A three degree of freedom manipulator used for store separation wind tunnel test

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Abstract. A three degree of freedom manipulator is presented, which is used for store separation wind tunnel test. It is a kind of mechatronics product, have small volume and large moment of torque. The paper researched the design principle of wind tunnel test equipment, also introduced the transmission principle design, physical design, control system design, drive element selection calculation and verification, dynamics computation and static structural computation of the manipulator. To satisfy the design principle of wind tunnel test equipment, some optimization design are made include optimizes the structure of drive element and cable, fairing configuration, overall dimension so that to make the device more suitable for the wind tunnel test. Some tests are made to verify the parameters of the manipulator. The results show that the device improves the load from 100 Nm to 250 Nm, control accuracy from 0.1° to 0.05° in pitch and yaw, also improves load from 10 Nm to 20 Nm, control accuracy from 0.1° to 0.05° in roll.

1. Introduction

The Store Separation Wind Tunnel Test is a wind tunnel test technology that studies the separation characteristics of aircraft external store. The main test device is the multi degree of freedom traverse system [1-3].

Many wind tunnels in the world are equipped with a multi degree of freedom traverse system [4]. The Royal Aeronautical Research Center has a five degree of freedom traverse system [5], with three linear displacement degrees of freedom of X, Y and Z and two Angular degrees of freedom of roll and yaw. The limitation is that there are only two Angular displacement degree of freedom, can not be completed at the same pitch and yaw angle position simulation. France ONERA Modane Wind Tunnel has a four degrees of freedom [6] traverse system, with X-directional linear displacement freedom and pitch, yaw, roll three angular displacement of freedom, when used with the tail boom strut installed. Together, the limitation is that the position simulation can only be done within a certain range on one side of the master model.

Many wind tunnels in China are equipped with multi-degree-of-freedom traverse system, including the China Aerodynamics Research and Development Center's FL-12, FL-14, FL-24 and FL-26 wind tunnels and the AVIC Aerodynamics Research Institute’s FL-2 Wind Tunnel, etc [7-9]. This paper investigates the six degrees of freedom traverse system (figure 1) equipped by the FL-12 wind tunnel in 1987. The advantage of this system is that it has a wide range of motion, many positions can be simulated, and the disassembly and assembly are convenient during the test. However, the device was affected by the current mission requirements and mechanical and electrical technology constraints; the design load is small, the design carrying weight of 2 kg, pitch moment of 100 Nm. At this stage, the
weight of the aircraft external store wind tunnel model has reached the level of 5 kg, and the maximum pitch moment reaches the magnitude of 200 Nm. Due to the lack of design load, the range of locations that the existing devices can simulate in the experiment is limited, and part of the experiment contents can not be completed. Therefore, it is necessary to redesign the six-degree-of-freedom traverse system of the FL-12 wind tunnel to meet the requirements of the Store Separation Wind Tunnel Test at the present stage and the next stage.

Figure 1. Existing traverse system diagram.

After checking the parts loss and checking calculation, the conclusion is: the installation foundation of the existing traverse system and the X, Y, Z linear displacement components meet the conditions of continued use, which need to re-design is the angular displacement components of the existing traverse system. The function of this part is to support the aircraft external store model to complete the rotation in the angular degree of freedom of pitch, yaw and roll. It is called as three degree of freedom manipulator. [12]

2. Research content
Based on the experience and user feedback of the existing three-degree-of-freedom manipulator (figure 2), it was found that the problems that can be improved are not only the load capacity of the device, but also the wind tunnel test device, which is also unsatisfactory in the applicability of the wind tunnel. To this end, this paper devoted to the design principles of wind tunnel test device, according to the conditions of use of wind tunnel test equipment, the following design principles are proposed:

Figure 2. Existing three degrees of freedom manipulator data photos.

- The device must be easy to install and disassemble, the parts can be disassembled and saved as a whole component;
- The Device must be easy to control and calibration, supporting a dedicated control software
and calibration tooling:

- The aerodynamic shape of the device should be smooth to reduce the impact on the flow field quality of the wind tunnel;
- Wind tunnel blockage ratio of the device cannot be too large, for reducing the impact of wind tunnel test section of the pressure;
- Shielding the power cable to reduce the signal interference of the balance measuring element;
- Try not to expose the cables in the wind tunnel to avoid the swaying lead to the connectors loose.

After the investigation of the model of the aircraft external store at the present stage, the aerodynamic load of a new type missile is selected as the estimation case, and the load capacity requirement of the three-degree-of-freedom robot is proposed. Device overall technical indicators are listed in Table 1.

| Project | Existing Ability | Design Requirements |
|---------|------------------|---------------------|
| Pitch   | Load             | 100nm               |
|         | Accuracy         | ±0.1°               |
|         | Speed            | ±0°/S               |
|         | Angle Range      | ±45°                |
| Yaw     | Load             | 100nm               |
|         | Accuracy         | ±0.1°               |
|         | Speed            | ±0°/S               |
|         | Angle Range      | ±45°                |
| Roll    | Load             | 10Nm                |
|         | Accuracy         | ±0.1°               |
|         | Speed            | ±0°/S               |
|         | Angle Range      | ±180°               |
| Weight  | \                | 60kg                |
| Blockage Ratio | \    | 1.2%                |

According to the above technical requirements, the research and development of the device has the following difficulties:

- At the same time reduce the blockage ratio of the device and enhance the load capacity will be mutually constrained. In order to reduce the blockage ratio of the device, the overall size of the device will be limited, and the components of the motor, the sensor and the driving arm may not be oversized. At the same time, the thrust provided by the small-size component may not meet the device load requirements.
- In order to reduce the impact of the device on the quality of the flow field, its shape must be smooth and rectified, and the cable buried. The requirements for the layout of the driving elements, the planning of the cable and the mode of mechanical transmission are higher.
- Control accuracy requirements also have brought difficulties to the design. In addition to the selection of control components higher requirements, the deformation of various parts, tolerances, processing methods and weight control is more stringent.

3. Structural design and optimization

In the transmission principle design, three sets of programs are designed: the worm gear in program one can provide a larger load, shown in figure 3, the advantage is large torque, self-locking function, the disadvantage is the size is too large, the blockage ratio does not meet the Requirements, solid worm impede the built-in cable; program two is to parallel arrangement the electric cylinder ball hinge form, shown in figure 4, the advantage is small axial size, simple structure, the disadvantage is the
radial size is too large, the blockage ratio does not meet the requirements, and parallel arrangement of the electric cylinder in the pitch and yaw direction of the two angles caused by the movement of the coupling lead difficulty to the control of decoupling; program three is arranged in axis series connection of the electric cylinder, shown in figure 5, the advantage is diameter size is small, in the pitch and yaw angle of the two directions without the coupling, the disadvantage is that the series connection of the electric cylinder will cause the device axial size larger than the other program.

Figure 3. Sketch map of program 1.

Figure 4. Sketch map of program 2.

Figure 5. Sketch map of program 3.

Figure 6. Sketch map of improved program 3.

According to the design requirements of the three-degree-of-freedom manipulator, program three is finally selected as the transmission scheme of the manipulator, and then, in order to reduce the axial size, an improved program three is proposed as shown in figure 6. After the research, the installation base of the X component is a hollow structure. After structural optimization, the yaw electric cylinder and the supporting components are arranged in the X component. The total length of the device with the improved program three is 1140 mm, optimized structure reduces the 240 mm in length, and the radial size can be controlled at about 210 mm. According to the numerical model, the maximum blockage area of the device is about 0.12 m$^2$ and the maximum blockage ratio is 0.12 m$^2$/10.72 m$^2$ (10.72 m$^2$ is the cross-sectional area of wind tunnel test section) = 1.12%, which meets the blockage ratio requirements.

The detailed design of the three degree-of-freedom manipulator is shown in figure 7, from the rear end to the front followed by a yaw component, pitch component and roll component, of which yaw angle axis, pitch angle axis and roll angle axis are continuously orthogonal. In order to meet the requirements of the smooth shape of the device, a conical fairing is designed. Through the internal structure optimization, the pitch and roll components are arranged in the conical fairing. The material of the fairing is made of high-strength aluminum alloy 7075-T6, which has the advantages of light weight and high strength, which not only reduces the weight of the pitch component but also effectively controls the deformation of the device under load.

Transmission structure of the device is shown in figure 8, the pitch component work by the electric cylinder to push the device along the main axis of rotation, in order to achieve the angle deflection, the angle sensor is arranged on the pitch axis, the acquisition angle is the pitch angle of the device. The
yaw component and drives the same way with the pitch component and are arranged in series connection. The advantage of this kind of structure is that the device has the advantages of small radial dimension, small backlash and no long-distance transmission, and the device has no motion coupling in the two directions of pitch and yaw. Rolling component work by the DC servo motor with harmonic gear reducer drive model probe rod to achieve rotation, the ring angle sensor is arranged in the probe rod, the acquisition angle is the body rolling angle, which is characterized by direct and reliable drive mode the angle of the encoder feedback signal is also the device roll angle, without the need for angle conversion.

**Figure 7.** Outline of the 3-DOF manipulator.

**Figure 8.** Transmission structure diagram.

Inside the conical fairing, the roller motor and pitch electric cylinder are dislocation to optimize the axial dimension of the device, as shown in figure 9. In order to meet the requirement of cable embedded, cable troughs are reserved in the interior of the conical fairing and the probe rod, which not only ensures the stable signal transmission but also ensures the smooth aerodynamic shape of the conical fairing and reduces the adverse effects on the flow field quality.

**Figure 9.** Structure inside the conical fairing.

**Figure 10.** Shaft fork sketch map.

Schematic diagram of the shaft fork structure is shown in figure 10, the angle sensor is arranged on the corresponding axis, the acquisition accuracy of the sensor is 0.0005°, the main axis of rotation angle signal feedback in the closed-loop control. Metal-based self-lubricating bearings (JDB) was selected, which can achieve oil-free lubrication, the friction coefficient is about 0.05, and can protect the device for a long time smooth operation. Photoelectric limit sensor will ensure the safety of the device, when the shaft fork beyond the angle range can trigger the limit sensor, through the control of computer software to stop running to prevent parts collide with each other.

4. **Driver selection and check**

4.1. **Pitch, yaw direction of the components selected calculation**

Yawing electric cylinder and pitch electric cylinder drive in the same form, so choose the larger load pitch electric cylinder to do the calculation. The device in the pitch direction of the technical indicators: the load is 250 Nm, the speed is 4 °/s, positioning accuracy is 0.05°. Because of the complexity of the
transmission of the electric cylinder, the simple statics calculation can not completely simulate the whole load and the movement state of the electric cylinder within the specified movement range of the device. Therefore, the ADAMS software is used to calculate the dynamics of the device, and the sensor is set at the position of the pitch electric cylinder, by analysing the thrust, displacement and speed curve of the electric cylinder, the parameters of the cylinder can be determined.

According to the three-dimensional model of the device, the yaw joint of the three-degree-of-freedom manipulator is set as the base point O, the pitch joint is the relay point A, the front end of the probe rod is the reference point B, then the transmission principle diagram is drawn as figure 11.

![Figure 11. 3-DOF manipulator transmission principle diagram.](image)

According to the transmission principle diagram of a three-DOF manipulator, the dynamic equation of the device is established, and the position equation of point A and point B is obtained:

- **A**: \((l_1 \cdot \cos \beta, 0, l_1 \cdot \sin \beta)\)
- **B**: \((l_1 \cdot \cos \beta + l_2 \cdot \cos \alpha \cdot \cos \beta, 0, l_1 \cdot \sin \beta + l_2 \cdot \cos \alpha \cdot \sin \beta)\)

Enter the dynamic equation into ADAMS, select -45° to +45° as the calculation range, the calculation of the settings taking the gravity of the parts, device load, friction and start characteristics into account, the pitch mechanism operating speed is set at 4°/s, the load is set at 250 Nm, and the displacement curve, thrust curve and speed curve of the electric cylinder of the device are obtained by calculation.

It can be seen from the displacement curve in figure 12 that the displacement of the electric...
cylinder has a good linear relationship with the pitch angle. When the pitch angle of the device runs from -45° to 0° and then to +45°, the total displacement of the electric cylinder is 38 mm + 34 mm = 72 mm, Therefore, the travel requirements of the electric cylinder should be more than 72 mm.

![Figure 12. Electric cylinder displacement calculation result.](image)

From the thrust diagram of figure 13 can be seen that although the electric cylinder affected by the start-up characteristics, friction torque, compression torque and arm changes and other factors, but its thrust in the device operating range is still gentle changes, no step-growth, The calculation results show that the maximum thrust required for the cylinder is 9800 N.

![Figure 13. Electric cylinder thrust calculation result.](image)

The speed of the device at different positions of the cylinder can be obtained from the speed diagram figure 14, and it can be seen that the speed requirement of the electric cylinder should be greater than 3.9 mm/s.

![Figure 14. Electric cylinder velocity calculation result.](image)

According to the dynamic calculation results, the selected electric cylinder has a continuous thrust of 12000 N, a maximum displacement of 100 mm, a maximum speed of 4 mm/s and a control precision of 0.01 mm. The accuracy of the mechanism in pitch direction is 0.016° <0.05°, which meets the design requirements.

4.2. Roll direction of the components selected calculation
The technical indicators of the rolling components are: the load is 20 Nm, the speed is than 10 °/s, the
accuracy is 0.1°. The drive components are selected by the above technical indicators.

Considering the internal structure of the device size, a 40 mm diameter motor is selected, the power of which is 150 W, the speed is 7000 rpm, the rated load is 0.184 Nm, the maximum load is 2.28 Nm.

When selecting the reducer, firstly considers the reduction ratio and secondly considers the reducer size, and thirdly considers the rotation speed. According to the selected motor reduction ratio calculation: 20 Nm/0.184 Nm = 109.29, considering the efficiency 80% and the overload allowance of 20%, the reduction ratio is suitable at about 160-170.

A harmonic reducer is selected, the deceleration ratio of which is 160, the outer diameter is 70 mm, grease lubrication efficiency is about 80%, and the reducer maximum input speed is 750 rpm, the maximum output torque is 49 Nm, which meet the load requirements.

Consider the control accuracy requirement, the resolution of the motor encoder should be greater than: 360 °/(0.1° × 160) = 22.5. The final selected encoder has 500 frames per turn to meet the requirements.

Calculate obtained the required starting torque is 60 Nm at maximum angular acceleration and the maximum overload torque is 2.28 Nm × 160 = 364 Nm, start-up characteristics to meet the requirements.

According to the selected technical indicators of the motor and reducer accounting device, the speed of the rolling mechanism is obtained as 262 °/s> 10°/s to meet the design requirements; the controllable precision of the rolling mechanism is 0.0045° <0.1°, satisfying Design requirements; Rolling body load capacity is 23.5 Nm> 20 Nm, which meets the design requirements.

5. Control system design

Device control structure is shown in figure 15. When the device is running, a command is given to the corresponding motor at an angle through the computer-controller-driver, and the angle signal is feedback by the angle encoder located on the main axial to make the closed-loop control of the angle. At the same time, the limit sensor at the front of the model and the photoelectric sensor signal mentioned above are also sent back to the controller. If the device exceeds the preset angle range or the risk of collision between the model and the aircraft, the software will automatically determine and send the command to stop the device.

![Figure 15. 3-DOF manipulator control architecture.](image)

This kind of control method has higher precision and better repeatability, and the control accuracy in pitch angle can reach 0.016°, and the integrated error is less than 0.05°. Its high degree of automation, during the wind tunnel test, the operator only need to enter a certain point of the control
software values, the software will automatically adjust the angle of the feedback signal to the device angle control values, during which no need to intervention.

6. Design verification

6.1. Stress calculation

According to the device bearing capacity, give an example of two key parts of the strength calculation. The shaft fork during work is under repeated thrust, choose aluminum alloy 7075-T6 as the material of the shaft fork, the mechanical properties of the parameters are listed in table 2. In order to ensure there is no risk of fracture during device work, the safety factor require is 5 [10-11].

| Material     | Yield Strength / MPa | Poisson's Ratio | Density / (kg · m$^{-3}$) |
|--------------|----------------------|-----------------|---------------------------|
| 7075-T6      | $5.05 \times 10^2$   | 0.33            | $2.81 \times 10^3$       |
| 30CrMnSiA    | $8.35 \times 10^2$   | 0.28            | $7.25 \times 10^3$       |

The result of stress calculation for the shaft fork is shown in figure 16. It can be seen from the calculation results that the maximum stress of the part after loading is 23.2 MPa, which is lower than the yield strength of material properties 505 MPa, and the safety factor of 21.7, which meets the safety factor requirements.

![Figure 16. Bushing stress calculation result.](image1)

Yaw electric cylinder and its supporting parts, under working conditions need repeatedly withstand thrust, choose alloy steel 30CrMnSiA as its material, its mechanical properties are listed in table 2, the safety factor require is 5.

The stress calculation results of the yaw electric cylinder and the supporting parts are shown in figure 17. It can be seen that the maximum stress of the part is 42 MPa, lower than the yield strength of the material of 835 MPa and the safety factor is 19.8, which meets the safety factor requirements.

![Figure 17. Electric cylinder stress calculation result.](image2)

6.2. Collision calculation

In order to control the overall size, the gap between the parts of the device is small, and with the device movement, there are some risk of collision between the electric cylinder and the other parts, so the three-dimensional software is used for check the minimum gap between the parts. Figure 18 illustrates several typical locations where the part clearance is less than 10 mm. The clearances of the parts in the first three pictures are more than 3 mm. There is no special requirement on the machining tolerances of the parts. The clearance of the parts in the latter picture is less than 3 mm, which indicates that there is a collision risk between the electric motor and the cover of the conical fairing. Therefore, the shape requirements of the corresponding parts and the position tolerance requirements are improved, to ensure that they will not collide with the electric cylinder.
7. Test verification
When the three degrees of freedom manipulator is assembled, the ground commissioning and debugging within the wind tunnel are made, shown in figure 19. Then the main performance indicators of the three-degree-of-freedom manipulator were tested check in the wind tunnel. The verification results show that the load capacity and angle control accuracy of the three-degree-of-freedom manipulator meet the technical indicators.

7.1. Load verification
Exert moment load Respectively on the three degrees of freedom of the manipulator to observe the operation of the device, if there are no jitter, or can not maintain a given position, then the test can pass. A certain position is selected on the probe rod at the tip of the manipulator and a moment load is applied by adding weights. Calculation of torque is according to the formula:

\[ M = F \times L \]

- \( M \) is the moment, in unit of Nm;
- \( F \) is the gravity of the weight, in units of N, wherein the weight standard is according to GB / T 4167-2011 M2 level;
- \( L \) is the distance from the axis of load application point, the measurement error does not exceed
Within the design load range, the manipulator is operating normally in the three degrees of freedom directions. The load is checked according to the evaluation criteria mentioned above. The test data are shown in table 3.

| Project            | Load (Nm) | Test Result |
|--------------------|-----------|-------------|
| Pitch Direction    | 100       | Pass        |
|                    | 150       | Pass        |
|                    | 200       | Pass        |
|                    | 220       | Pass        |
|                    | 250       | Pass        |
| Yaw Direction      | 100       | Pass        |
|                    | 150       | Pass        |
|                    | 200       | Pass        |
|                    | 220       | Pass        |
|                    | 250       | Pass        |
| Roll Direction     | 5         | Pass        |
|                    | 10        | Pass        |
|                    | 15        | Pass        |
|                    | 18        | Pass        |
|                    | 20        | Pass        |

7.2. Accuracy verification
The angle of the three degrees of freedom of the manipulator is measured by the electronic inclinometer (the accuracy is 1") and the angle checking tool in figure 20, and compared with the angles given by the software to evaluate the angle positioning accuracy. Tolerances on shape and position of the angle checking tool shall be Level 6 in GB / T 1182-2008.

![Figure 20. Pitch direction accuracy check.](image)

After testing, the maximum error of the three directions are no more than 3', that is less than 0.05°, the accuracy verification is passed. Tables 4-6 show the test data.

| Nominal Angle (°) | Measured Angle | Software Angle | Error |
|-------------------|----------------|----------------|-------|

Table 4. Angle test results of pitch direction.
Table 5. Angle test results of yaw direction.

| Nominal Angle (°) | Measured Angle | Software Angle | Error |
|-------------------|----------------|----------------|-------|
| 0                 | 0°0’ 30”       | —              | —     |
| 5                 | 5°1’ 0”        | 5°0’ 30”      | 30”   |
| 10                | 10°0’ 55”      | 10°0’ 25”     | 25”   |
| 15                | 14°59’ 55”     | 14°59’ 25”    | 35”   |
| 20                | 19°59’ 15”     | 19°58’ 45”    | 1’ 15”|
| 25                | 24°59’ 45”     | 24°59’ 15”    | 45”   |
| 30                | 29°59’ 10”     | 29°58’ 40”    | 1’ 20”|
| 35                | 34°59’ 20”     | 34°58’ 50”    | 1’ 10”|
| 40                | 39°59’ 35”     | 39°59’ 5”     | 45”   |

Table 6. Angle test results of roll direction.

| Nominal Angle (°) | Measured Angle | Software Angle | Error |
|-------------------|----------------|----------------|-------|
| 0°                | -0°0’45”       | —              | —     |
| -5°               | -5°1’20”       | -5°0’35”       | 35”   |
| -10°              | -10°1’55”      | -10°1’10”      | 1’10” |
| -15°              | -15°0’45”      | -15°0’0”       | 0”    |
| -20°              | -20°1’25”      | -20°0’40”      | 40”   |
| -25°              | -24°59’15”     | -24°58’30”     | 1’30” |
| -30°              | -30°2'40”      | -30°1’55”      | 1’55” |
| -35°              | -35°2’45”      | -35°2’0”       | 2’0”  |
| -40°              | -40°1’35”      | -40°0’50”      | 50”   |

8. Conclusion

- In this paper, the design of small-size and large-load three-degree-of-freedom manipulator is the research content. Through the investigation of the requirements of the aircraft external store model, the technical indicators of the device are proposed. At the same time, design principle of wind tunnel test device is researched, covering the device blockage ratio, aerodynamic shape and cable layout.

- In the design of transmission principle, an improved program three is selected with orthogonal three degrees of freedom. The advantage is that the angle changes will not be coupled to each other and the control process does not need to be decoupled. The angle sensors are all located on the rotating axial. The collected angle signals No need to convert and can directly feedback to the closed-loop control, with less conversion process, higher reliability.

- According to the research contents, the structural design and optimization of the three-DOF manipulator, control system design, design verification and test verification are carried out. The results are shown in table 7. The results show that all the technical indicators of the device
meet the design requirements.

- The three-DOF manipulator has the ability to complete the store separation wind tunnel test at present and in the future. However, the accuracy of the model positioning accuracy caused by factors such as the shape and position tolerance of the part and the deformation by loading of the device also needs further research and exploration, to improve the data quality of store separation test.

### Table 7. Three degrees of freedom manipulator developed results.

| Project | Existing ability | Design requirements | Verification results |
|---------|------------------|---------------------|---------------------|
| Pitch   | Load 100 Nm      | 250 Nm              | pass                |
|         | Accuracy 0.1°    | 0.05°               | pass                |
|         | Speed 10°/s      | 4°/s                | pass                |
| Yaw     | Load 100 Nm      | 250 Nm              | pass                |
|         | Accuracy 0.1°    | 0.05°               | pass                |
|         | Speed 10°/s      | 4°/s                | pass                |
| Roll    | Load 10 Nm       | 20 Nm               | pass                |
|         | Accuracy 0.1°    | 0.05°               | pass                |
|         | Speed 10°/s      | 10°/s               | pass                |
| Weight  | \                | 60 kg               | 56 kg               |
| Size (mm) | 1070×295×295   | \                  | 1140×Φ210           |
| Blockage Ratio | \          | 1.2%               | 1.12%               |

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