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Research on Influence of Eccentricity on Submersible Motor and its Solution

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Abstract: The working efficiency and stability of submersible motor are very important for energy utilization, and dynamic eccentricity is the main factor affecting its efficiency and fatigue life. This paper takes a 2-pole 60kW vertical three-phase cage induction motor with static eccentricity as the research object. Through finite element analysis, the mechanical structure and coordination of submersible motor shaft and spiral pump are analyzed. The influence caused by motor shaft eccentricity is regarded as external interference received by the system. The idea of auto disturbance rejection controller to eliminate this disturbance, thereby restraining the negative effects caused by motor shaft eccentricity. By using the state expansion observer of the active disturbance rejection model to estimate and compensate the internal disturbance and uncertainty of the system in real time, the rotation error of the shaft of the submersible motor is eliminated, and the motion inconsistency between the rotor of the screw pump and the shaft of the submersible motor caused by shaft eccentricity is suppressed.

Keywords: Finite Element Calculation; Dynamic and Static Eccentricity; Submersible Motor; Active Disturbance Rejection Control.

1. Introduction

Although oil is currently an important energy source that the country urgently needs for economic development, most oil fields have entered or are about to enter the medium to high water cut stage. In modern industrial production, submersible motors have the characteristics of high efficiency and high power. However, due to the limitations of assembly and pricing processes in actual production, the problems of incomplete overlap of rotor axes and uneven distribution of air gaps have occurred, resulting in adverse effects such as noise, rotor loss, and torque pulsation. Moreover, submersible pumps operate in complex and harsh underground environments. Once a fault occurs, the maintenance cost is expensive, causing great economic damage to it. Therefore, this article analyzes the structure of the submersible motor and studies the reasons for its formation and impact, and then compensates for eccentricity through the self-disturbance rejection model to achieve the goal of elimination.

2. Submersible Motor Structure

The design of an electric submersible pump mainly includes three modules: the pump unit, grounding electrical devices, and power cables. The so-called submersible pump is actually an important component of the submersible pump, which is the underground submersible pump unit [1]. It is a rodless Pumpjack composed of motor, protector, separator and centrifugal pump. It is mainly composed of four parts: motor, protector, separator and centrifugal pump. Submersible motor is a special three-phase asynchronous motor that operates vertically, with a slender structure. The stator and rotor adopt a segmented structure, and each two segments of the stator and rotor are equipped with magnetic isolation sections and centering bearings.

In submersible hydropower, the submersible motor is the most precise component. Currently, a three-phase squirrel cage three-phase asynchronous motor is used. The Submersible is vertically suspended and consists of stator, rotor, thrust bearing, centralized bearing and other components. Each section is 1.5~10m long. Adopting a high capacity, multi-level series structure. There are two types of stator slots, namely closed and semi closed, while submersible motors use a through coil structure.

3. Eccentricity Effect of Submersible Motor Shaft

3.1. Hardware Fatigue Impact

In the oil production system, a submersible motor needs to work continuously for one cycle. During the working cycle, the eccentricity of the rotor of the Screw pump and the shaft of the submersible motor will increase the circulating load, causing tiny cracks in the keyway and other parts of the submersible motor structure. This will linearly increase the damage process of the submersible motor. The initial load pressure will produce local stress points, and the stress point return stroke will lead to mesh fatigue fracture. Later, there will be material cracks under normal stress, Metal materials can also cause slip band deformation, which increases the cyclic load. Under the cyclic stress of the load, mechanical damage can occur to the hardware, affecting the fatigue life of the submersible motor and the working efficiency of the oil extraction system [2].

3.2. Impact of Rotor Eccentricity on Output Torque

Eccentricity widely exists in generators and motors due to manufacturing and installation errors, deviation of guide bearings, deformation of stator cores, and other reasons, resulting in uneven air gaps between the stator and rotor (large air gap on one side and small air gap on the other side). According to different eccentricities, air gap eccentricity can be divided into static eccentricity (with the minimum air gap position fixed), dynamic eccentricity (with the minimum air gap position changing with the rotation of the rotor), and mixed eccentricity (with both static and dynamic eccentricities) [3].

The eccentricity of the rotor has a very significant impact on the air gap of the submersible motor, which in turn changes the distribution of the internal air gap of the motor, which will have a significant impact on the output performance and energy conversion of the motor. Through the basic finite element numerical simulation of the electric motor, the effect of the rotor off axis on its torque was studied. Due to the relatively small local variation of this torque, the number of slots corresponds to the frequency of vibration, and therefore the influence of slots can cause some torque changes. The excitation magnetic field of the magnetic pole formed by harmonic magnetic field and coil distribution factor has a significant impact on the torque variation of the motor [4]. The results indicate that in the trend of torque variation of the electric motor, both the fluctuation and variation of torque tend to decrease.

Torque can be divided into two categories: static torque and dynamic torque. Static torque is a type of torque that does not change over time and does not experience significant torque. It includes static torque, constant torque, slow torque, and micro pulsation torque [5]. The value of static torque is a constant, which represents the torque magnitude when the drive shaft does not rotate, and when the drive shaft rotates evenly, the torque magnitude is also a constant, such as the torque of an electric motor in steady-state operation; However, in the short term, the instantaneous fluctuation of torque is relatively large, while the instantaneous fluctuation of torque is relatively small. Dynamic torque is a type of vibration torque that significantly changes over time, including vibration torque, transient torque, and arbitrary torque [6]. The torque of the system is a periodic fluctuation of the torque during the transition from working state, which is an uncertain and irregular rotational torque. The variable relationship between torque and slip is shown in Figure 1.

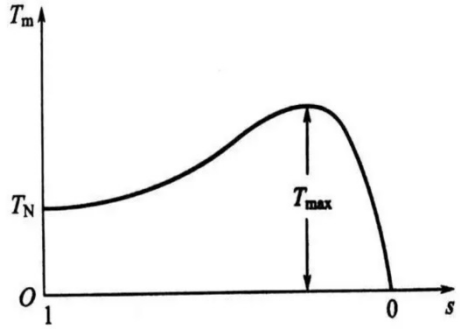


Fig 1. Variable relationship between torque and slip

Various torque testing methods have been adopted for different working conditions.

The torque calculation formula is as follows:

$$S \propto R_2 \tag{1}$$

$$M = CU_1^2 \tag{2}$$

$$S(m) = R_2 / X_{20} \tag{3}$$

Among them, C is a constant related to the characteristics of the motor itself; U_1 is the input voltage; R_2 is the rotor resistance; X_{20} is the rotor leakage reactance; S is the slip rate; $S(m)$ is the critical slip rate.

According to equation (2), the torque is proportional to the square of the supply voltage, and when the input voltage is M_2, the electromagnetic torque M decreases due to a decrease in voltage; When M_2 remains unchanged, the balance of M is smaller than that of M_2, which reduces the speed of the motor, increases the slip rate S, and also changes the voltage balance formula of the rotor, causing the rotor current I_1 to increase. The stator current I_1 (known from the mutual relationship of the transformer) correspondingly increases. At this point, the speed of the motor tends towards a new level of stability. Usually, the resistance value of the rotor circuit is $R_2 = X_{20}$, $S(m) = 1$, and the maximum slip is generated at the moment of starting, which shortens the starting time, reduces the current, and reaches the maximum starting torque.

3.3. Effect of Eccentricity on the Fatigue Life of Submersible Motor Shafts

Due to its own structure, operation, and adjustment characteristics, the stator screw of a submersible motor will undergo significant deformation under high pressure, and at the same time, the screw of the bearing shell will also undergo significant deformation. Due to the deformability of rubber, the large deformation of bearings is mainly to increase the axial movement of the motor, thereby increasing the eccentric motion of the motor [7]. Under the action of centrifugal force, the Screw pump rotor will produce a certain amount of eccentricity when matching with the main shaft of the submersible motor, which will cause the Screw pump to bear the eccentric load of the submersible motor. The appearance of Screw pump rotary pumping unit is directly related to the working life of submersible motor [8].

3.4. Impact of Rotor Eccentricity on Losses

The eccentricity of the rotor can lead to uneven distribution of air gap magnetic density, resulting in fluctuations in output torque, and the uneven distribution of air gap magnetic density has a significant impact on losses. Although the static and dynamic eccentric air gap magnetic fields have the same magnetic field distribution in a static state, the uneven and different forms of air gap magnetic density distribution caused by eccentricity in dynamic operation also have significant differences in losses. After calculating the results of dynamic and static eccentricity on motor losses, static eccentricity is more pronounced than dynamic eccentricity on rotor losses. Therefore, the study of the mechanism is very important for the changes in the development law, and the analysis of the eddy current loss mechanism focuses on the study of its changing air gap magnetic field. At any position on the motor rotor, the maximum magnetic density changes. As both the increase and decrease of magnetic density occur at the position where the length of the motor air gap changes, the length of the air gap remains unchanged in the spatial distribution of the motor during static eccentricity. Therefore, no matter how the rotor rotates, it is subject to changes in the air gap magnetic field, while the spatial distribution of eddy current density remains unchanged. During the rotation process, the length of the dynamic eccentric air gap will change, but the impact on it at the rotor is not as significant as the change in static eccentricity [9]. Usually, when the rotor is statically eccentric at any position, the length of the air gap generated on the surface does not change. Therefore, dynamic eccentricity lacks some of the eddy current losses caused by different air gap lengths compared to static eccentricity. Due to the reduction of eddy current losses, the losses generated

by dynamic eccentricity are not as significant as those generated by static eccentricity.

4. Finite Element Analysis of Submersible Motor

Generally, finite element methods are used to solve electromagnetic problems. For solving computer problems, any solving problem must discrete the boundary value problem, Initial value problem and other problems, and convert them into a finite Linear algebra equation [10]. Firstly, a mesh segmentation was performed on the solving region, replacing the continuous region with a finite number of mesh nodes; Secondly, the Differential operator is Discretization, which makes the problem become the solution of a class of Linear algebra equations. The main difference between the two methods is that they are Discretization in the second step [11]. The corresponding Linear algebra equation is derived from the variational equation in the problem-solving problem using Ritz Galerkin method, but the basic function must be selected in a certain way.

The Screw pump body of QYZQYB75-27 specification is selected for numerical simulation with FEM software, so that it can get different shapes in the finite element numerical simulation, so that it can reflect the changes of displacement, stress and strain to a certain extent. The deformation amount is 0.031317 millimeters, and the rubber material can withstand the pressure of this deformation. The simulation is shown in Figure 2.

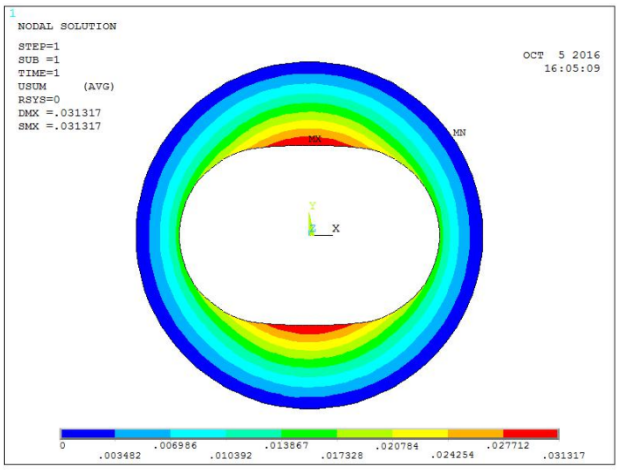


Fig 2. Stator displacement diagram

5. ADRC Eliminates the Eccentricity Error of Submersible Motor

5.1. Composition of ADRC

Active Disturbance Rejection Control (ADRC) is mainly composed of three parts:

(1) Tracking differentiator (TD);

(2) Extended State observer (ESO);

(3) Nonlinear state error feedback control law (NSEFL).

The working principal box is shown in Figure 3:

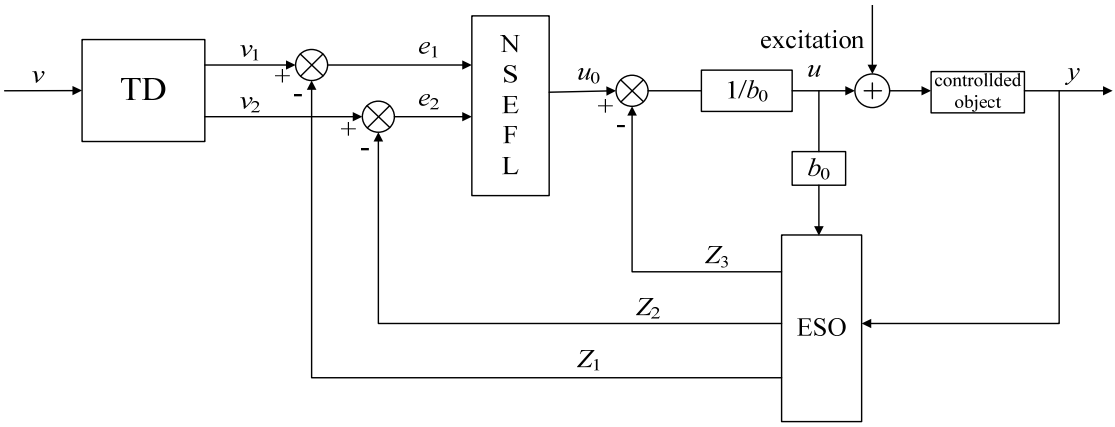


Fig 3. Active disturbance rejection controller schematic diagram

5.2. Tracking Differentiator

Since Active disturbance rejection control does not depend on the mathematical model of the system, the disturbance of the whole system can be estimated by using the extended State observer, and the compensation value in the controller can be used for effective compensation, so as to achieve better suppression effect [12]. ADRC has strong resistance to uncertain effects, so you can refer to mathematical models instead of relying solely on them, so its control objects can be widely used. In addition, the algorithm has a simple structure, easy parameter adjustment, and good dynamic performance.

By using a tracking differentiator to correct the shaft transformation of the submersible motor, sudden changes in the input signal can be made, thereby reducing the conflict between speed and overshoot in PID technology. This method utilizes signals from submersible motors for detection, effectively overcoming the problems that are difficult to achieve in practical applications and avoiding noise amplification; And a more efficient nonlinear combination method was adopted instead of simple weighted summation, significantly improving the efficiency of feedback.

ADRC system with n-order nonlinear system:

$$\begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = x_3 \\ \cdots\cdots \\ \dot{x}_{n-1} = x_n \\ \dot{x}_n = f(x_1, x_2, \ldots, x_{n-1}, x_n, t, \omega(t)) + b(u) \\ y = x_1 \end{cases} \tag{4}$$

Among them, x_n is system state variable; y is system output variables; u is system control variables; f is System uncertainty factors; $\omega(t)$ is unknown external interference.

The essence of this method is to estimate the dynamic disturbances of the entire system in real-time and compensate them dynamically. An extended State observer is used to estimate the total interference by introducing interference and

compensate it in real time, so that the complex system containing uncertainty and unknown interference becomes "integral series type". This controller has good adaptability and does not need to be designed according to the corresponding mode of the object.

5.3. Expansion State Device

The application of the expansion state controller is suitable for controlling the motion parameters of the submersible motor shaft, and the expansion observer is shown in the following equation:

$$\begin{cases} e = z_1 - y \\ \dot{z}_1 = z_2 - \beta_{01}\varphi_1(e) \\ \dot{z}_2 = z_3 - \beta_{02}\varphi_2(e) \\ \cdots\cdots \\ \dot{z}_n = z_{n+1} - \beta_{0n}\varphi_n(e) + b(u) \\ \dot{z}_{n+1} = -\beta_{0(n+1)}\varphi_{n+1}(e) \end{cases} \tag{5}$$

In order to facilitate system debugging, each ω_0 point in the ESO characteristic equation is achieved by observing the frequency domain. The advantage of this approach is that it can make the system more stable and adjust faster. Usually, when the ω_0 value is large, ESO can better estimate the disturbance and compensate for it, thus making it have good anti-interference performance. However, if the ω_0 measurement value is too large, it will generate higher noise, and due to the influence of sampling frequency, it will affect the observation distance and user response. So, the ω_0 value must strike a balance between speed and noise resistance.

5.4. Auto Disturbance Rejection Model

The Active disturbance rejection control technology is a modification of the traditional PID control technology. It uses tracking differentiators to solve the sudden change of input signals, alleviate the error of input signals and feedback signals in the PID control process, reduce the error overshoot of the submersible motor shaft rotation and the preset value of submersible motor shaft rotation in the PID controller, and solve the contradiction between the rapidity and overshoot of the controller without affecting the speed of the control closed-loop, The control process of self-disturbance rejection is achieved by replacing weighted sum with nonlinear combination, applying output signals to extract input signals, and solving the problem of noise amplification in differential signal extraction. The following is the ADRC control model. As shown in Figure 4.

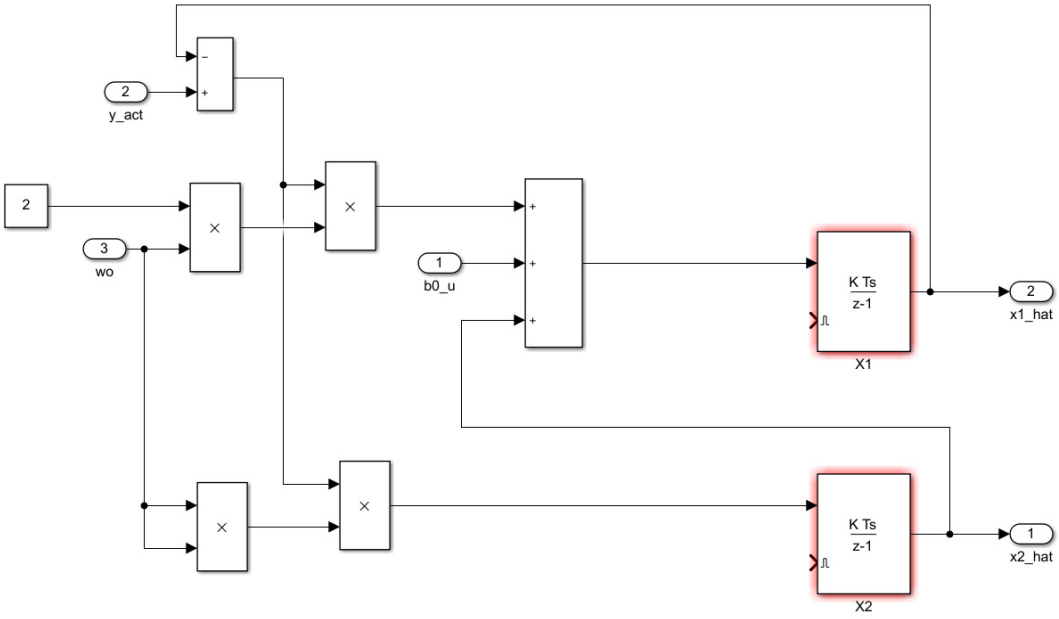


Fig 4. Active disturbance rejection model

Place all poles of the controller at $-\omega c$ and compare the control effect of bandwidth close to the controller. The mathematical model is:

$$\frac{Y(s)}{R(s)} = \frac{kp}{s + kp} = \frac{\omega c}{s + \omega c} \rightarrow kp = \omega c \tag{6}$$

$$\frac{Y(s)}{R(s)} = \frac{kp}{s^2 + kd \cdot s + kp} = \frac{\omega c^2}{(s + \omega c)^2} \rightarrow kp = \omega c^2 \tag{7}$$

$$\frac{Y(s)}{R(s)} = \frac{kp}{s^3 + kd \cdot s^2 + kdd \cdot s + kp} = \frac{\omega c^3}{(s + \omega c)^3} \rightarrow kp = \omega c^3 \tag{8}$$

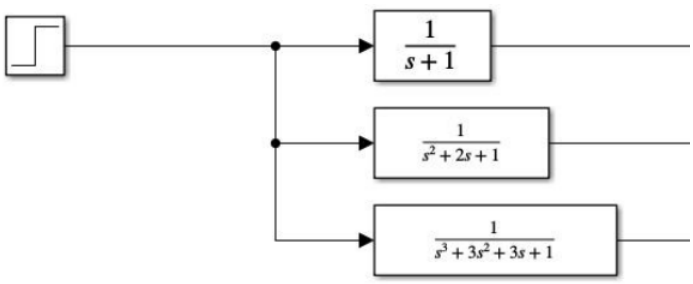


Fig 5. Simulation of mathematical model of control bandwidth

Placing the controller poles at $-\omega c$ (controller bandwidth) has the fastest response time at $kp = \omega c^3$, which can quickly meet control requirements and solve the eccentricity effect of the submersible motor. The experimental results are shown in Figure 6.

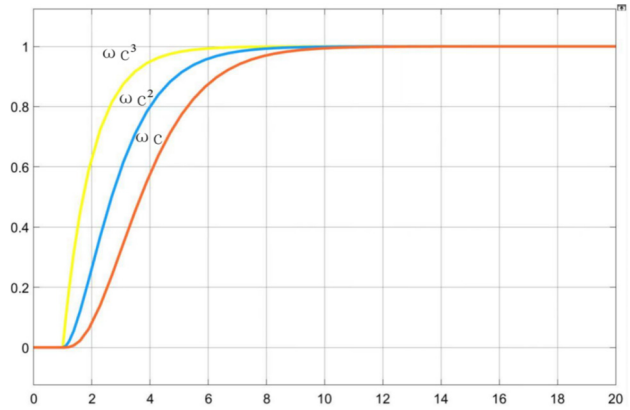


Fig 6. Observed experimental results

As shown in the above figure, the parameter settings of controlled objects of different orders also vary, but they can all achieve rapid convergence by placing the poles at position $-\omega c$ without overshoot.

6. Conclusion

This article addresses the static eccentricity caused by incorrect installation of the stator or rotor, as well as the dynamic eccentricity caused by bending of the rotor shaft, through the study of relevant data. Analyze the variation pattern of internal harmonic magnetic field loss caused by different static and dynamic eccentricities of submersible motors, and study the mechanism influence of static and dynamic eccentricities on motor performance. Eccentric rotor refers to the situation where the axis of its axis is inconsistent with its central position. This places a greater load on one side of the rotating centerline than the other, causing the spindle to sway on irregular tracks. This is an inherent instability issue, a potential source of malfunction or vibration. Although sometimes this deviation is dynamically balanced, more vibrations will continue. Due to the high eccentricity of the rotor, it is difficult to achieve good dynamic balance. Now we need to focus on increasing the rotational speed and eliminating deviations. The state expansion observer of the auto disturbance rejection model is used to determine the rotation state of the submersible motor shaft, and the tracking differentiator is used to extract differential signals. The internal disturbances and uncertainties of the system are regarded as total disturbances, and real-time estimation and compensation are carried out. Finally, the rotation error of the submersible motor shaft is eliminated, and the inconsistent movement of the Screw pump rotor and the submersible motor shaft caused by the shaft eccentricity is suppressed.

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