The Key Technology of Large Telescope Tracking System Based on Integrated Super-low Speed Bearingless Motor

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ABSTRACT

With the continuous exploration of the universe and astronomy's development, the telescopes are bigger and bigger. Horizon structure is widely used in the modern large telescopes rack, which carries dozens, even thousands of tons of the rotary parts and demands high accuracy and good stability. Therefore, it is one of the key technologies for large telescope to develop the precision support technology integrated direct drive with large load, high stiffness, low friction , even frictionless. Magnetic suspension bearing has not only the advantage of non-contact, no friction, high rigidity, high precision, low power, low mechanical assembly requirements, but also is integrated with the driven torque motor, which simplifies the structure, reduces the cost. This paper explores one kind of active bias magnetic suspension bearing integrated with direct drive technology based on multidisciplinary design optimization (MDO), which provides a new choice and view for the modern large astronomical telescope tracking system.

Keywords: Super-low speed bearingless motor, Active bias magnetic suspension bearing, Suspension stiffness, Large telescope tracking system, Double redundant drive system.

1. INTRODUCTION

With the continuous exploration of the universe and astronomy's development, the telescopes are bigger and bigger. The outstanding features are reflected as large diameter, high precision and high resolution, integrated with active optics and adaptive optics in the same time, such as VLT, GTC, TMT, E-ELT, which requires the telescope tracking system to guarantee a very high tracking accuracy, in spite of unbalanced and sudden loads such as wind disturbance, load fluctuation and in spite of a structure that, because of its giant size, cannot be infinitely stiff. However, there are many severe challenges for the telescope tracking system.

Horizon structure is widely used in the modern large telescopes, which carries dozens, even thousands of tons of the rotary parts and demands high accuracy and good stability. The transmission way of the telescope mainly includes worm, gear, friction drive and direct drive. The gear or friction drive are widely used in the small and medium telescopes drive system, which's shaft is also mainly supported by the traditional roller bearings or double row ball bearing, such as 4.2 m SOAR[16]. The LAMOST adopts static hydraulic bearing to support the telescope's rack and friction transmission to drive [5]. While static hydraulic bearing support technology and direct drive system is adopted in the 8-10 meter telescopes, such as

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VLT[1,7], SUBARU[4] and GTC[12], similarly in the 30-50 meters CFGT, E-ELT,TMT[3]. Although the large and extreme great telescope tracking rack basically adopts the technology of hydrostatic bearing with direct drive to support and drive the telescope, but its performance of hydraulic oil is greatly influenced by temperature, which must strictly be controlled, and in addition, additional reliable fuel supply system and independent standby power supply system should be also provided. On the other hand, the hydrostatic bearing must meet higher requirements in the processing, assembling, which is undoubtedly severe problem for the 30~50 meters hydrostatic bearing.

It is very difficult to separate the support technology from drive system in the telescope rack because of the more complexity of large telescope. Therefore, it is one of the key technologies for large telescope to develop the precision support technology integrated direct drive with large load, high stiffness, low friction , even frictionless. Magnetic suspension bearing has not only the advantage of non-contact, no friction, high rigidity, high precision, low power, low mechanical assembly requirements, but also is integrated with the driven torque motor, which could simplify the structure, reduce the cost. This paper explores one kind of active bias magnetic suspension support integrated with direct drive technology.

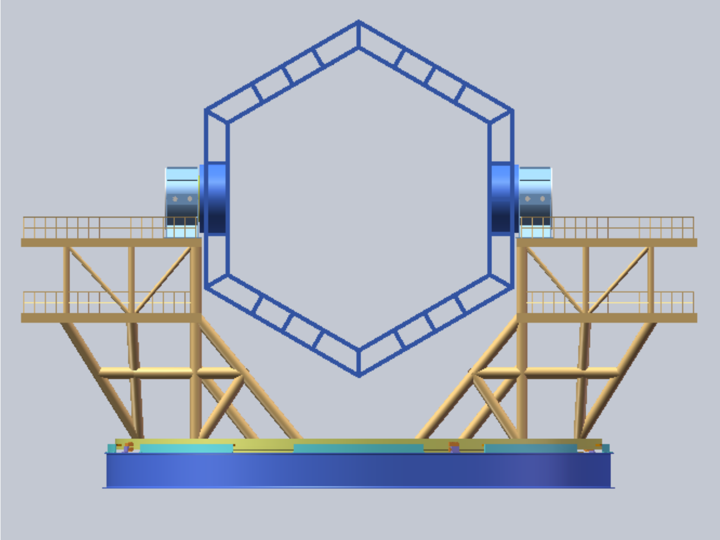

Figure 1. Large telescope tracking system model based on active bias magnetic suspension bearing integrated with direct drive motor

2. DESIGN PROGRESS OF TELESCOPE TRACKING SYSTEM BASED ON INTEGRATED SUPER-LOW SPEED BEARINGLESS MOTOR

Modern large telescopes is a very complex systems involved in mechanical engineering, optics, electronic engineering, control engineering, computer engineering and so on. The key of the design is that the problem involved in all filed must be comprehensively set up and considered from the beginning, embodied as integration and coordination in the design process. It is very important to improve the system integration, optimize system software and hardware, simplify and optimize the design and manufacturing process to reduce the product cost as well as improve product quality and performance. However, the difficulty is that many factors need to focus on to consider, the interaction between various systems, system modeling, feedback control and the stability of the system, etc. Design concept of complex mechatronic system includes the drive system, mechanical dynamics, the complexity of the control system, the veracity and reliability of electronic products, coupling and decoupling between each subsystem. In the whole design circle life of modern large telescope, the optimization of tracking system should be carried on continuously to meet the quality and requirements of the product. A good telescope system design process should be characterized by short development cycle, low cost, high quality, high reliability and high performance.

In the design of large telescope, different tasks would conflict each other. The purpose of synergy is to eliminate conflict, the balance is the key to success, that is, to maintain a balance between modeling /analysis, implementation/measurement, and subsystems. For example, for task A, with evaluation function $f_A(X_g^A, X_o^A)$, mathematical model M_A is set up, solve it to get the solution set C_A:

$$M_A:\begin{cases} G_A: g_i(X_g^A, X_o^A) \le 0 \\ \mathrm{H}_A: h_j(X_g^A, X_o^A) = 0 \\ (j=1,\ldots,k_{q_A})(i=1,\ldots,l_{q_A}) \end{cases} \tag{1}$$

Where, X_g^A public design variables in task A, X_o^A design variables except public design variables in task A。

Similarly, for task B, with evaluation function $f_B(X_g^B, X_o^B)$, mathematical model M_B is set up and solve it to get the solution set C_B:

$$M_B:\begin{cases} G_B: g_i(X_g^B, X_o^B) \le 0 \\ \mathrm{H}_B: h_j(X_g^B, X_o^B) = 0 \\ (j=1,\ldots,k_{q_B})(i=1,\ldots,l_{q_B}) \end{cases} \tag{2}$$

Normally, there exits conflicts between solution C_A and C_B. Even if the conflicts do not exist or have been eliminated, the evaluation criteria of different tasks are inconsistent with each other. It is difficult to achieve the optimal requirements for all tasks at the same time. For example, no matter how optimal design scheme , it is hard to get satisfied solution in the constraints of project funds, technical requirement, the project's overall evaluation index need to be modified and assigned to each task to optimize the design, repeated and repeated until getting an acceptable solution. However, for some kind of large telescope, the evaluation criterion should be a dynamic index, that is, the evaluation criterion and value fall within a certain range of values, which can be applied and satisfied by all designer in the design of the large telescope tracking system model based on active bias magnetic suspension support integrated with direct drive motor as the following.

1. Different types of drives and bearings systems can be implemented between the azimuth-altitude structures. However a typical angular accuracy of arc second, must be well within the performance of the adopted solution, while interfaces and kinematics must ensure a homogeneous load transfer to the foundation.
2. The large telescope is direct driven by three-phase permanent magnet synchronous torque motor. According to the structure characteristics of the azimuth and altitude axis, azimuth drive motor uses the radial magnetic field structure, while the altitude drive motor adopt disk structure with axial magnetic field.
3. The modular design idea is used in the two kinds of permanent magnet torque motors with different structures, especially, for the large diameter permanent magnet synchronous torque motor, the motor is designed to be 2L (L= 1,2,3,4,⋯) minimum units (motors). The 2L smallest unit can be combined flexibly and freely into P more powerful and larger unit motors, P= 1, 2, 3, 4,⋯. Each individual unit motor can be run separately as a motor, or run synchronously.

4. Motor cooling system is considered and designed for both azimuth and altitude axis, temperature gradient is strictly controlled under 2 °.
5. In order to restrain the azimuth 3 translation DOF and protect the telescope when the magnetic suspension bearing fails, azimuth roller bearing system is consisted of active magnetic suspension bearing and protected bearings.
6. Defines the telescope azimuth and altitude axis rotary encoder supply the position signal of the telescope tracking system.
7. In order to restrain the altitude 3 translation DOF and protect the whole telescope when the magnetic suspension bearing fails, altitude roller bearing system is consisted of active magnetic suspension bearing and protected bearings.
8. Braking system is designed in order to brake the telescope under the emergency condition, brake equipment is optimized to electromagnetic brake, hydraulic or pneumatic brake device is also considered. According to the optimization design scheme, Z (Z=1, 2, 3,4 ,⋯) electromagnetic brake is installed.
9. Two symmetrical disk permanent magnet torque motors are designed for the altitude axis, which not only realizes the symmetry of axial force but also improve the reliability of the system. Two motors are synchronized and driven during normal condition, while one fault occurs, another on start to work.

3. STRUCTURAL DESIGN DEVELOPMENT

To begin the discussion outlining the design of the telescope structural support system, it is necessary to outline some of the key design constraints. The primary design constraints are related to the LOT telescope rack configuration. The main design indexes of azimuth axis are as follows:

1. The direct drive motor of the azimuth axis is a three-phase permanent magnet synchronous torque motor, 1024 poles, which of rotor is composed of 64 rotor unit. Double redundant drive system is realized by two spicing unit stator (motor) that each can meet the requirement of the telescope. The two spicing unit stator (motor) can be run synchronously or separately.
2. Motor cooling system is considered and designed for azimuth, temperature gradient is strictly controlled under 2 °.
3. In order to restrain the azimuth 3 translation DOF and protect the whole telescope when the magnetic suspension bearing fails, azimuth roller bearing system is consisted of active magnetic suspension bearing and protected bearings.

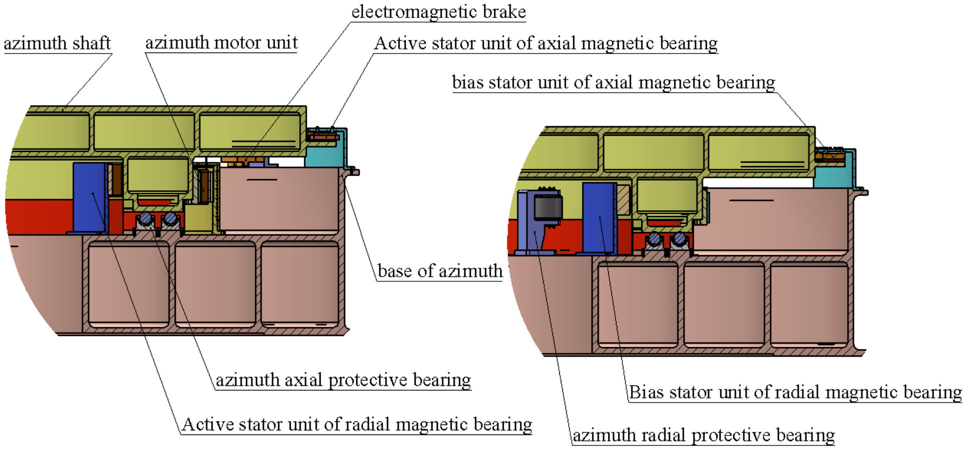

Figure 2. Detailed structure model of azimuth drives and bearings systems based on active bias magnetic suspension support integrated with direct drive motor

4. Defines the telescope azimuth axis and a rotary encoder supply the position signal of the azimuth structure.
5. The axial active bias magnetic suspension bearing of the azimuth is a hybrid bearings, which is mainly composed of 4 bias magnetic suspension bearing unit and 4 active controlled electromagnetic bearing unit and are alternately installed on the same circumference. There are 4 orthogonal axial position sensors to measure z direction two orthogonal displacement.
6. According to bearing load capacity, there are 36 axial auxiliary bearing units to be installed uniformly on the same circumference, every bearing unit is consistent gap with the support plane of the azimuth shaft, normally 0.5-2 mm. In addition, the pressure sensor was designed and installed on every bearing unit to detect whether there is contact or overload. According to the pressure sensor signals, monitor the condition of the azimuth axis.
7. Same design method is adopted on radial active bias magnetic suspension bearing to restrain the azimuth radial DOF.
8. According to bearing load capacity, there are 8 radial auxiliary bearing units to be installed uniformly on the same circumference, every bearing unit is consistent gap with the support plane of the azimuth shaft, normally 0.5-1.5 mm.
9. There are four electromagnetic brake to be symmetrically and uniformly installed to brake urgently under emergency condition. When losing the power, the each brake contacts on the azimuth braking surface, braking the azimuth axis.

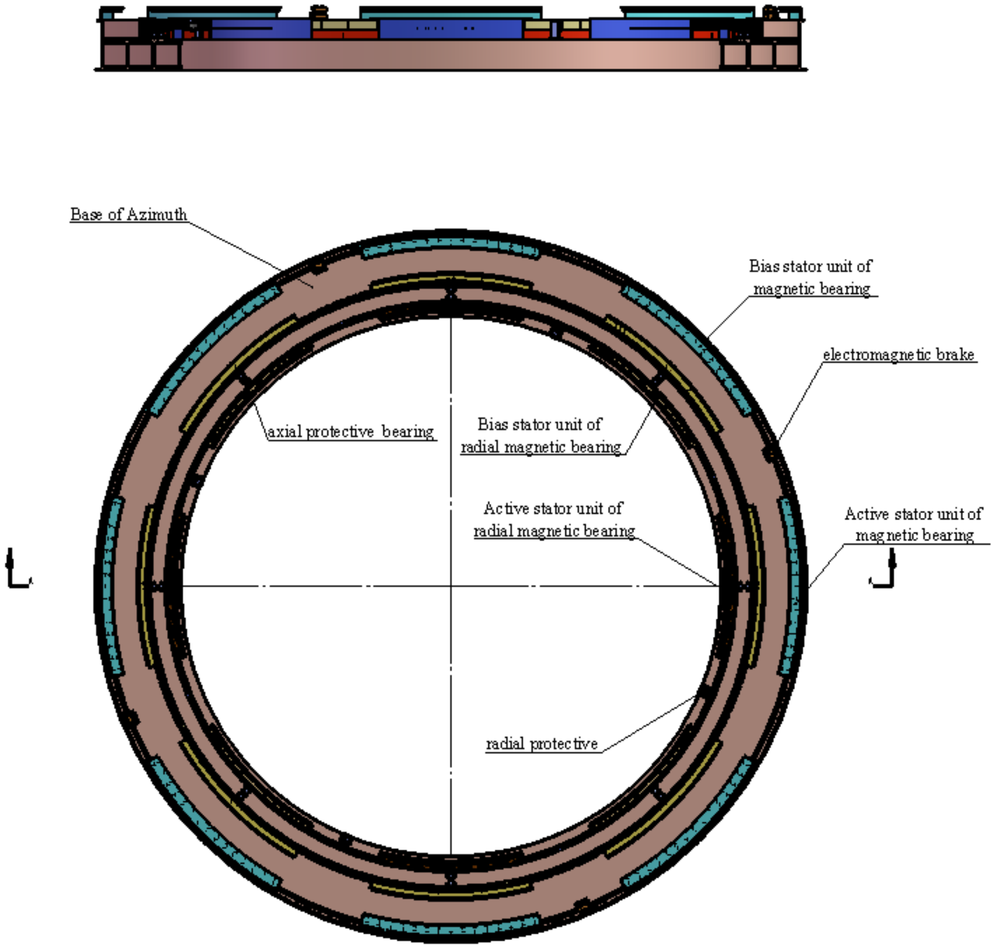

Figure 3. Azimuth drives and bearings systems based on active bias magnetic suspension bearing integrated with direct drive motor

The main design indexes of altitude axis are as follows:

1. The direct drive motor of the altitude axis is a three-phase permanent magnet synchronous torque motor, 384 poles, which of rotor is composed of 32 rotor unit. Double redundant drive system is realized by two spicing unit stator (motor) that each can meet the requirement of the telescope. The two spicing unit stator (motor) can be run synchronously or separately.
2. Motor cooling system is considered and designed for altitude, temperature gradient is strictly controlled under 2 °.
3. In order to restrain the altitude 3 translation DOF and protect the whole telescope when the magnetic suspension bearing fails, altitude roller bearing system is consisted of cone active magnetic suspension bearing and auxiliary bearings.
4. Defines the telescope altitude axis and a rotary encoder supply the position signal of the altitude structure.
5. The cone active bias magnetic suspension bearing of the altitude is a hybrid bearings, which is mainly composed of 4 bias magnetic suspension bearing unit and 4 active controlled electromagnetic bearing unit and are alternately installed on the same circumference. There are 4 orthogonal axial position sensors to measure z direction two orthogonal displacement and 4 orthogonal radial position sensors to measure x, y direction two orthogonal displacement.
6. The altitude shaft protection bearing is mainly used to protect the whole device from damage when the altitude shaft is subjected to a large external load impact or the failure of the conical active bias magnetic suspension bearing. The altitude auxiliary bearing radial is designed and used symmetry in pairs, the contact angle α is optimized to protect and restrain axial and radial displacement. According to bearing load capacity, there are 8 auxiliary bearing units to be installed uniformly on the same circumference, every bearing unit is consistent gap with the support plane of the altitude shaft, normally 0.5-1.5 mm. In addition, the pressure sensor was designed and installed on every bearing unit to detect whether there is contact or overload. According to the pressure sensor signals, monitor the condition of the altitude axis.

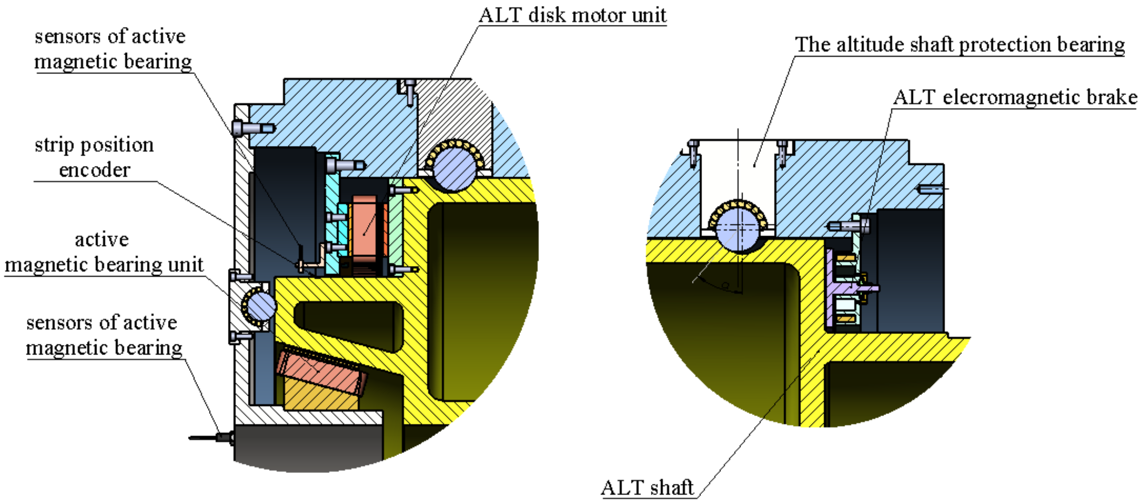

Figure 4. Detailed structure model of altitude drives and bearings systems based on conical active bias magnetic suspension support integrated with disk direct drive motor

7. There are four electromagnetic brake to be symmetrically and uniformly installed to brake urgently under emergency condition. When losing the power, the each brake contacts on the braking surface, braking the altitude axis.

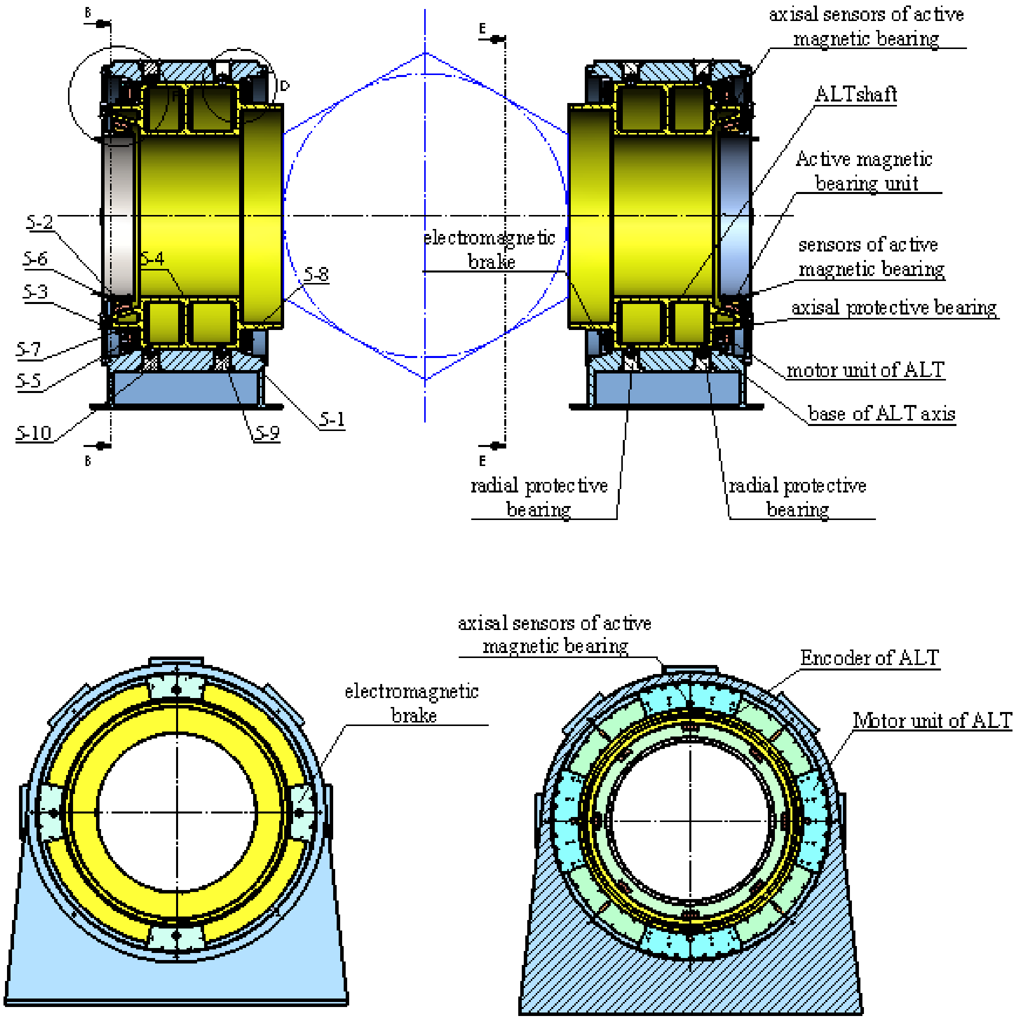

Figure5. Altitude drives and bearings systems based on conical active bias magnetic suspension support integrated with disk direct drive motor

4. CONTROL METHOD OF THE BEARINGLESS MOTOR

4.1 magnetic suspension bearing and control method

Roller bearing system is consisted of active magnetic suspension bearing and protected bearings to restrain 6 DOF (3 DOF of the altitude, 3 DOF of azimuth) and protect the whole telescope when the magnetic suspension bearing fails. According to an optimal design scheme, two symmetric cone active bias magnetic suspension bearing is designed for the ALT axis, while axial-radial active bias magnetic suspension bearing adopt by the azimuth axis. However, cone active bias magnetic suspension bearing could be a choice for the azimuth. Here, the key technology of active bias magnetic suspension bearing is discussed.

Two symmetric cone active bias magnetic suspension bearing is adopted to limit three degrees of freedom of altitude axis, which is mainly consisted of the offset stator, active control coils, rotor and rotor position sensor, each of cone active bias magnetic suspension bearing is integrated biased permanent magnetic bearing with active magnetic bearings unit, sharing a common rotor, while it works, the coil is controlled , according to axial and radial position sensors, to restrain the altitude axis in the central position. The magnetic flux density generated by the permanent magnet and active control coil is equal due to the symmetry of the structure. The axis deviation from the reference position would be generated when there is some disturbance, sensors detect the rotation axis deviation from the reference position offset in the x, y orientation and send this signal to controller. According to space-vector decoding algorithm, the controller turns the signal into current signal I to generate electromagnetic flux in the core, which make the altitude rotation axis return to its original equilibrium position. the rotor could be keep at the equilibrium position by controlling exciting winding current, regulating about the size of the air gap magnetic flux through position feedback of the permanent magnet biased axial magnetic bearing system. In the condition of disturbance.

Voltage - current power amplifier is adopted in the ALT cone active bias magnetic suspension bearing, the closed loop control system block is shown in figure 6. Where, power amplifier is approximately think as proportion scale K_a , eddy current sensor is used for the position sensor, which of transfer function can be approximate think proportional scale K_s .The controller transfer function is scale $K_c(s)$. Traditional PID control is adopted in controller, however, some new modern intelligent control algorithm are explored for more higher performance.

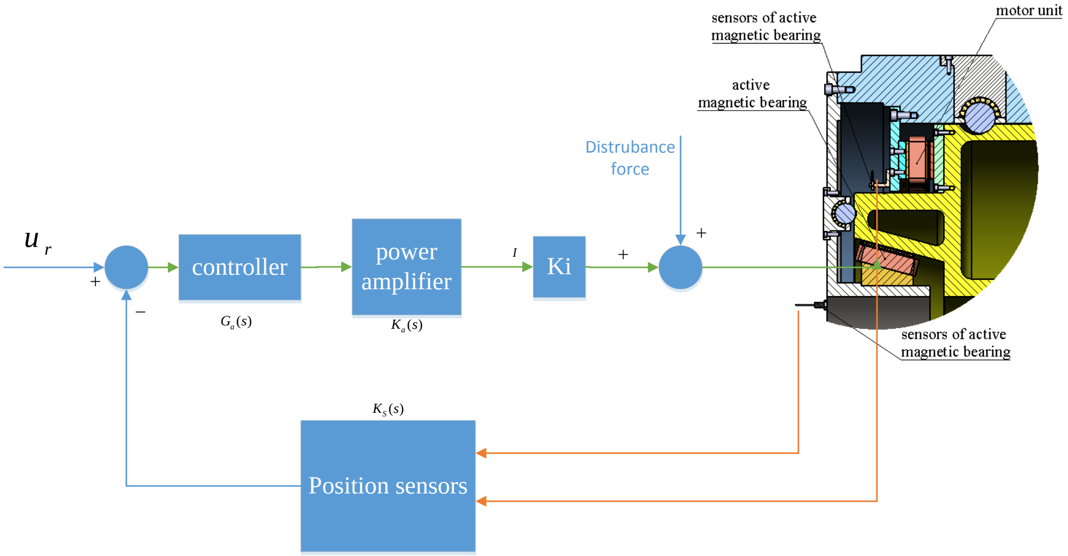

Figure 6. The closed loop control system block of ALT cone active bias magnetic suspension bearing

The suspension stiffness is an important index to characterize the suspension performance of the active bias magnetic suspension system， which is associated with the structural parameters of electromagnetic part, control algorithm, the characteristics of permanent magnet and the structure of the permanent magnet. Every unit of the magnetic bearing force is shown as follows, then the total force is got very easily.

$$F_i = \mu_0 H^2 S = \frac{\mu_0 S\left[Ni + 2\delta_m H_c\right]^2}{4(\delta + \frac{\delta_m S}{\mu_r S_m})^2} \tag{3}$$

$$F=\sum_{i=1}^{M}F_i=M\cdot\mu_0H^2S=M\cdot\frac{\mu_0S\left[Ni+2\delta_mH_c\right]^2}{4(\delta+\dfrac{\delta_mS}{\mu_rS_m})^2} \tag{4}$$

Where, μ_0 - vacuum permeability, μ_r - relative permeability of permanent magnetic materials, H_c - permanent magnet coercivity, S - equivalent magnetic pole area, S_m - cross-sectional area of the permanent magnet, S_m -permanent magnet thickness, δ - suspension gap, H - the intensity of air gap magnetic field, i - the electromagnetic coil current, N -the winding number, M -the number of the magnetic bearing unit, F_i -magnetic force of every unit of the magnetic bearing, F - total magnetic force of the magnetic bearing.

The displacement stiffness of the active bias magnetic suspension system can be obtained by the partial derivative of the total magnetic force of the magnetic bearing F to the suspension gap δ .

$$K_\delta=\frac{\partial F}{\partial\delta}=-M\cdot\frac{\mu_0S\left[Ni+2\delta_mH_c\right]^2}{2(\delta+\dfrac{\delta_mS}{\mu_rS_m})^3} \tag{5}$$

The current stiffness of the active bias magnetic suspension system is expressed by partial derivative of the total magnetic force of the magnetic bearing F to the electromagnetic coil current i .

$$K_i=\frac{\partial F}{\partial i}=M\cdot\frac{\mu_0NS\left[Ni+2\delta_mH_c\right]}{2(\delta+\dfrac{\delta_mS}{\mu_rS_m})^2} \tag{6}$$

So, the stiffness of the active bias magnetic suspension system is expressed as following.

$$K=\frac{\Delta F}{\Delta\delta}=K_\delta+K_i\cdot\frac{\Delta i}{\Delta\delta} \tag{7}$$

The system can be linearized near the balance point (δ_0,i_0), according to function (5), (6), K_δ , $K_i\cdot\dfrac{\Delta i}{\Delta\delta}$ is the function of the structure characteristic of permanent magnet and electromagnetic coil structure. In addition, the suspension stiffness must be positive for a closed-loop stability, we have $K>0$, that is, $\dfrac{\Delta i}{\Delta\delta}>-\dfrac{K_\delta}{K_i}$, near the balance point (δ_0,i_0), magnetic levitation bearing static stiffness is expressed as following:

$$K=M\cdot(\frac{\mu_0\delta_mH_cNS}{(\delta+\dfrac{\delta_mS}{\mu_rS_m})^2}\frac{\Delta i}{\Delta\delta}-\frac{\mu_0NS(\delta_mH_c)^2}{(\delta+\dfrac{\delta_mS}{\mu_rS_m})^3}) \tag{8}$$

For the sectional area of the permanent magnet, the deflection of the suspension stiffness of the permanent magnet is obtained:

$$\frac{\partial K}{\partial S_m}=M\cdot\frac{2\mu_0 H_c\delta_m{}^2 S^2/(\mu_r S_m{}^2)}{(\delta+\dfrac{\delta_m S}{\mu_r S_m})^4}\cdot\left[N(\delta_0+\frac{\delta_m S}{\mu_r S_m})\cdot\frac{\Delta i}{\Delta\delta}-3H_c\delta_m\right] \tag{9}$$

So when $\frac{\Delta i}{\Delta\delta}>\frac{3H_c\delta_m}{N(\delta_0+\dfrac{\delta_m S}{\mu_r S_m})}$, suspension stiffness can be improved by increasing the sectional area of permanent magnet. In the same way, a permanent magnet with a larger relative permeability μ_r can also improve the suspension stiffness.

For permanent magnetic coercive force H_c, we have.

$$\frac{\partial K}{\partial H_c}=M\cdot\frac{\mu_0\delta_m S}{(\delta+\dfrac{\delta_m S}{\mu_r S_m})^3}\cdot\left[N(\delta_0+\frac{\delta_m S}{\mu_r S_m})\cdot\frac{\Delta i}{\Delta\delta}-4\delta_m H_c\right] \tag{10}$$

So, when $\frac{\Delta i}{\Delta\delta}>\frac{4\delta_m H_c}{N(\delta_0+\dfrac{\delta_m S}{\mu_r S_m})}$, improve the suspension stiffness by take the permanent magnet with a larger relative permeability μ_r .

The following useful conclusions are obtained by analyzing and discussing the structure and control method of the active bias magnetic suspension system:

- The suspension stiffness of active bias magnetic suspension system can be improved by modifying and optimizing the size of the permanent magnet or selecting better permanent magnet material. In the condition of fixed electromagnet structure and reasonable value of $\frac{\Delta i}{\Delta\delta}$.
- The performance of suspension stiffness can be significantly improved by increasing the cross-sectional area of permanent magnet in the case of fixing the permanent magnet thickness.
- When the permanent magnet thickness is lower than a certain value, improve the system suspension stiffness by increasing the thickness of the permanent magnet. While the value exceeds the thickness of permanent magnet, weaken the suspension stiffness.
- The suspension stiffness has a direct effect on the control power consumption of the system, increasing the suspension stiffness will greatly reduce the power consumption under certain conditions of fixed controller parameters.
- Increasing the number of bearing unit will provide the suspension stiffness.

4.2 The main axial control method

Some major parameters were considered as the following in modeling the main axis of the large telescope, including the inductance of armature, the resistance of armature, back EMF constant, motor constant, rotor inertia and damping coefficient, and so on. This paper also takes the major nonlinear disturbance, for example, ripple torque, wind buffet and uncertainty of the model.

Suppose the telescope tracking system meets the following conditions: the motor, the rotor shaft and the load have the same viscous friction coefficient and the stiffness of the system is big enough. In order to analyze the performance of the direct drive tracking system, the mathematical model was established as follows.

$$J\frac{d\theta^2}{dt}+B\frac{d\theta}{dt}+K\theta+T_{riple}+T_W=T_e \tag{11}$$

Where, $\theta=\begin{bmatrix}\theta_1 & \theta_2\end{bmatrix}$-Rotor mechanical angle, $T_e=\begin{bmatrix}T_1 & T_2\end{bmatrix}$-Motor electromagnetic torque, J-Inertia of system converted to the motor rotor shaft, B-Viscous friction coefficient of system converted to the motor rotor shaft, K-Stiffness matrix, T_W-Wind disturbance torque, T_{riple}-torque ripple of motor.

Wind disturbance is one of the most common nonlinear disturbance outside of the telescope system. Wind disturbance torque T_W in equation 11 was expressed by Davenport model, which is consisted of the static disturbance T_{const} and the dynamic disturbance $T_{\text{var}y}$, T_{const} and $T_{\text{var}y}$ were descripted respectively in equation 12 , 13.

$$T_{const}=1/2C_T\rho v^2AD \tag{12}$$

$$T_{\text{var}y}=\frac{4K_0v^2(\rho vC_TAD)^2(fK_a/v)^2}{f[1+(fK_a/v)^2]^{(4/3)}} \tag{13}$$

Where, C_T-torque coefficient of wind disturbance, ρ-air density, v-wind speed, A-contact area, D-shaft radius perpendicular to contact area, K_a-Terrain roughness coefficient, $K_0=[0.4/\ln(z_r/z_0)]^2$, z_0-local terrain roughness, z_r-reference height, f - wind frequency.

m phase air-gap flux emf harmonic synthesis v can be expressed as:

$$\begin{gathered}Fv=\frac{\sqrt{2}}{v\pi}K_{wv}wI(mK_{V+}+mK_{V-})\\ K_{V+}=\frac{\sin(v-1)\pi}{m\sin\frac{v-1}{m}\pi}\qquad K_{V-}=\frac{\sin(v+1)\pi}{m\sin\frac{v+1}{m}\pi}\end{gathered} \tag{14}$$

from the equation (14), it can be seen that synthesis air-gap flux emf contains only two groups of component, clockwise and reversal.The clockwise group consists of m equal amplitude and $2\pi(v-1)/m$ electric Angle turn in the space, The reversal group consists of m equal amplitude and $2\pi(v+1)/m$ electric Angle wave form turn in turn in the space; which harmonic is existed or eliminated can be judged by analysing $K_{V+} + K_{V-}$. So there are only the following harmonic waves in the sysetm.

$$v = 2km + 1 \qquad k = 0, \pm 1, \pm 2, \pm 3, \cdots\cdots \tag{15}$$

In three-phase system, because of the interact between air-gap flux emf 5th harmonic wave and base wave, it will generate 6th torque ripple, which has influence on system dynamic and static performance. To elimate 6th torque ripple, one torque ripple minimum PWM algorithm is used in three-phase system. With improving the number of motor phase and mini harmonic, the pulse frequency will become higher and the torque ripple drop dramatically.

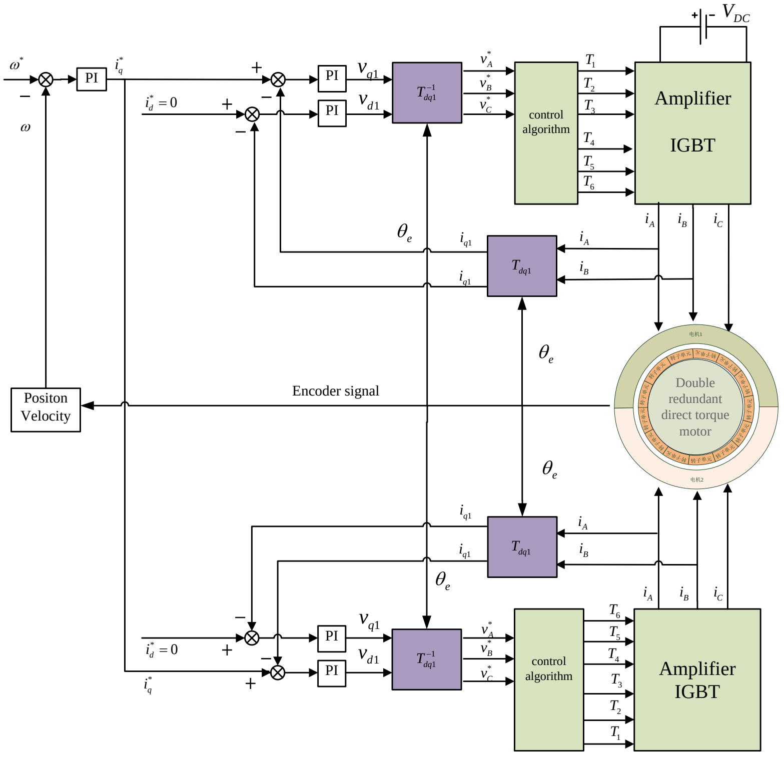

Figure 7. The control structure diagram of the double redundant motor

Suppose direct drive motor meets the following conditions: The air gap in the MMF space is sine distribution; The core eddy current is saturated, hysteresis losses is neglected; The stator winding is symmetric star distribution in space, usually, variable frequency speed regulation of rotor has no damping winding, which mathematical model is shown as following:

$$\psi_d = L_d I_d + \psi_f \tag{16}$$

$$\psi_q = L_q I_q + \psi_f \tag{17}$$

$$u_d = r i_d + L_d p i_d - \omega L_q i_q \tag{18}$$

$$u_q = ri_q + L_q pi_q + \omega L_q i_q + \omega \psi_f \tag{19}$$

$$T_e = np[\psi_f i_q + (L_d - L_q) i_d i_q] \tag{20}$$

Where, p -differential operator, L_d - stator winding's equivalent inductance of the axis d, L_q - stator winding's equivalent inductance of the axis q, T_L- load torque; ω_r -the rotor mechanical angular velocity.

Double redundant drive system is realized by two redundant motor units unit that each can meet the requirement of the telescope. The two redundant unit motors can be run synchronously or separately. When the two motors are running synchronously, more powerful drive force is obtained to accelerate to change the observation target stably. The control structure diagram is shown in figure 7.

5. CONCLUSIONS

This paper proposes large astronomical telescope tracking system based on active bias magnetic suspension support integrated with direct drive motor, which integrated with active magnetic suspension bearing with direct drive motor. Some key technology and the optimization process are discussed by multidisciplinary optimization design method, make the design criteria and the modular design idea, and provide global optimal solution for the modern large telescope tracking system.

Two different magnetic suspension bearing and direct drive solutions ideas are studied for azimuth and altitude axis, then discuss the active magnetic suspension bearing, the spicing unit motor, protected auxiliary bearing, heat radiator and cooling system and encoder technology in detail.

The suspension stiffness problem of the hybrid magnetic bearing with electro and bias permanent magnets is one of the important indicators to characterize the magnetic levitation performance. Based on the levitation mechanics model, the paper presents the constraint relation between levitation stiffness and the structural and material property of permanent magnets. Furthermore, the relation between levitation stiffness and controller parameters is also analyzed.

The dynamic equation, considering some nonlinear disturbance, of the telescope tracking system with active bias magnetic suspension support integrated with direct drive motor is explored and established, which of control scheme is also discussed. By magnetic suspension bearing and direct drive technology, simplify the telescope rack's structure, reduce the mechanical assembly requirements, improve the reliability, which make the telescope tracking system have many advantage such as free maintenance, no friction, low power consumption, excellent acceleration performance. The technology will provide a new solution for the large telescope tracking system.

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