Structure Design and Analysis of Two-Dimensional Aerostatic Motion Platform Based on Box Plate

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Abstract—In the current study of two-dimensional aerostatic motion platform, there are problems such as poor uniaxial motion straightness, poor two axis verticality accuracy and small bearing capacity. In this study, a two-dimensional aerostatic motion platform with precision box plate as its structural reference was designed. It is designed with integral aerostatic guideways, and all components are based on precise granite box plate. It uses the high planeness, parallelism and perpendicularity of the precise granite box plate itself to ensure the linear accuracy of the moving guide and the perpendicularity between the two moving guides. And the aerostatic motion platform is driven by linear motor, which eliminates the error caused by traditional mechanical transmission. This two-dimensional air floating platform features high stability, high motion straightness, easy installation and maintenance, and can be widely used in precision machining and precision measurement.

Keywords-Closed Aerostatic Guideways Two-Dimensional Aerostatic Worktable; Precision; High Stiffness; Box Plate

I.   INTRODUCTION

With the rapid progress of modern manufacturing engineering technology, China has put forward higher requirements for machining precision technology, which makes the two-dimensional aerostatic motion platform for precision machining equipment have further research and application[1-2].The precise direct-drive aerostatic guide pair is a precision mechanical component developed by utilizing the principle of gas lubrication. It takes the linear motor as the driving element and uses the pressure generated by compressed gas to suspend the moving guide and realize zero contact with the stationary guide. Therefore, there is no mechanical friction between themoving and stationary guideways. At the same time, with the help of gas film's gas error homogenization, the influence of the guideway's surface profile error can be reduced so that it can achieve a high operating straightness. The two-dimensional aerostatic motion platform with the box plate as the structural reference is what our team designed with high uniaxial motion straightness, high two-axis verticality accuracy and large bearing capacity based on the design and development of aerostatic guide and aerostatic bearing, as well as a large number of experimental testing and debugging experience. It has strong stability, wide application and convenient installation and maintenance, which is of important guidance and reference significance to the motion linear accuracy, bearing capacity, stroke and reliability of precision equipment used for precision measurement and precision machining.

II.   WHOLE SCHEME DESIGN

The two-dimensional aerostatic motion platform by this research mainly includes the integrated design of aerostatic guide rail with box plate, the design of pneumatic system and the design of driving system. The overall design is mainly composed of precision box plate, X-axis aerostatic guide, Y-axis aerostatic guide, linear motor and grating ruler. The two-dimensional aerostatic motion platform combines the advantages of high verticality and flatness of the precision box plate itself with the frictionless and high precision of the aerostatic guide. And it directly adopts linear motor direct drive technology, with precision box plate as the benchmark, aerostatic guide as the support guide, linear motor as the driving device, grating ruler as the position feedback device. The research mainly designs and demonstrates the integrated components of the precision box plate and the aerostatic guide rail in X and Y directions, and conducts a static analysis of the bearing capacity and overall performance of the aerostatic guide rail. The overall structure of the two-dimensional aerostatic motion platform is shown in figure 1.

1.X-axis static guide 2.precision box plate 3.grating ruler 4.Y-axis moving guide 5.X-axis linear motor 6.Y-axis linear motor 7.granite platform
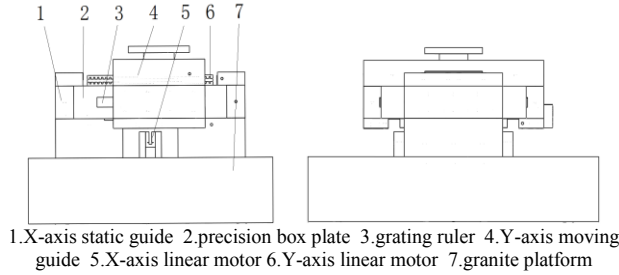
Figure 1. Overall plan

In the overall structure of the two-dimensional aerostatic motion platform shown in figure 1, the stator of the linear motor on the X-axis is fixed on the fine-tuned granite platform, and the actuator of the linear motor is connected to the precision box plate, so as to realize the direct drive of the X-axis. The stator installation of linear motor on the Y-axis is fixed on the precision box plate. The sliding frame with grooves can install the stator of linear motor and connect the actuator of linear motor with the sliding frame, so as to realize the direct drive of Y-axis.

A. Integrated design of aerostatic guide and precision box plate

The precision box plate is a measuring instrument commonly used in the mechanical manufacturing industry. It is a hexahedron with high flatness, parallelism and perpendicularity. It is often made of cast iron or granite. Aerostatic guide pair is one of many kinds of guide pairs. It uses the air buoyancy generated by an extremely thin air film between the guide surfaces to suspend the moving guide rail so as to achieve zero contact. The principle is shown in figure 2.The distribution of gas pressure p in the gap between the bearing surfaces of the aerostatic guide pair can determine the performance of the pneumatic guide pair. The equations determining the pressure distribution can be derived from the momentum equation, the continuity equation, the energy equation and the gas state equation. According to the gas pressure distribution equation in the gap of air floating guide, the fluid Reynolds equation can be obtained:

$$\partial \frac{\partial}{\partial x}\left(\frac{\rho h^3}{\eta}\frac{\partial p}{\partial x}\right)+\frac{\partial}{\partial y}\left(\frac{\rho h^3}{\eta}\frac{\partial p}{\partial y}\right)= \\ 12\frac{\partial(\rho h)}{\partial t}+6u\frac{\partial(\rho h)}{\partial x}+6v\frac{\partial(\rho h)}{\partial y} \tag{1}$$

In formula (1) : x and y are the horizontal and vertical coordinates in the rectangular coordinate system; η is the gas viscosity; h is the thickness of gas film; ρ Is gas density; u, v are the velocities in the x and y directions respectively; T is the time; P is gas film pressure.
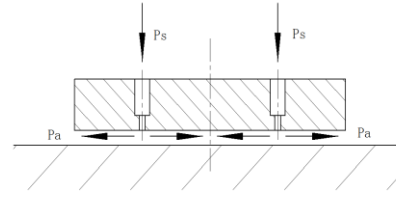

Figure 2. Principle of aerostatic guide pair

Based on the advantages of aerostatic guide and precision box plate, the integrated design is adopted. Among all the structures of the aerostatic guide, the closed plane aerostatic guide has relatively small deflection in the working process, so it theoretically has high operating accuracy and stiffness, and large bearing capacity, which is very suitable for the requirements of the scheme, as shown in figure 3.When the aerostatic guide works, the air film of a certain thickness can homogenize the contour error of the guide surface. It has been verified by previous experimental studies that the operating straightness accuracy of the aerostatic guide is about 1 times higher than that of the aerostatic guide not under aerated state, and the accuracy is about 2 times higher than that of the contour error of the stationary guide [3].
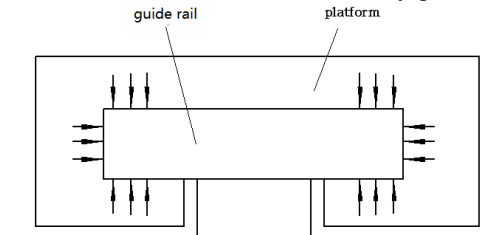

Figure 3. The closed plane aerostatic guide

1) Integrated design of X-axis aerostatic guide and precision box plate

In the integrated design of the box plate and the X-axis aerostatic guide, the selected precision box plate's processing flatness of each surface shall be less than $1\mu m$. The box plate is used as the moving guide for the aerostatic guide in the direction of X axis. The size of the box plate is $400\times400\times100mm$. The total length of the X axis aerostatic guide is $260mm$ and the total height is $200mm$. Aerostatic guide adopts the structure design scheme of closed plane guide. The X axis aerostatic guide is divided into three layers. The box plate is closed in the middle as a moving guide. When the guide works, gas is communicated to the lubrication surface through the static guide. According to the gas error homogenization effect, when the flatness profile error of the box plate and the X-axis static guide is 0.4 ~1 μm, the linear accuracy theory can reach about 0.1~0.3 μm after the gas error homogenization effect [4].Each layer of the static guide is connected with screws, and the air film gap between each layer of the static guide can be adjusted with a feeler to achieve the purpose of adjusting the performance of the guide.

2) Integrated design of Y-axis aerostatic guide and precision box plate

The integrated design of the Y-axis aerostatic guide and the box plate is the same as that of the X-axis structure, but different from the X-axis guide, we take the box plate as the Y-axis static guide and the sliding frame suspended on the box plate as the moving guide. The dimension of the box is $400 \times 400 \times 100mm$. The total length of the Y-axis moving guide is 200mm and the total height is 180mm. The side length of the box is 400mm, larger than the Y-axis moving guide $200mm$. The slide frame is composed of three parts, namely upper air floating block, side air floating block and lower air floating block. The precision box plate is closed in the middle to form a closed air floating guide structure. The air floating blocks are connected with screws, and the air film gap between the air floating blocks is adjusted with a feeler.

B. The design of pneumatic system

When the air floating guide works normally, the air path of the aerostatic guide needs to be filled with clean, dry, sufficient flow and stable pressure gas. Therefore, in order to ensure the continuous supply of high-quality gas, a set of high-performance pneumatic system is needed [5-7].

The aerostatic motion platform combines the air supply supply paths of X axes and Y axes. In order to ensure the stability of the aerostatic motion platform in the working process and avoid the unstable phenomena such as air hammer and vibration, the gas pressure value of the aerostatic guide should be kept constant. Firstly, clean constant-current and constant-pressure gas is prepared through a constant-current and constant-pressure gas supply system. High pressure air is prepared by air compressor, water and oil are filtered through the filter, and the overall gas flow is controlled through the flowmeter and the general pressure reducing valve, and the initial pressure reduction of gas pressure is carried out. Finally, the air supply pressure of the X and Y axis aerostatic guide rail is controlled by the three-way pipe shunt to two precision pressure reducing valves respectively, so as to realize the stable work of the air floating movement platform. The schematic diagram is shown in figure 4.
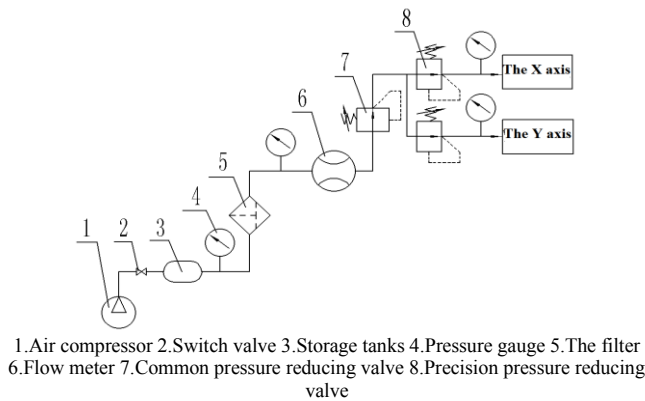

1.Air compressor 2.Switch valve 3.Storage tanks 4.Pressure gauge 5.The filter 6.Flow meter 7.Common pressure reducing valve 8.Precision pressure reducing valve

Figure 4.   Pneumatic schematic diagram

C. The design of driving system

The X and Y axis aerostatic guide rail of the designed aerostatic motion platform are driven by linear motor. There is no other transmission device among them, which avoids the problems of friction, deformation and clearance caused by relying on mechanical contact to transfer thrust, and improves the driving efficiency and response frequency. Therefore, high linear operation accuracy can be guaranteed [8].In principle, linear motor is a rotating motor spread along the cylindrical section, and its structure is shown in figure 5.In this design, the stator of the linear motor on the X-axis is fixed and installed on the granite platform, and the actuator of the linear motor is connected with the precision box plate with screws, so as to realize the direct drive of the X-axis. The installation of the linear motor stator on the Y-axis is fixed on the precision box plate, and the sliding frame with grooves can accommodate the installation position of the linear motor stator. The actuator of the linear motor is connected with the slide frame with screws so as to realize the direct drive of Y axis. The two linear motors are driven by two actuators, which are controlled by a two-axis motion control card connected to the IPC. The grating ruler on the X and Y axis guide rail feeds back the motion positions of the two axes respectively, thus forming a closed loop control.
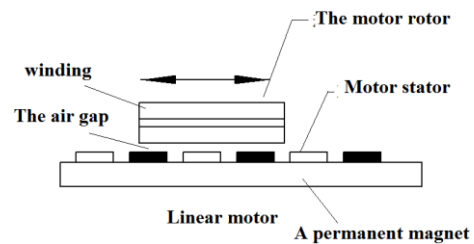

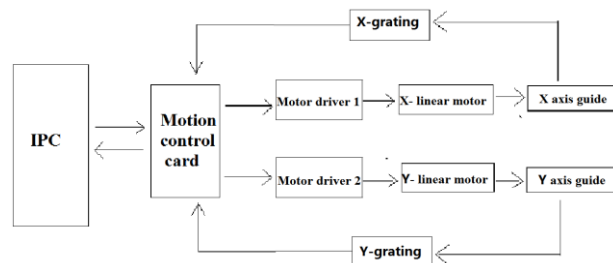Figure 5.   Linear motor working principle

Figure 6.   Principle of drive system

In the technical index of this design, the maximum speed of X axis and Y axis is $0.02m/s$ and the maximum acceleration is $1.5m/s^2$, so it is necessary to calculate the continuous thrust required by the two-axis linear motor. The total weight of the Y-axis aerostatic frame is $50kg$, and the total weight of the X-axis box plate is $70kg$, so the total weight of the motor dragged in the X-axis direction is:

$$mx = 70 + 50 = 120 \ kg$$

The total weight of the motor dragged in Y-axis direction is:

$$m_y = 50 \ kg$$

The friction coefficient of aerostatic guide is about 0, so the friction is negligible. Then the maximum acceleration thrust required by X axis is:

$$Fx = 120 \times 1.5 = 180\ N$$

The maximum acceleration thrust required by Y-axis is:

$$Fy = 50 \times 1.5 = 75\ N$$

III. AIR FLOATING BEARING CAPACITY OF AEROSTATIC GUIDE

The bearing capacity of the designed aerostatic guide is obtained by adding up the bearing capacity of the integral aerostatic guide pair of each part of the working bearing surface and subtracting the bearing capacity of the auxiliary surface.The bearing capacity of the integrated aerostatic guide pair is calculated by integrating the distribution of air film pressure on the air floating surface along the whole air floating surface [9]. The bearing capacity of the aerostatic guide is:

$$W = \int_{\Lambda} (p_s - p_a)dA \qquad (2)$$

The bearing capacity of the integral air floating guide pair is:

$$W = W_2 - W_1 \qquad (3)$$

W is the static bearing capacity of air floating guide rail; p_s is the air supply pressure of air film of air floating guide.; p_a is ambient atmospheric pressure; A is the surface area of the gas film; W_2 is the bearing capacity of working face;W_1 is the bearing capacity of auxiliary surface [10-12].According to the engineering estimation, when the air supply pressure is $0.4MPa$ and the effective coefficient is 0.25, the maximum bearing capacity of the X-axis air floating guide is:

$$W_x = W_2 - W_1 = 3570\ N$$

The maximum bearing capacity of the Y-axis aerostatic guide is:

$$W_y = W_2' - W_1' = 5625\ N$$

IV. SIMULATION ANALYSIS OF STATIC STRUCTURE AND DYNAMIC PERFORMANCE OF AEROSTATIC GUIDE

A. Static analysis

The aerostatic motion platform of this design requires a high running straightness. After preliminary calculation and design of the dimensions of each part, we need to verify the rationality of the size design of the air floating table as a whole. We used ANSYS workbench simulation software to conduct static structure simulation analysis on the two axes of the aerostatic motion platform .The aerostatic motion platform of this design adopts ji`nan green granite material as a whole, and its main physical parameters are as follows: The density is 3070 kg/m^3, compressive strength is 257 MPa, elastic modulus is 120 GPa, water absorption rate is 0.6%,

poisson's ratio is 0.26. The static model of Y-axis aerostatic guide and the static force model of X-axis aerostatic guide were imported into ANSYS workbench for analysis. The total deformation nephogram, total strain nephogram and total stress nephogram of the model under the maximum load can be obtained intuitively by adding constraints and boundary adjustment and setting physical parameters of the material. As shown in figure 7.

a) Total deformation cloud image   b) Total strain cloud map
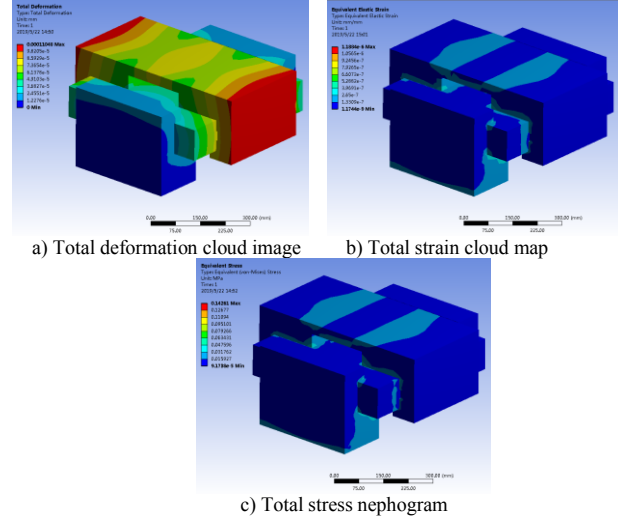

c) Total stress nephogram

Figure 7.   Simulation result diagram

It can be seen from ANSYS workbench simulation analysis that the maximum deformation of the air floating movement platform in figure a is $0.11\mu m$, and it is in the outermost part of the slide frame rather than the guide surface, which has little impact on the whole. The maximum deformation of the guide surface is about 0.03~0.08 μm, and the gas film thickness of the air floating guide system is generally controlled at 10~40 μm, so the shape variable of the guide surface is extremely small compared with the thickness of the gas film, and has little influence on the overall stiffness of the gas film. Figure b shows that the maximum strain of the air floating platform is 1.18×10^{-6}, and its value is very small and almost negligible. In figure c, the maximum stress of the floating platform is 0.14MPa, far less than its compressive strength. From the content of simulation analysis, it can be seen that the total deformation, total strain and total stress can meet the design performance requirements of the aerostatic motion platform.

B. Modal analysis

Modal analysis, as a branch of vibration engineering theory, its reliable analysis results are often used as an effective standard for product performance evaluation. By means of modal analysis, the characteristics of the main modes of the structure in a certain susceptible frequency range can be known, so as to predict the actual vibration response of the structure under the action of various internal and external vibration sources in this frequency band. Thus, the structure can avoid resonance in practical application. Modal analysis is to analyze the natural vibration characteristics of mechanical structure, each mode has a

specific natural frequency and mode. The modal analysis of the air floating table is carried out by finite element method. A simplified three-dimensional model of the air floating platform was established in solidworks, a three-dimensional parametric modeling software (including the removal of screw holes, tiny holes and other relevant elements that do not affect the dynamic characteristics analysis of the air floating platform).Import the x_t file of solidworks into fea platform ansys-workbench. After that, the grid division and solver are set to solve the problem, and the results of the first six orders of natural frequency and modal mode analysis are extracted. Figure 8 shows the results of modal analysis. Figure 9 shows the analysis of the first-six natural modes.
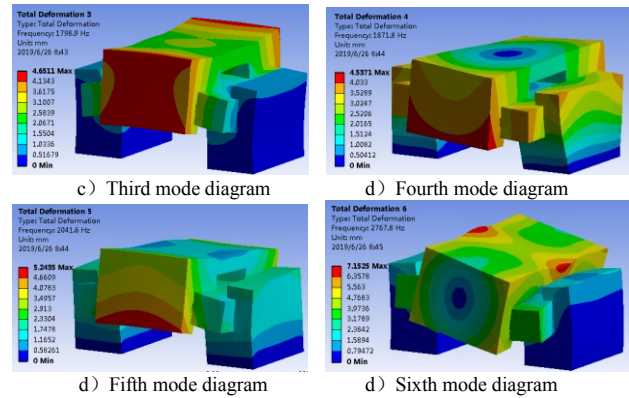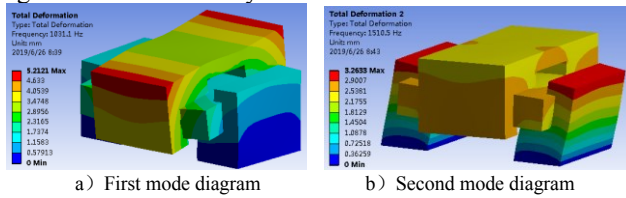
c）Third mode diagram

d）Fourth mode diagram

d）Fifth mode diagram

d）Sixth mode diagram

Figure 8.　Modal analysis results

a）First mode diagram

b）Second mode diagram

Order number	frequency(Hz)	Modal descriptions
The first order frequency	1031.1	The end of the slide frame is tilted in the X direction
The second order frequency	1510.5	The whole platform tilted in the Y direction
The third order frequency	1798.9	The middle of the box slide is twisted downward
The fourth order frequency	1871.8	The overall platform twists in the vertical direction
The fifth order frequency	2041.6	The box is twisted in the X direction
The six order frequency	2767.8	Slide frame with box on Y axis box torsion

Figure 9.　Description of each mode

From the analysis of the first six natural modes, it can be seen that the lowest first-order frequency is 1031.1Hz, which is much higher than the first-order frequency of the traditional two-dimensional floating platform structure, which indirectly reflects the stability of the overall structure.

V.　CONCLUSION

A two-dimensional aerostatic motion platform with precision box plate as its structural reference is designed. The position of all parts of the platform is based on the precision box plate. The high flatness, parallelism and perpendicularity of the precision box plate ensure the uniaxial motion straightness and biaxial perpendicularity of X and Y axes. The design of integral aerostatic guide rail improves the bearing capacity of aerostatic guide and the stability of the whole structure. According to the principle of equalization of air floating errors, a high planeness aerostatic guide and a precision box plate design are adopted to maximize the linear accuracy of aerostatic guide and achieve the purpose of precise linear operation. At the same time, the static analysis and modal analysis of the structure of the aerostatic motion platform are carried out through the analysis of the simulation software, which verifies the rationality and feasibility of the design of the aerostatic motion platform, and provides new guidance for the relevant research of the aerostatic guide rail and the aerostatic motion platform.

REFERENCES

[1]　Slocum A, Basaran M, Cortesi R, et al. Linear motion carriage with aerostatic bearings preloaded by inclined iron core linear electric motor [J] . Precision Engineering, 2011, 27(4):382-394.

[2]　H. Shinno, H. Yoshioka, K. Taniguchi. A Newly Developed Linear Motor-Driven Aerostatic X-Y Planar Motion Table System for Nano-Machining[J] . CIRP Annals-Manufacturing Technology, 2007, 56(1):369-37

[3]　LIU Xiyao, ZHAO Xiaolong, LIU Bo, ZHANG Jun-an. Research on Error Averaging Effect of High Accuracy Plane Gas Floating Guide [J]. Lubrication Engineering, 2016, 41(06) :49-53.

[4]　ZHANG Meihong, DONG Hao, ZHAO Xiaolong, LIU Bo, ZHANG Jun'an. Comprehensive Fractal Simulation for Surface Flatness and Roughness of Rectangular Hydrostatic Thrust Bearings [J]. Bearing, 2018(04):55-58.

[5]　LIU Bo, LU Zhwei. Design of Pneumatic Balance for Precise Gas Hydrodynamic Guides Package [J]. Chinese Hydraulics & Pneumatics, 2007(01):36-39.

[6] Lu Zhiwei, Liu Bo, Zhang Jun-an, Wei Mingming . Design and Analysis of Super-pressurized Gas Hydrodynamic Guides Package [J]. Lubrication Engineering, 2007(02):165-167+183.

[7] WEN Ming,YAO Yong,HE Kanghao,CHEN Huaming,YANG Lei,DENG Li,LI Peilong,JIANG Fei,Simulation and Dynamic Characteristic Optimization of the Ultra-precision Stage with Air-bearing [J]. Machine Tool & Hydraulics, 2017,45(2):20-24.

[8] ZHANG Xuzhong, LU Zhiwei, LIU Bo, ZHANG Jun'an. The design and research of aerostatic guideways performance testing bench [J]. Chinese Hydraulics & Pneumatics, 2012(02):50-52.

[9] WANG Yunfei. Gas Lubricated Theory and Design Manual of Gas Bearings [M]. Bei Jing:China Machine Press, 1999:153-154.

[10] ,LONG Wei, WANG Jiyao, LI Fashe, WU Mimi, DENG Wei, Numerical analysis and experimental research on self-excited micro-vibration of aerostatic thrust bearings ［J］. Journal of Vibration and Shock,,2019,38(16):224-232.

[11] MO Deyun, MA Ping, GONG Manfeng. The Effects of the Interface Structure Fit on the Aerostatic Guideway Performance of T-Type Air Bearing Table [J]. Machinery Design & Manufacture, 2015(07):211-214.

[12] ZHONG Wei, GUO Zongliang, LI Xin, LU Bo. Multi-objective Optimization of Partial Porous Air Conveyors [J]. Chinese Hydraulics & Pneumatics, 2014(06):6-9