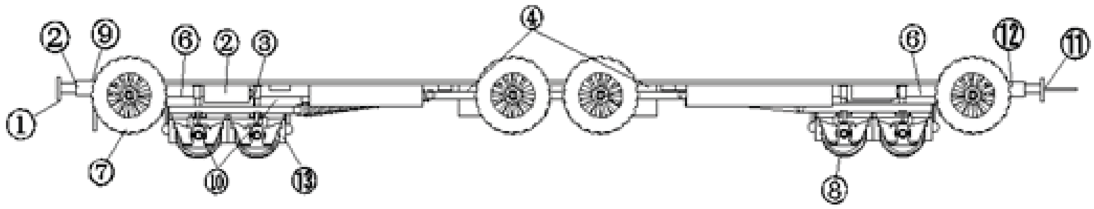

Fig. 4. Elevation of vehicle body under railway model

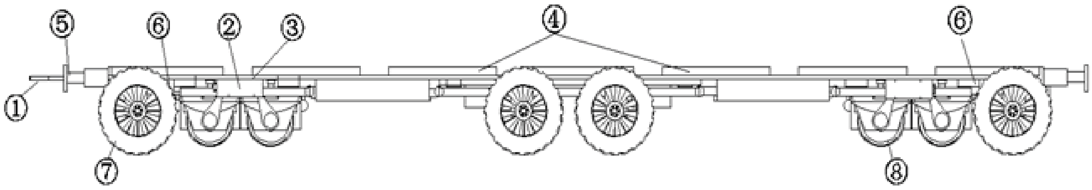

Fig. 5. Elevation of vehicle body under highway model

4) Hydraulic lift, whose function is to withdraw bogie with the discharge of hydraulic oil;
5) Lifting device and mounting frame connecting part (locking and retaining ring devices)
6) Shock absorber, with a sleeve structure and hinged connections with retaining ring and the vehicle body. The shock absorber is inwardly contracted, which is not subject to lateral forces but only serves to connect the vehicle body, lifting device and bogie.

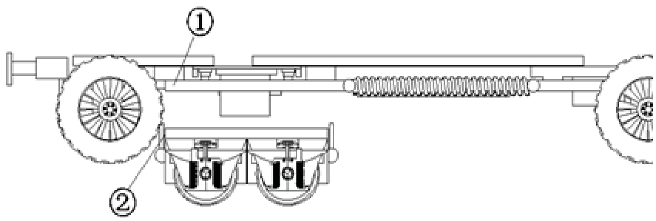

Fig. 6. Locking and retaining ring devices

1) Locking device
2) Retaining ring device
3) According to the force analysis, a single hydraulic device should have a pushing weight of 10*t*, and a lifting height of 30*cm*. The lifting device in the automatic lifting system is connected with the bogie by a locking device and a retaining ring device, and the locking device can be automatically locked or unlocked. Its operation is controlled by the vehicle's central control system. It can be rapidly transformed into the bogies for railroad tracks of other countries during cross-border railway transportation (Figure 7).

(3) Design of automatic docking system

It is composed of induction unit, control unit and connection unit, which are distributed in the front and back of the unmanned transfer vehicle. The induction unit consists of a laser positioning device and a magnetic induction device, which is responsible for positioning calibration and docking before the vehicle is

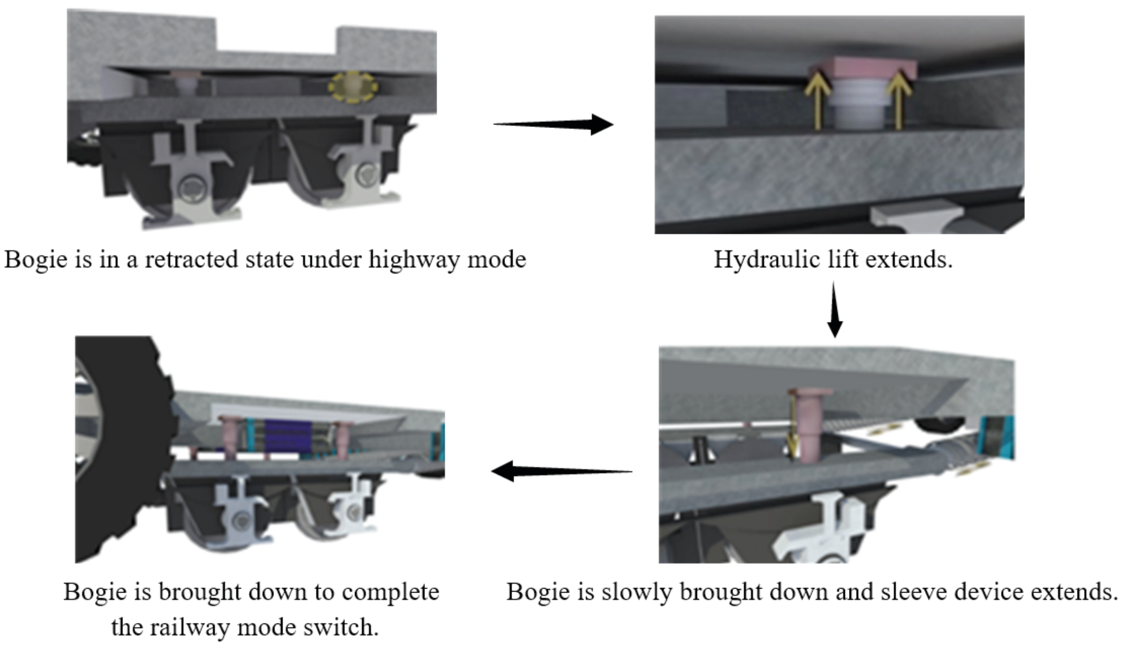

Fig. 7. Working process of lifting system

connected. Mainly composed of an autonomous processing decision system and a control system, the control unit has self-processing and operating functions, which is responsible for receiving and processing signals from the sensing unit and controlling the docking unit to disconnect or link after receiving signals from the sensing unit. The automatic connection is performed when the vehicle is switched from the highway mode to the railway mode to form the container vehicle group [6].

(4) Design of security system

Composed of locomotive sensors, information processing system, display screen, speed measuring system, speed comparison system and brake control section, this system is mainly used to prevent speeding, collision and other dangerous conditions that may be caused when the train is running too fast. In addition to the speed limit effect, it is equipped with dirt-proof jacket and sealing device, which are distributed in the steering shaft of the steering mechanism;

An ABS (anti-lock braking system) is provided in the highway mode. In railway mode, the system transmits the highest safe speed limit signal to the train via the rails and continues to compare with the actual speed of the train, so as to avoid the danger caused by the train speeding. When the train is in braking, the system can automatically identify the vehicle's safe braking distance and ensure vehicle braking [7].

(5) Design of bogie and wheel alignment system

The wheel alignment uses laser radar. The device is mainly composed of an emission system, a receiving system and information processing. The emission system is composed of various lasers, such as a carbon dioxide laser. The receiving system uses a combination of telescopes and various forms of photodetectors, such as photomultipliers, semiconductor photodiodes, and avalanche photodiodes, infrared and visible light multiple detectors. Through the automatic control system, the wheel and track can be accurately docked.

The train bogie is mainly composed of a frame, a vibration damping device, a motor drive device, a single stage suspension system, a secondary suspension device, a traction rod, a centre pin seat, a unit brake cylinder and a height adjustment valve, a speed sensor, and a grounding device. The design parameters meets the following requirements. The height of the vibration damper spring should be greater than the rise of the damper caused by the damper and friction plate. According to the axle weight, the allowable stress is 1050*MPa*. The height of the top surface of the side frame from the rail surface should be less than 775*mm* to ensure that it can pass the minimum curve. The position and size of the moving lever of the basic braking device shall be determined by the braking ratio and the position of the joint. It shall be ensured that the centre distance of the side frame is consistent with the center distance of the journal, and that the height of the side frame from the rail surface is less than 160mm.

(6) Design of vehicle power supply system

Double closed-loop control of voltage and current is adopted to realize constant current and constant voltage charging of storage battery. The soft switching technology is used to reduce the high frequency switching loss of IGBT with an efficiency of 92% [8]. Advanced amorphous cores are used to make transformers and reactors, and to reduce the size of the charger.

(7) Fixing device of container corner piece

The device is installed at each top corner of the container, whose function is to stabilize the container to ensure that the force on the container is even during the transportation process, so as to prevent the vehicle body from losing the balance because of the huge collision force, avoiding the damage to the container [9].

(8) Composition and function design of other systems

The vehicle is mainly composed of automatic docking system, lifting system, central processing system, automatic guidance system, security system, power system, highway wheel set, railway wheel set and braking device [10]. The overall system structure of the vehicle will be described below.

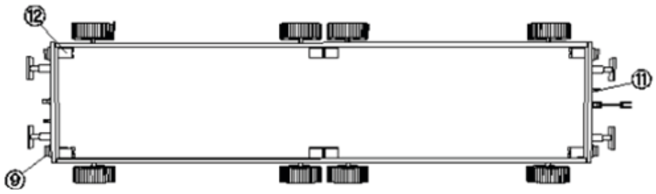

Fig. 8. Illustration of vehicle parts

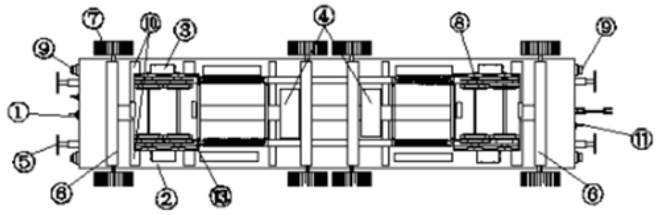

Fig. 9. Illustration of vehicle parts

Where, 1) and 5) automatic docking system and other electrical equipment information transmission power supply device inside the vehicle; 2) automatic guidance system; 3) automatic lifting system; 4) central processing system and power system; 6) security system; 7) highway wheel set and braking device; 8) railway wheel set and braking device; 9) automatic guidance device; 10) bogie and wheel alignment system; 11) highway traction device; 12) corner device; 13) breaking device. [11]

FORCE ANALYSIS OF VEHICLE LIFTING DEVICE

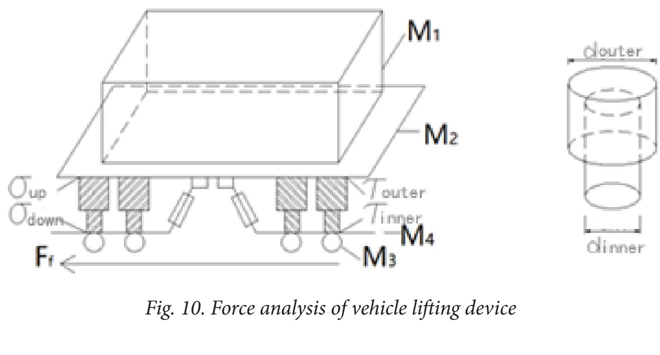

Fig. 10. Force analysis of vehicle lifting device

CALCULATION OF LOCAL NORMAL STRESS OF LIFTING HYDRAULIC JACK

The calculation of normal stress includes the following situations: rail wheel lowers in railroad mode and rail wheel rises in highway mode [12]. The thrust on a single jack, the local compressive stress at the outer guide tube joint during the elongation of the jack, and the local pushing stress at the inner guide tube joint are analysed for the two cases [13]. It is assumed that the acceleration of gravity is 9.81m/s^2.

When the rail wheel is lowered to contact with the rail, the container and the floor rise, then:

$$\begin{cases} F_t = \dfrac{(m_1 + m_2)g}{8} \\ \sigma_{up} = \dfrac{F_t}{A_{outer}} \\ \sigma_{down} = \dfrac{F_t}{A_{inner}} \end{cases} \quad (1)$$

Where, F_t–the pressure on the jack (N); m_1–container mass; m_2–body mass with removal of rail wheel mass; g–gravity acceleration; σ_{up}–local compressive stress at the outer guide tube joint during the hydraulic jack elongation process (MPa); σ_{down}–local pushing stress at the joint of inner guide tube (MPa); A_{outer}–circular cross-sectional area of outer guide tube of the hydraulic jack; and A_{inner}–circular cross-sectional area of inner guide tube of the hydraulic jack [14].

When the rail wheel rises and retracts, the force is:

$$\begin{cases} F_t' = \dfrac{\left(m_3 + \dfrac{m_4}{4}\right)g}{8} \\ \sigma_{up}' = \dfrac{F_t'}{A_{outer}} \\ \sigma_{down}' = \dfrac{F_t'}{A_{inner}} \end{cases} \quad (2)$$

Where, F'_t–pulling force of the jack (N); m_3–the mass of a single rail wheel; m_4–the mass of single side lower panel; σ'_{up}–local tensile stress at the outer guide tube joint during the shortening process of the hydraulic jack (MPa); σ'_{down}–local tensile stress at the inner guide tube joint (MPa).

CALCULATION OF LOCAL SHEAR STRESS OF LIFTING HYDRAULIC JACK

The calculation of the local shear stress includes the shear stress of the inner and outer guide tubes. When the container carrier is transported on the rails, the rolling friction force on the rail wheel is analysed, and then the force received by the single jack can be obtained by balancing the force and ignoring the force exerted on the side lower plate, thereby obtaining the shear stress on the outer guide tube and inner guide tube of the hydraulic jack [15].

$$\begin{cases} F_f = (m_1 + m_2 + 8m_3 + 2m_4)gu \\ F_\tau = \dfrac{1}{8}F_f \\ \tau_{outer} = \dfrac{F_\tau}{A_{outer}} \\ \tau_{inner} = \dfrac{F_\tau}{A_{inner}} \end{cases} \quad (3)$$

Where, F_f–rolling friction forces on all rail wheels (N); μ–rolling friction coefficient between iron wheel and rail, 0.05; F_τ–shear stress on a single jack (N); τ_{outer}–shear stress on the outer guide tube (MPa); and τ_{inner}–shear stress on the inner guide tube (MPa).

By substituting known data into the above formula, it is obtained that when the rail wheel set descends, the local compressive stress at the joint of the outer guide tube is 13.9MPa, and the local pushing stress at the joint of the inner guide tube is 55.5MPa; when the rail wheel set rises, the tensile stress at the joint of the outer guide tube is 1.8MPa, and the tensile stress at the joint of the inner guide tube is 7.1MPa; when the vehicle under load is in a railway mode, the shear stress of the outer guide tube of the hydraulic jack is 0.78MPa and the shear stress of the inner guide tube is 3.13MPa [16].

THE ANALYSIS OF THE OVERALL FORCE ON THE VEHICLE

The force on a single carriage is as shown below. The train is on the rails and during the start-up to transportation, there is:

$$F_{traction} - F_x - F_f = a(m_1 + m_2) \quad (4)$$

Where, $F_{traction}$–traction force on the carriage; F_x–horizontal force of the rear compartment on the carriage; F_f–friction force on the carriage; m_1–container mass; m_2–mass of a single empty carriage; and a–train acceleration. When the total traction force of the train is $F_{overall}$ and there are n carriages in the process of transportation:

$$F_{traciton} - F_x = \frac{F_{overall}}{n} \quad (5)$$

It can be obtained from the symmetry of carriages and containers:

$$F_Y = F_y' \Rightarrow F_{N1} = F_{N2} = F_{N3} = F_{N4} \quad (6)$$

Where, F_y–the vertical force of the rear compartment on the carriage; F'_y–the vertical force of the front compartment on the carriage; and $F_{N\text{i}}$–vertical support forces provided by a single rail wheel.

The maximum friction force on the train is:

$$(F_f)_{\max} = (m_1 + m_2)\,gu \quad (7)$$

Where, μ–Friction coefficient of rail and train wheel.

Before acceleration, the frictional force experienced by the vehicle is static friction.

$$F_f = F_{traction} - F_x \Rightarrow F_y = (F_{traction} - F_f)\cdot\frac{a}{l} \quad (8)$$

At the critical point when the train just gets acceleration, then the frictional force of the train changes from static friction to sliding friction ($a = 0$):

$$F_{traction} - F_x = (F_f)_{max} = (m_1 + m_2)g \quad (9)$$

At this point, the moment of the o point is $\Sigma Mo = 0$.

$$F_y \cdot l = F_f \cdot a \Rightarrow F_y = (m_1 + m_2)g\mu\cdot\frac{a}{l} \quad (10)$$

Where, a–vertical height of train bottom plate to lower plate; and l–overall train length.

When the train obtains the maximum traction force, the maximum acceleration it obtains at this time is:

$$(F_{traction})_{max} - F_x - (m_1 + m_2)gu = (m_1 + m_2)a$$
$$\Rightarrow a_{max} = \frac{(F_{traction})_{max} - F_x}{(m_1 + m_2)} - gu \quad (11)$$

FINITE ELEMENT ANALYSIS

THE ESTABLISHMENT OF FINITE ELEMENT MODEL

THREE-DIMENSIONAL MODEL HYPOTHESIS

(1) The vehicle is composed of three parts, namely, the loading board, the bearing and the tire.
(2) The container acts on the vehicle with a uniform load.
(3) The plate can be replaced by Q345 steel with the isotropic and homogeneous materials after conversion.
(4) The bearing is replaced by Q420 after conversion.
(5) The bearing is connected with the plate at the fixed end. The bearing can rotate but cannot move.

ESTABLISHMENT OF SAP FINITE ELEMENT MODEL

After simplification and substitution, the model in SAP is as shown in Figure 11.

Fig. 11. SAP model of the vehicle

DEFINITIONS OF MATERIAL AND CROSS SECTION ATTRIBUTE AND LOAD

FRAME SEGMENTATION

The tire model is processed by polyline. Divide the tire into 50 equal parts, that is, the number of rods is 50.

DEFINITION OF MATERIAL ATTRIBUTES

In the material definition of the loading board, the same Q345 steel after conversion is used; in the definition of the bearing, Q420 is used to define the material; and finally, in the material definition of the tire, the related parameters of the giant tire 2700R49 are used, as shown in Table 2.

Tab. 2. Material attributes data settings

Material attributes	Data settings
Weight density	10380(unit: N, cm, C)
Mass density	1058.4654(unit: N, cm, C)
Modulus of elasticity E	6.000E+9
Poisson ratio U	0.45
Coefficient of linear expansion A	6500E+06
Shear modulus G	2.069E+09

DEFINITION OF CROSS SECTION ATTRIBUTES

Q345 rectangular cross-section steel with equivalent weight of 3000×254 (mm) (width×height) is used according to the cross section attributes of the plate; the bearing is converted into Q420 (length×width) of 3000×600 (mm); and the tire is defined as a cylinder with an outer radius of 550 mm and an inner radius of 228 mm. With two tires in the same cross-section, the relevant area, resistance moment and mass have to be doubled, as shown in Figure 12.

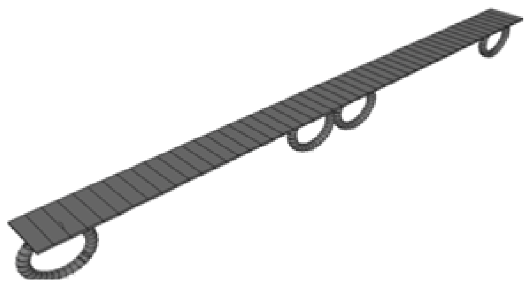

Fig. 12. Cross section model after definition

LOAD DEFINITION

According to the assumption, the weight of the container is a uniform load acting on the board, the maximum weight of the load on the board is 70 t, and the uniform distribution force is 528.23 N/cm. When setting load conditions, its own weight shall be considered, and it shall be noted that the tire mass shall be doubled.

OUTPUT AND ANALYSIS OF THE RESULT

The actual deformation of the model is shown in Figures 13 and 14.

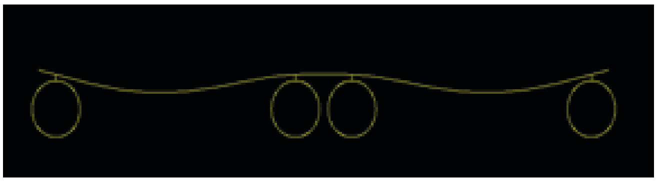

Fig. 13. Demo after model deformation

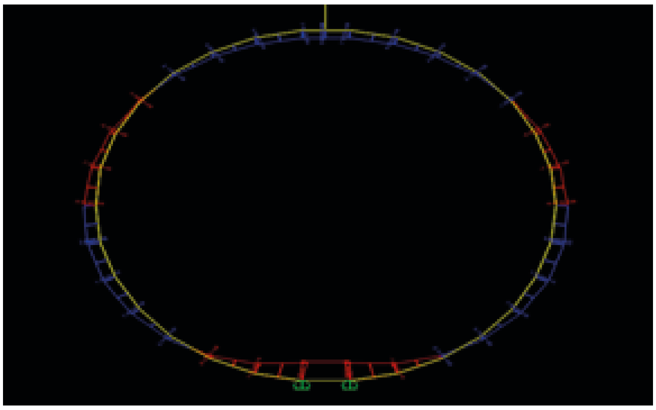

Fig. 14. ire shear diagram

According to the output analysis, the axial stress of the bearing and the sheer force of the tire are the parts with the greatest stress. The maximum axial force of the bearing is $14.8MPa$, and the bearing stress is required to be at least 15MPa upon consideration of the safety reserve. The tire design shall meet the above parameters.

SIMULATION ANALYSIS

The simulation model is established in Flexsim software and the input parameters are as shown in Table 3:

According to the analysis of the results, the number of standard containers in the model without the automatic transfer vehicle is 2,738, while that of the model with automatic transfer vehicle is 3,390. It can be seen that the container throughput of the automatic terminal has been increased by 23.813 % after the adoption of highway and railway ocean port containers.

Tab. 3. Parameter settings of automatic terminal simulation model 2 after using unmanned transfer vehicles for highway and railway ocean port containers

Tag name	State/parameter
Container ship	the Number of Initial "BOXES", 4000
Quay crane	Maximum speed, 2.87m/s
Container parking platform 1	Processing time, 0
Container unmanned transfer vehicle 1	Maximum speed, 6.87m/s
Yard	Maximum capacity,100000
Gantry crane 1	Maximum speed, 2.87m/s
Container parking platform 2	Processing time, 0
Container unmanned transfer vehicle 2	Maximum speed, 6.87m/s
Waiting area for train conversion	Maximum capacity, 20
Conveyor belt	Accumulated cargo flow 15: Transmission speed, 6.87m/s
Train	Processing time, 4s
Model running time	86400s

CONCLUSIONS

The automatic transfer vehicle for highway and railway ocean port containers has the advantages of improving the efficiency of logistics transportation and reducing costs while solving "seamless connection" and market demand. In addition, the vehicle can be combined with the Internet platform to incorporate many services such as ocean port container insurance, finance, import and export business on the same platform, and integrate all business and transportation forces, thus to make trade activities more efficient and convenient. Finally, it will promote the transformation and upgrading of ocean port container service mode to the "Internet +" mode, which will play a positive role in developing modern port logistics and serving "Belt and Road" strategy and economic development of China.

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