Azimuth Control for Large Aperture Telescope Based on Segmented Arc Permanent Magnet Synchronous Motors

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Abstract A tracking control algorithm based on active disturbance rejection controller (ADRC) is proposed to overcome the telescope’s mount fluctuation. The fluctuations are caused by internal and external disturbance when the large aperture telescope runs at ultra-low speed with direct drive. According to the high-precision and high-stability requirements of the large aperture telescope, the ADRC position controller is designed based on the segmented arc Permanent Magnet Synchronous Motors (arc PMSM). The tracking differentiator of ADRC is designed to arrange a transition process to avoid overshoot in the position loop. The speed of target tracking process is observed by the extended state observer and the position information in the system is estimated in real time. The current control variable of the segmented arc PMSM is generated by using non-linear state error feedback control law. The simulation results demonstrate that the proposed control strategy can not only accurately estimate the position and speed of tracking target, but also estimate the disturbance to compensate the control variables. Experiments showed that the speed error is less than 0.05”/s when use the ADRC, and it can realize the high tracking performance when compared with PID controller, which improves the robustness of large aperture telescope control system.

Key words: techniques: telescopes — instrumentation: miscellaneous: — methods: miscellaneous: — techniques

1 INTRODUCTION

The control systems of large aperture ground-based telescopes differ somewhat from those of small/space telescopes because of the different nature of disturbances encountered. It is hard to ignore the external and internal disturbances for the large aperture optical telescope. Disturbances include external torques such as those due to wind or space environment and internal torques like backlash, friction in the bearings, cogging torque and changes of the moment of inertia in the telescope and instruments (Bely 2003).

The large aperture telescope servo control system should resist the disturbance torques that mentioned above to overcome the tracking jitter to ensure higher tracking performance. In recent years, many

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large aperture optical/infrared telescopes were constructed in the world, and the segmented permanent magnet arc motors were adopted as the optimal drive solution, such as the Very Large Telescope (VLT) (Leonardi et al. 1994) and the Gran Telescopio Canarias (GTC) (Cavaller & Siegel 2006). The European Extremely Large Telescopes (E-ELT), when completed, will be the world’s largest optical/infrared telescope. It also plans to use the segmented motors to drive the telescope axes because of the acquired experience of VLT and ALMA (Giacomel et al. 2008). All telescopes that are mentioned above choose the segmented discs-shaped arc motors as the mount drive, because they have large output torques and their thrust is distributed along the structure, they can reduce installation time and improve the reliability and maintainability.

To collect more visible light to learn faint celestial bodies, designs for next-generation extremely large optical telescopes with primary mirror diameters ranging from 20 to 100m have been developed. They are always found at high mountains, deserts, island, Antarctica or other harsh environments. Also, when telescopes become larger and larger, they have voluminous bodies, vulnerable servo stiffness and the lower resonant frequencies. In addition, more additional structures are needed for accurate observation. Therefore, they are very sensitive to the disturbances. For a long time, researches have focused on the Proportional-Integral-Derivative (PID) controller in many telescopes. VLT constructed PI controller with feed-forward and some filters in angular velocity loop and position loop (Ravensbergen 1994). The position controller of SUBARU telescope used a P controller to adjust the tracking position according to the size of the error (Kanzawa et al. 2006). GTC selected a feed-forward with PI and a second order Butterworth filter in amplifier current loop to avoid unacceptable current noise amplification, a dual-feedback PI controller with velocity and acceleration feed-forward actions and proportional damping, also includes some filters in the position loop (Suárez et al. 2008). PI and Linear-Quadratic-Gaussian (LQG) are used in the NASA Deep Space Network antenna control systems of the main axes to compensate the antenna-pointing errors (Gawronski 2001). A fuzzy adaptive PID was studied to suppress the vibrations in system of telescope axes’ drive (Lukichev & Demidova 2016). In their studies, the PID controller with feed-forward was widely used for the angular velocity control because of its simplicity. However, the VLT is difficult to resist wind disturbances, the GTC is ineffective to control disturbance caused by extremely fluky wind and other uncertain sources that suddenly appear.

So, it is difficult to achieve high precision by using the classical PID controller for a large aperture telescope because of its complex structure, the unknown wind disturbance and friction non-linear disturbance. It is necessary to find an efficient method that can improve the tracking performance for the large aperture telescopes. In this studies, a large aperture telescope tracking control system, ADRC, is designed to make the system more robust and less dependent on the detailed mathematical model of the physical process. It can estimate and compensate for unknown dynamics and disturbance in real time, such as the change of the inertia moment of the motor and wind disturbance.

2 STRUCTURE OF SEGMENTED ARC PMSM

2.1 Structure of drive system

To solve the disturbance and the stabilization problems on the main axes control system, pre-research work about 4.2-meter segmented arc PMSM is carried out according to the azimuth characteristics of the large aperture telescope. Fig. 1 is the distribution of segmented arc PMSM. It is a large torque motor, powered by the segmented motors, supported by hydraulic bearings. The whole platform is composed of 16 sub-motors, includes 12 motors and 4 tachometer generators, any of the sub-motor can work separately. It has cylindrical-shaped rotors and radial flux, so it has the traits of curved motors. Fig. 2 shows the general view of 4.2-meter segmented arc PMSM. The parameters of the motor are shown as Table 1. Erm & Seppey made a comparison about the useful torque and its ripple between segmented discs-shaped arc motors and segmented cylindrical-shaped curved motors. The results of comparison showed that the cylindrical-shaped segmented arc PMSM has the greater useful torque, smaller cogging torque than the discs-shaped arc motor of the same size (Erm & Seppey 2006). The conceptual design architecture of large aperture telescope is shown in Fig. 3, the details of the structure can be seen at
Table 1: Parameters of Segmented Arc PMSM.

<table>
<thead>
<tr>
<th>No</th>
<th>Motor Item</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Peak torque</td>
<td>87</td>
<td>KN·m</td>
</tr>
<tr>
<td>2</td>
<td>Rated Torque</td>
<td>43.5</td>
<td>KN·m</td>
</tr>
<tr>
<td>3</td>
<td>Back EMF Constant</td>
<td>90</td>
<td>Kv/Krpm</td>
</tr>
<tr>
<td>4</td>
<td>Torque Constant</td>
<td>1500</td>
<td>N·m/A</td>
</tr>
<tr>
<td>5</td>
<td>Rotor Inertia</td>
<td>18000</td>
<td>kg·m²</td>
</tr>
<tr>
<td>6</td>
<td>Electrical Inductance</td>
<td>1.2</td>
<td>H</td>
</tr>
<tr>
<td>7</td>
<td>Electrical Resistance</td>
<td>20</td>
<td>Ω</td>
</tr>
<tr>
<td>8</td>
<td>Diameter</td>
<td>4.2</td>
<td>m</td>
</tr>
</tbody>
</table>

The reference of "Mechanisms for the elevation structure of a giant telescope" (Hu et al. 2018). The azimuth and elevation structure includes the primary mirror, the secondary mirror, the tertiary mirror and instruments.

Fig. 1: Distribution schematic of segmented arc PMSM. Fig. 2: 4.2-meter segmented arc PMSM general view.

Fig. 3: Conceptual design architecture of large aperture telescope.
2.2 Mathematical model of Segmented arc PMSM

According to the theory of PMSM, 3-phase static reference is converted to \( d-q \) (Direct axis - Quadrature axis) synchronous rotate reference by \( abc - dq \) convert matrix. If a field oriented control strategy is adopted, the axes two-phase synchronous rotate reference is utilized to develop segmented arc PMSM equations. The mathematical model of PMSM is derived under the assumption that saturation, eddy-current high-order harmonic components are negligible, the stator windings are symmetric in space and that the stator currents produce sine magnetic motive forces. According to these assumptions, the differential equations of currents and electric angular velocity can be expressed as equation (1) in \( d-q \) synchronous rotate reference coordinate when the segmented arc PMSM is in a steady state.

\[
\begin{align*}
\frac{di_d}{dt} &= \frac{1}{L_d} u_d - \frac{R_s}{L_d} i_d + \frac{1}{L_d} \omega_r i_q \\
\frac{di_q}{dt} &= \frac{1}{L_q} u_q - \frac{R_s}{L_q} i_q + \frac{1}{L_q} \omega_r i_d - \frac{1}{L_q} \omega_r \psi_f \\
\frac{d\omega_r}{dt} &= \frac{1}{J} p_n \psi_f i_q + \frac{1}{J} p_n (L_d - L_q) i_d i_q - \frac{1}{J} T_L - \frac{1}{J} B \omega_r
\end{align*}
\]  

(1)

Where \( i_d, i_q, u_d, \) and \( u_q \) are stator currents and voltages, respectively, in \( d-q \) synchronous rotate reference coordinate, \( L_d \) and \( L_q \) are \( d-q \) axes inductances, \( R_s \) is the stator armature resistance, \( \omega_r \) is the electrical angular velocity of the rotor, \( \psi_f \) is rotor flux, \( J \) is the moment of inertia, \( B \) is the viscous friction coefficient, \( T_L \) is the load torque and \( p_n \) is number of pole pairs.

From the differential equation the electric angular velocity, we can notice that velocity is influenced by the variables of stator current \( i_d \) and \( i_q \), the load torque \( T_L \) and the viscous friction coefficient \( B \). If the \( i_d = 0 \) strategy is adopted, the control structure of segmented arc PMSM is shown in Fig. 4. The Equation (1) can be simplified into

\[
\begin{align*}
\frac{di_d}{dt} &= \frac{1}{L_d} u_d - \frac{R_s}{L_d} i_d - \frac{1}{L_d} \omega_r \psi_f \\
\frac{di_q}{dt} &= \frac{1}{L_q} u_q - \frac{R_s}{L_q} i_q - \frac{1}{L_q} \omega_r \psi_f \\
\frac{d\omega_r}{dt} &= \frac{1}{J} p_n \psi_f i_q + \frac{1}{J} p_n (L_d - L_q) i_d i_q - \frac{1}{J} T_L - \frac{1}{J} B \omega_r
\end{align*}
\]  

(2)

3 ADRC IN SEGMENTED ARC PMSM

The proposal of ADRC technology is derived from overcoming disadvantage of PID control theory and creating a system to achieve high dynamic performance. Professor Han put forward the new concept of "Abandoning the old concepts of linearity and non-linearity, giving full play to the power of feedback". In recent years, it has established itself as a powerful control technology in dealing with the vast
internal and external uncertainties disturbance in control engineering. It can reject disturbance before it
hurts. Researches show that it can adjust for changing variables and cancel the effects of disturbance.
Theoretical system of the ADRC consists of three parts which are the tracking differentiator (TD), the
extended state observer (ESO), and the non-linear state error feedback control law (NLSEF) (Han 2009;
Zhang & Han 2000; Ye et al. 2017).

3.1 Tracking Differentiator

For a non-linear second order system, with unknown disturbance, the state space equation of uncertain
object is as follows

\[
\begin{align*}
\dot{x}_1 &= x_2 \\
\dot{x}_2 &= f(x_1, x_2) + w(t) + bu \\
y &= x_1
\end{align*}
\]  

(3)

where \( f(x_1, x_2) \) is an unknown system, \( w_t \) is an unknown disturbance, \( u \) is the input signal of the
system, \( b \) is the gain of input signal and \( y \) is the output of the system.

In order to solve the defects of classic differentiators, a transient process is necessary, here it is
called TD. The TD introduces the idea of fastest control to track the input signal and then differentials
the tracking signal to obtain the approximate differential of the input signal. In addition to obtaining
a high quality differential signal, it also has strong noise rejection ability and small phase lag, which
solves the problem of noise amplification. The tracking of a step signal can sometimes enter the steady
state without overshoot at a limited time. For a second order system, a discrete system is derived as

\[
\begin{align*}
\dot{r}_1(k + 1) &= r_1(k) + h \cdot r_2(k) \\
\dot{r}_2(k + 1) &= r_2(k) + h \cdot f_{han}(r_1(k) - v(k), r_2(k), \delta, h_1)
\end{align*}
\]  

(4)

where \( v(k) \) is the input signal at \( k \) time, \( r_1(k) \) is the estimation of the input signal at \( k \) time, \( r_2(k) \) is the
estimation of the differential of the input signal at \( k \) time, \( \delta \) and \( h_1 \) are controllers parameters, \( h \) is the
sampling step length (\( h_1 > h \)) and \( f_{han}(\cdot) \) is the fastest control function, it can be described as

\[
f_{han}(\cdot) = -\delta \begin{cases} 
\frac{a}{d} & |a| \leq d \\
\text{sgn}(a) & |a| > d
\end{cases}
\]  

(5)

where \( \text{sgn}(\cdot) \) is the sign function, \( a \) and \( d \) are means of

\[
\begin{align*}
d &= \delta h, \quad d_0 = dh, \quad y = r_1 + hr_2 \\
a &= \begin{cases} 
\frac{r_2 + \text{sgn}(y) \cdot (a_0 - d)/2 |y|}{y} > d_0 \\
\frac{r_2 + y/h |y|}{d} \leq d_0 \\
a_0 &= \sqrt{d(d + 8\delta |y|)}
\end{cases}
\end{align*}
\]  

(6)

Equation (4) is a time optimal solution that guarantees the fastest convergence from \( r_1(k) \) to \( v(k) \) and
\( r_2(k) \) to \( \dot{v}(k) \), respectively. Also, the differentiator can filter the noise when \( v(k) \) is a signal with some
noise.

3.2 Extended State Observer

ESO, which was proposed by professor Han, is such a method that can filter the output signal, reduce
the influence of sensor noise, estimate the differential of the output signal and can estimate all the
disturbances that affect the output of system. For the large aperture telescope, the tracking accuracy
greatly depends on the quantities of total disturbances estimated by the ESO.

For a system as equation (3), it can be supposed that \( x_3 = f(x_1, x_2) + w(t), \) \( u = (u_0 - a(t))/b. \)
Here, \( a(t) \) represents the combined effect of internal dynamics and external disturbance, i.e., the total
disturbances. However, it is very difficult to know the exact value of \( a(t) \) in practical engineering. Then,
a new extended variable is equivalent to the total disturbance, which is always observable, and the plant can be built as

\[
\begin{align*}
\dot{x}_1 &= x_2 \\
\dot{x}_2 &= x_3 + bu \\
\dot{x}_3 &= a(t) \\
y &= x_1
\end{align*}
\]

(7)

Now, according to non-linear feedback effect, a state observer is constructed and ESO of the plant is expressed as

\[
\begin{align*}
e &= z_1 - x_1 \\
z_1 &= z_2 - \beta_1 \text{fal}(e, \alpha_1, \delta) \\
z_2 &= z_3 - \beta_2 \text{fal}(e, \alpha_2, \delta) + bu \\
z_3 &= \beta_3 \text{fal}(e, \alpha_3, \delta)
\end{align*}
\]

(8)

where \( \beta_i \) is observer gains, there are many ways to select the values of the parameter, \( y \) is the output of the system, \( z_1(t) \) and \( z_2(t) \) are the observed state variables of ESO and \( z_3(t) \) is the total disturbance of the system observed by ESO. The \( \text{fal}(\cdot) \) is the saturation function whose function is to inhibit signal chattering, in form of

\[
\text{fal}(e, \alpha, \delta) = \begin{cases} 
\frac{e}{\delta}, & |e| \leq \delta \\
|e|^{\alpha} \text{sgn}(e), & |e| > \delta
\end{cases}
\]

(9)

where \( e \) is the difference between output and input, \( \alpha \) is the linear factor and \( \delta \) is the filter coefficient. When \( \alpha < 1 \), the function of \( \text{fal}(\cdot) \) has the characteristics of small error with large gain and large error with small gain to make the controller more efficient.

As long as the total disturbance is bounded, ESO can effectively estimate the state of the system, that is \( z_1(t) - > x(t), z_2(t) - > \dot{x}(t) \) and \( z_3(t) - > a(t) \).

3.3 Non-linear State Error Feedback Control Law

The NLSEF control law is developed from error feedback of the classical PID control method, which is independent on the nominal mathematical model. The NLSEF control law deals with the difference between the tracking signal generated by the TD and the differential signal of each order and the estimated value of the state variable generated by ESO, and combines it with the estimated value of the total disturbance of the system by ESO to form the control quantity of the system. Furthermore, it needn’t eliminate the steady error caused by the external disturbance and avoid the disadvantages such as phase lag, saturation and overshoot caused by integration. For a second order system, the control variable can be described as

\[
\begin{align*}
e_1 &= x_1 - z_1 \\
e_2 &= x_2 - z_2 \\
u_0 &= \beta_{01} \text{fal}(e_1, \alpha_1, \delta) + \beta_{02} \text{fal}(e_2, \alpha_2, \delta) \\
u &= u_0 - z_3/b
\end{align*}
\]

(10)

According to the theory of ADRC, the large aperture telescope position controller is designed as Fig. 5. Here, \( \theta \) is the target tracking position of the telescope, \( \theta^* \) is the target’s reference position, \( \dot{\theta} \) is the estimated target’s position through TD, \( \dot{\theta} \) is the tracking angular velocity and \( z_3 \) is the disturbance of the tracking position. In the light of the angular velocity being in differential of the position, if \( i_q \) is the control variable, the dynamic mathematical models of position loop can then be governed by an equation of a second-order, the form is

\[
\frac{d^2\theta}{dt^2} = \frac{d\omega}{dt} = \frac{1}{J} \psi \psi' i_q - \frac{1}{J} T_L - \frac{1}{J} B \omega_r
\]

(11)
Define the position of the segmented arc PMSM $\theta_1 = x_1$ and $\omega_r = x_2$, here, $\theta$ is detected by the tape encoder, suppose that $f(x_1, x_2, t, w(t)) = -B\omega_r/J - T_L/J$ and $y = x_1$. Because of $\dot{\theta} = \omega_r$, so the non-linear state equations of segmented arc PMSM rotor position are

$$\begin{align*}
\dot{x}_1 &= \omega_r = x_2 \\
\dot{x}_2 &= f(x_1, x_2, t, w(t)) + bu = a(t) + bi_q \\
y &= x_1
\end{align*}$$

(12)

where $a(t) = -B\omega_r/J - T_L/J$, $b = p_n\Psi_f$. According to the ADRC theory, the equation (8) and (10) can be used as ESO and NLSEF control laws.

4 SIMULATION AND EXPERIMENT

The segmented arc PMSM position servo control system is a double loop to estimate the position of the large aperture telescope and the result of its differential (i.e. the angular velocity). A sinusoidal photoelectric scanning tape encoder with distance-coded absolute reference marks is used for azimuth axis position feedback.

For the large aperture telescope, it is difficult to achieve accurate position and real-time estimation of the disturbance because of its large moment of inertia and its non-linear dynamic characteristics. Meanwhile, the tracking signal of position will lag the input signal when the frequency is high, and the unknown disturbance are also lagged. Therefore, the steady state precision of the system will be influenced. Fig. 6 shows the simulation results of position and the estimation of the tracking angular velocity when the input signal’s frequency is different. It can be seen that the response bandwidth of the position loop is very narrow because of the large quality and moment of inertia.

To demonstrate the performance of the ADRC controller, several experiments have been done between the PID and ADRC controller based on 4.2-meter segmented arc PMSM. Fig. 7 is the hardware of drive and control system for the segmented arc PMSM. Fig. 8 shows the comparison of two methods that the position and speed tracking performance when the objective speed is 1.5"/s. It can be observed that the speed error is bigger than 5"/s when the controller is PID and the speed error is less than 0.05"/s when the controller is ADRC. Also, the PID and $H\infty$ were experimented in the same laboratory on the same plant, the results can be seen in the “$H\infty$ controller design for a 4-meter direct-drive azimuth axis” (Chen et al. 2015).

5 CONCLUSIONS

For recent years, the ADRC theory has stood out among various control system due to its advantages for a complex uncertain physical system. In this paper, the proposed control strategy (i.e. ADRC) estimates the position of tracking target without nominal mathematics model of the segmented arc PMSM and the total disturbance for the large aperture telescope. The results show that ADRC can ensure the robustness and adaptability under mathematics uncertainties if the total disturbance is unknown. It can observe the position of segmented arc PMSM and estimate the angular velocity and position of the tracking target.
(a) When the frequency of input signal is 5Hz.  
(b) When the frequency of input signal 0.1Hz.

Fig. 6: Simulink of Position and speed tracking of ADRC.

Fig. 7: The hardware of drive and control.

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Fig. 8: Actual position and speed tracking performance under PID and ADRC in the case of 1.5°/s reference speed.