CHEMICAL ENGINEERING TRANSACTIONS

VOL. 83, 2021

A publication of
AIDIC
The Italian Association
of Chemical Engineering
Online at www.cetjournal.it

Guest Editors: Jeng Shiun Lim, Nor Alafiza Yunus, Jiří Jaromír Klemeš

ISBN 978-88-95608-81-5; **ISSN** 2283-9216

DOI: 10.3303/CET2183047

The Design of Magnetic Suspended Spiral Sludge Dewatering Machine

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The bearings used by the stacked screw sludge dewatering machine are traditional bearings. The use of traditional bearings pollutes the environment. The noise is relatively large, and the energy utilization rate is also low. In the long-term continuous heavy-load operation, the bearings need frequent maintenance, while the maintenance cost is high, and the life of the bearings is generally short. The electromagnetic bearings have advantages of no contact, no need for lubrication, and no friction. They can be used to replace the traditional bearing to solve the key problem of the support of the stacked screw machine. In this paper, the design and development of the electromagnetic bearing structure are carried out based on the performance and technical indicators of a stacked screw sludge dewatering test prototype, combined with its supporting layout and shafting structure. The mathematical model of a rotor with single degree of freedom is established, and the control system is simulated in Simulink of MATLAB. In the simulation of Simulink, through the constant adjustment of PID controller, when the proportional coefficient, integral coefficient and differential coefficient are 20,000, 100 and 1, the rotor can quickly return to the origin (about 0.02s).

1. Introduction

With the progress in modern control theory, rotor dynamics theory research, and the advanced application of hardware such as power electronics and signal processors, France, Japan, the United States and other developed countries have conducted plenty of research on the practical applications of active electromagnetic bearing. They took the lead in applying electromagnetic bearings to such fields as rotating machinery, energy storage technology and aerospace (Tang, 2013). Up to now, the technological development and practical application of electromagnetic bearings have reached a relatively high level.

The traditional stacked screw sludge dewatering machine represents a novel type of high-efficiency spiral squeeze filter. The continuously rotating spiral shaft can be filtered on a continued basis as the sludge progresses, generating a substantial amount of internal pressure to achieve full dehydration. Requiring a large rated torque, the screw shaft is driven by a high-speed motor fitted with a reducer. In the meantime, the mechanical bearings at both ends are continuously loaded. It is of much practical significance to alleviate bearing wear and address lubrication issues for the improved system performance. This paper is innovative in applying the electromagnetic bearing technology to the traditional stacked screw sludge dewatering machine. Active magnetic bearing (AMB) is capable to provide a sort of non-contact support for a fixed rotor through a controlled electromagnetic force. It demonstrates such desirable advantages as high speed, the elimination of wear, no need for lubrication system, low power consumption, and unbalanced active control, which makes it especially suitable for all types of rotating machinery (Mao and Zhu, 2019). As for the stacked screw dewatering machine, its advantages are mainly reflected in the removed need for maintenance, low energy consumption as well as low vibration and noise level. At present, energy consumption has been on the increase steadily across the world and there are many developing countries experiencing an exponential growth in the level of energy demand (Syn et al.,2019). The application of magnetic bearings is conducive to alleviating those energy-related problems.

In 2009, Li et al. from Beijing University of Chemical Technology, demonstrated the advantages of the stacked screw-type dehydration mobile static ring structure filter in solving the clogging problem, based on which the law was determined behind the impact of the dynamic and static ring structure filter on the flow rate of different

Paper Received: 29/05/2020; Revised: 19/10/2020; Accepted: 27/10/2020
Please cite this article as: Liu H., Si H., Shen Z., Zhang S., 2021, The Design of Magnetic Suspended Spiral Sludge Dewatering Machine, Chemical Engineering Transactions, 83, 277-282 DOI:10.3303/CET2183047

materials (Li et al., 2009). In 2010, Zeng Xiangqin from Beijing University of Chemical Technology and others conducted study on the static ring used in the dynamic and static ring structure filter, based on which the design of the static ring was optimized to improve the performance of the equipment and extend its service life (Zeng, 2010). In 2012, Wei Kai from Shandong University and others carried out study on the screw shaft and the critical component of the screw dehydrator. In this study, MATLAB was applied to optimize the design of the screw shaft and ascertain the optimal size, providing some practical guidance on the fabrication of screw dehydrator (Wei, 2012). Despite the significant development of stacked screw sludge dewatering machine, some problems with traditional bearings remain unsolved.

Electromagnetic bearings are clearly advantageous in reducing the level of energy consumption. In the rotor systems at the same power level, the energy consumed by electromagnetic bearings is merely 5-20 % that of traditional ball bearings or sliding bearings. Energy conservation is essential for environmental preservation. Reliant on such active vibration control technologies as unbalanced control, the electromagnetic bearing stacker can reduce vibration and noise to extremely low levels.

The purpose of this study is to replace the mechanical bearings of the stacked screw sludge dewatering machine with magnetic bearings. It involves the design and calculation of both bearing magnetic bearings and radial magnetic bearings. In order to demonstrate the feasibility of the scheme, MATLAB modeling was performed to verify the scheme as practically viable.

2. Scheme design of electromagnetic bearing system of stacked screw machine

The requirement placed on the magnetic bearing structure of the stacked screw machine is to properly modify the electromagnetic bearing without affecting the support function. The electromagnetic bearing is required to be not only as compact as possible in structure, but also small in volume and mass. Figure 1 shows the mechanical structure of the modified stacked screw machine.

To facilitate the active control of bearings, either active electromagnetic bearings or hybrid magnetic bearings can be employed. The hybrid support method is effective in reducing the loss of system power. Due to the relatively complicated structure of electromagnetic and permanent magnets, the installation process is difficult to conduct. Since the experimental device remains in the initial stage of development, the main purpose of this paper is to make the suspension function achievable while reducing the difficulty and cycle of research and development, for which the active electromagnetic bearing support scheme is carried out.

As the rotor used in this study has a working load of 330 kg and a heavy weight, it requires a large motor torque when getting started. The radial bearing is capable to support the entire rotor, and it is requisite for accidental protection bearings to be fitted on both sides of the shaft end. Based on the above-mentioned factors, the overall configuration of the electromagnetic bearing system used for the screw-stacking machine can be obtained, as shown in Figure 1.

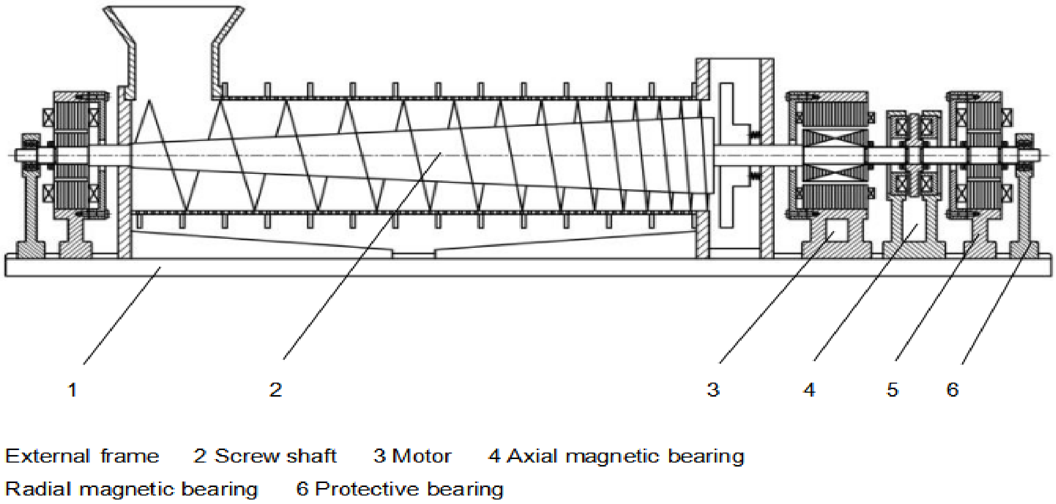

Figure 1: Schematic diagram of the supporting layout of the electromagnetic bearing system of the stacked screw machine

3. Structure design and development of electromagnetic bearings

3.1 Structural design and development of radial electromagnetic bearings

The stator core design can refer to the corresponding motor stator manufacturing process, see Table 1 (Zhu, 2007).

Table 1: Selection of rotor diameter and number of magnetic poles

Rotor diameter/ mm	Number of magnetic poles
0-60	8
60-80	16
80-200	24
>200	32

Since the diameter of the rotating shaft of this prototype is known data, the outer diameter of the rotor is 60 mm, so the radial bearing uses 8 magnetic poles.

The rotor of the radial electromagnetic bearing is similar to that of the shaft sleeve which is connected with the shaft of the energy storage flywheel through the interference fit, and forms a magnetic circuit with the radial bearing stator, which is affected by the electromagnetic attraction of the stator pole, so that the radial bearing rotor and the flywheel main shaft are integrated, so as to maintain the overall suspension state.

The structural parameter design of the stator core is based on the known outer diameter of the rotor. After the rotor parameters are determined, it is used as the initial data of the stator design, and the approximate range of the inner diameter of the stator can be determined.

3.2 Structural design and development of axial electromagnetic bearings

The axial magnetic bearing is composed of an intermediate thrust disc rotor and a symmetrically distributed axial stator iron core. The thrust disc is connected to the rotating shaft with interference, and the rotating shaft drives the thrust disc to rotate during operation. The thrust disc rotor and stator core are made of pure electric iron.

4. Mathematical model

In Figure 2, x_0 is the radius air gap of the electromagnetic bearing. The rotor moves by the distance x in the direction shown in the figure. It can be considered that the rotor mass distribution is very uniform. When the offset of the rotor's axis in the *X* direction is x, the electromagnetic forces are as shown in Eq(1) and Eq(2) (Ren and Li, 2018):

$$F_1 = \frac{\mu_0 S_0 N^2 (I_0 - i_c)^2}{4(x_0 - x)^2} \tag{1}$$

$$F_2 = \frac{\mu_0 S_0 N^2 (I_0 - i_c)^2}{4(x_0 - x)^2} \tag{2}$$

Among them, μ_0 represents air permeability, S_0 represents a single magnetic pole area, I_0 represents the bias current component, i_c represents the control current component caused by x, and N represents the number of turns of the coil.

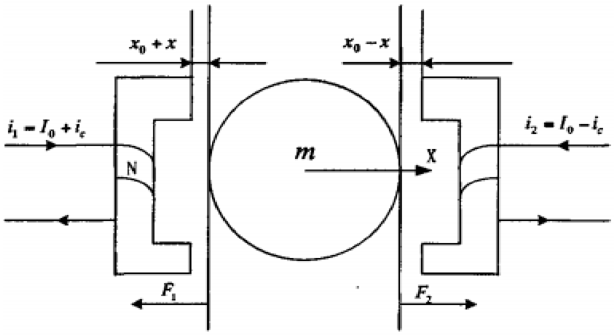

Figure 2: The mathematical model of a single-degree-of-freedom rotor

The force equation of the rotor can be expressed as Eq(3) and Eq(4):

$$f = m\overline{x} = F_1 - F_2 = \frac{\mu_0 S_0 N^2}{4}[(\frac{I_0+i_c}{x_0+x})^2 - (\frac{I_0-i_c}{x_0-x})^2] \tag{3}$$

$$f = \frac{\mu_0 S_0 N^2}{4} \cdot \frac{{I_0}^2}{{x_0}^2}[(\frac{1-\frac{x}{x_0}+\frac{i_c}{I_0}+\frac{x}{x_0}}{1-\frac{x}{x_0}})^2 - (\frac{1+\frac{x}{x_0}-\frac{i_c}{I_0}-\frac{x}{x_0}}{1+\frac{x}{x_0}})^2] \tag{4}$$

m represents the rotor.

$x << x_0$, $\frac{x}{x_0} \approx 0$, get Eq(5).

$$1 - \frac{x}{x_0} = 1 + \frac{x}{x_0} \approx 1(x << x_0) \tag{5}$$

The above formula can be simplified to Eq(6):

$$f = m\overline{x} = \frac{\mu_0 S_0 N^2}{4} \cdot \frac{{I_0}^2}{{x_0}^2}[(1 + \frac{i_c}{I_0} + \frac{x}{x_0})^2 - \left(1 - \frac{i_c}{I_0} - \frac{x}{x_0})^2\right] = \frac{\mu_0 S_0 N^2 I_0}{{x_0}^2} \cdot i_c + \frac{\mu_0 S_0 N^2 {I_0}^2}{{x_0}^3} \cdot x \tag{6}$$

Let K_i be called current-force coefficient, K_x be called displacement-force coefficient. Eq(7) and Eq(8) can be obtained as follows.

$$K_i = \frac{\mu_0 S_0 N^2 {I_0}^2}{{x_0}^2} \tag{7}$$

$$K_x = \frac{\mu_0 S_0 N^2 I_0}{{x_0}^2} \tag{8}$$

The resulting differential equation of motion is as Eq(9).

$$f = m\overline{x} = K_i i_c + K_x x \tag{9}$$

After pulling transformation, get Eq(10).

$$F(s) = ms^2 X(s) = K_i I(s) + K_s X(s) \tag{10}$$

The transfer function of a single-degree-of-freedom rotor can be expressed as Eq(11).

$$G(s) = \frac{X(s)}{I(s)} = \frac{K_i}{ms^2 - K_x} \tag{11}$$

In this design, the rotor movement in the vertical direction is studied, the gravity of the rotor must also be considered, so the equation of motion obtained is as Eq(12).

$$ma = f - mg \tag{12}$$

Both sides of Eq(12) are divided by m to obtain Eq(13).

$$a = \frac{f - mg}{m} = \frac{f}{m} - g \tag{13}$$

5. Simulation research

The control system adopted PID control system, the block diagram of the control model is as Figure 3:

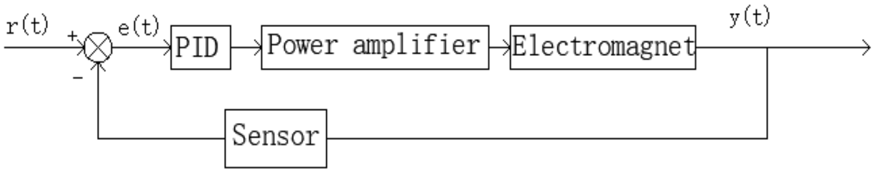

Figure 3: Control system model block diagram

In this control system model, the output of the controlled object is displacement x. When the sensor receives the displacement signal x, it is converted into a voltage signal and sent to the PID controller. Among them, the output voltage signal of the sensor is compared with the reference input voltage signal as the input signal of the PID controller. The controller sends the signal to the power amplifier. The output of the power amplifier is current, and the current signal is sent to the controlled object. The control system is formed.

The permeability of the electromagnet is 9.2×10^{-5} (Vs / Am), the pole area is 0.0168 m^2, the number of coil turns is 477, and the obtained gain is 8.792×10^{-2}. The gain of the power amplifier and displacement sensor were both set to 1. The size of the bias current was set to 10 A.

The Simulink model of the single-degree-of-freedom rotor control system built under MATLAB's Simulink (Li, 2017) environment is shown in Figure 4:

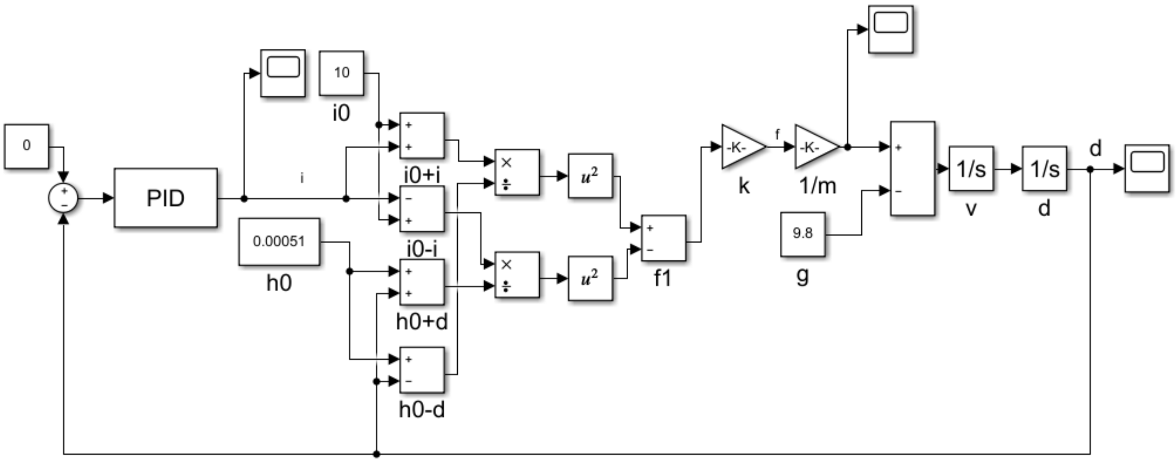

Figure 4: Simulink model of single-degree-of-freedom rotor control system

Through constant adjustment of PID, when the proportional coefficient, integral coefficient, and differential coefficient were 20,000, 100, and 1 (Han, 2009), the rotor could quickly (about 0.02 s) return to the origin (Liu et al., 2019).

The oscilloscope image is shown in Figure 5.

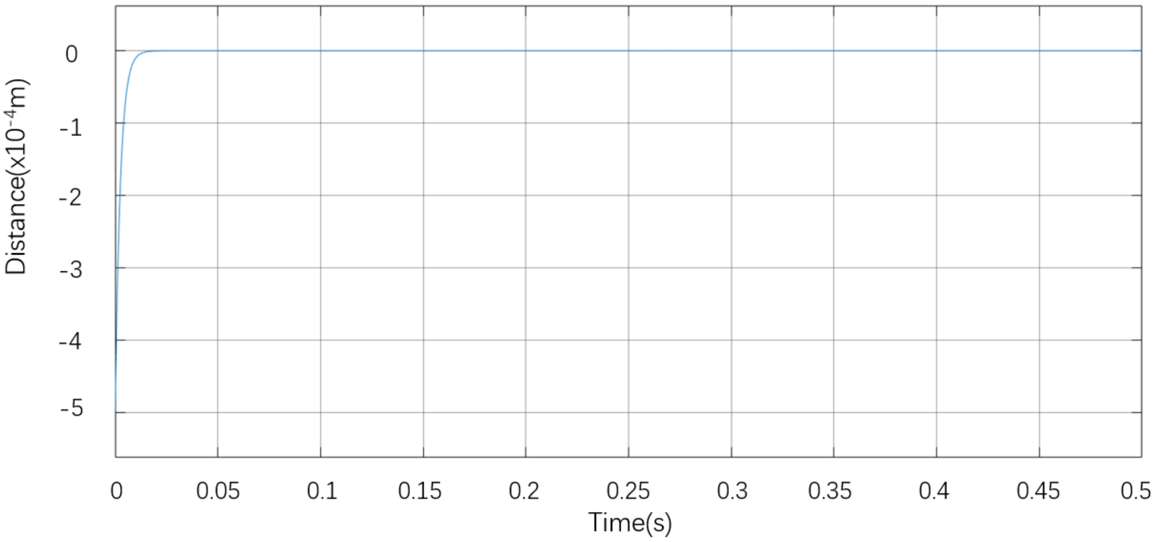

Figure 5: Oscilloscope image

6. Conclusions

Based on the traditional stacked screw sludge dewatering machine, this paper innovatively replaced the traditional bearing with a magnetic levitation bearing, and designed and developed the structure of the magnetic levitation bearing. The designed magnetic levitation type screw machine had the characteristics of compact electromagnetic bearing structure, small volume and mass, structurally placed outside the filter housing, and electrical control cabinet placed outside the control room. Compared with the traditional stacked screw sludge dewatering machine, the energy consumption of the magnetic suspension stacked screw sludge dewatering machine was significantly reduced, which had extraordinary significance for environmental protection. The design of electromagnetic bearing structure included the design of radial electromagnetic bearing and axial electromagnetic bearing. The mathematical model of the single-degree-of-freedom rotor was established, and the control system of the single-degree-of-freedom rotor was simulated in Simulink of MATLAB. The simulation results achieved the expected results, and the rotor could quickly return to the center position after deviating from the center position.

The research on the maglev stack screw sludge dewatering machine is a sophisticated, systematic and long-term project, and the current research is only in its infancy. Due to various reasons, the work which has been done currently is relatively limited. There are still many issues in this field that need to be studied and perfected. For example, the improvement of the control system, the use of a fuzzy control system to replace the PID control system has solved the disadvantage of the PID control system that requires an accurate mathematical model. The active magnetic bearing rotor system is a mechanical-electronic coupling system, so rotor dynamics analysis should be carried out in the design process, such as structure and strength, rotor unbalance excitation, system stability and dynamic response, etc.

Acknowledgments

This work was supported by National Key Research and Development Program of China (No. 2018YFD1100503 and 2017YFC0212900), the National Natural Science Foundation of China (No. 21978224 and 21676205) and Agricultural Science and Technology Innovation Project of Chongming District (No. 2019CNKC-08).

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