Mechatronics 54 (2018) 52–67

Contents lists available at ScienceDirect

Mechatronics

journal homepage: www.elsevier.com/locate/mechatronics

Implementation of active magnetic control system for piston centering in labyrinth piston compressor☆

Xie Jing[a], Zeng Xiangjun[a,*], Zhang Meimei[a], Cheng Junming[b], Wang Hang[a]

[a] School of Electrical Engineering, XI'AN Jiao Tong University, Xi'an 710049, China
[b] School of Energy and Power, XI'AN Jiao Tong University, Xi'an 710049, China

ARTICLE INFO

Keywords:
Active magnetic control system
Control strategy of three closed-loops
Eccentric running
Labyrinth piston compressor
Linearization method
Speed observation method

ABSTRACT

This paper introduces a kind of active magnetic control system (AMCS) to solve the problem of the eccentric running of the piston in labyrinth piston compressor. Besides, a new control strategy based on three closed-loops of current, speed and displacement is applied to the control system. Firstly, the structure of the labyrinth piston compressor and the typical force condition to the piston are given. According to this, the AMCS that mainly contains the electromagnetic guiding sleeve, the displacement sensor, the piston rod and the control circuit is designed. And the model of the AMCS is built. Hereinto, the model of the electromagnetic coil in the guiding sleeve is nonlinear and a linearization method is proposed. Secondly, the three closed-loops control strategy is modeled and the regulators are designed. And the speed closed-loop is built on a new speed observation method of the least square linear fitting using the displacement data. Finally, simulation and experiments are done to verify the feasibility of the control system. The experimental results are in accordance with the simulated. It shows that the system can implement the precise centering of the piston. And the controller presents good robustness and high control precision.

1. Introduction

With the development of modern industry, the labyrinth piston compressor is widely used in many industry fields, such as metallurgy, oil refining and military. The most typical characteristic of labyrinth piston compressor is the non-contact labyrinth seal, which realizes absolutely protection for the compressor gas from dusts and pollution [1]. In the running process of the compressor, the high concentric between the piston and the cylinder is a prerequisite to ensure the effect of labyrinth seal. However, caused by many factors such as the periodic change of the great piston force, vibration of the compressor, and the bending effect of the piston rod, the piston always runs eccentrically in cylinder. The eccentric running of the piston will lead to the inner leakage increase by 1.5–2 times [2]. And the volumetric efficiency of the traditional labyrinth piston compressor is only about 50%–60% [3,4]. In addition, the eccentric running of the piston may even result in the friction between the piston and the cylinder, which seriously reduces the efficiency and life span of the compressor. But until now, there is still no effective method to systematically solve this problem.

The existing methods to implement the precise centering of the piston mainly focus on the optimizing of the mechanical structure. A method that changes the shape of piston to form a convergence zone has been used, and a radial force will be generated when the gas leak and pass through this zone [5]. However, the radial force is not enough to maintain the precise centering of the piston. Besides, it has been discovered that the position of the guide bearing influences the natural frequency and the lateral vibration of the piston rod sharply [6]. And the way to find the optimal installation position of the guide bearing has been studied [7]. But, the inner structure of the compressor will be complicated in this way.

This paper adopts an active magnetic control (AMC) system to implement the precise centering of the piston in cylinder. To achieve this goal, the new piston rod will run through the piston in the cylinder and the part above the cylinder is called guiding rod. The guiding rod is surrounded by the electromagnetic guiding sleeve which is on the top of the cylinder. And the guiding sleeve will provide attractive electromagnetic force to the guiding rod to keep it in the central position when the electromagnetic coil is energized. If the guiding rod is centering precisely, so does the piston. And then the design value of the clearance between piston and cylinder can be decreased. Thus, the inner leakage will be reduced and the volumetric efficiency of the compressor will be greatly improved.

☆ This paper was recommended for publication by Associate Editor Prof. Paolo Rocco.

* Corresponding author.
E-mail address: zengxj@mail.xjtu.edu.cn (X. Zeng).

https://doi.org/10.1016/j.mechatronics.2018.07.006
Received 7 March 2017; Received in revised form 29 May 2018; Accepted 19 July 2018
0957-4158/

The magnetic control theory of the active magnetic bearing (AMB) system has been reported or utilized in other fields, like the turbine machines. But, it is the first time for this paper to use the active electromagnetic control in labyrinth piston compressor. Although the magnetic control in turbine machines can be referenced, there are many differences about the mechanical properties between the turbine machine and labyrinth compressor. Therefore, without modification, the control strategies will not be applicable to the labyrinth piston compressor. The most important issues of the magnetic control are the regulator design and the nonlinear problem of the electromagnetic coil.

In the turbine machine, the most widely used regulator is the PID regulator because of its simplicity and flexibility [8]. Besides, some researchers combine the PID regulator with other intelligent control strategies. For example, the genetic algorithm has been proposed but there exists the problems of convergence and prematurity [9,10]. In addition, the Linear-Quadratic-Gaussian (LQG) is also introduced [11], which is proved to be not robust enough compared to the PID type fuzzy control. Although the fuzzy control is commonly used, there are a large number of parameters in defining the fuzzy rule base which makes the fuzzy control difficult to be implemented [12–14].

The nonlinear relationship among the electromagnetic force, the coil current and the displacement of the piston rod will cause the instability of the controller, which exists both in the AMB and the AMC system. The conventional PID controller has been combined with fuzzy logic for AMB in [14]. Though a rough model can be used for a fuzzy controller, it needs to be determined by the difficult experimental methods, which are not clear in [14]. Several meta-heuristic optimization algorithms are employed to ensure that the optimal PID parameters are obtained. Therefore, the processing time and the calculation complexity are increased. In [15], the idea of the state-dependent bias is extended to the switching mode of operation for AMB. In [16,17], a variable bias current approach is exploited for AMB to achieve a required dynamic performance with minimum power consumption. But only a one-degree-of-freedom AMB system has been discussed.

Despite of the theoretical significance, the main drawbacks of the existing approaches are as follows: (1) these control strategies are built on an assumption regarding AMB as a strong nonlinear and time-varying system. Hence, the controlled object is difficult to be modeled. In addition, most of them have no experimental verification. And the controller structure and parameter designs are obscure. (2) The effects caused by the gravity of the rotor are neglected. It should be noted that the rotor in AMB is horizontal. The gravity of the rotor has to be counteracted by a bias current, which will cause uneven magnetic-field distribution, further increase the complexity of the nonlinear problem in AMB. (3) These control strategies introduce the closed 2-loop control system only with rotor position and coil current feedbacks, however adding a velocity feedback will no doubt contribute to the stability of the control system.

In fact, the exact model can be obtained if we keep leaving a certain air gap between the rotor and the guiding sleeve. In this way, a control strategy based on the accurate model can be developed. This is due to the fact that the magnetic reluctance of the air gap is much bigger than that of the steel material. Hence the air gap will greatly reduce the effects of the nonlinear factors such as magnetic saturation and hysteresis derived from the steel material. Further, a simple compensation stage can be applied to linearize the control system. In addition, different from AMB, an AMC system is applied to the labyrinth piston compressor, which has a vertical piston rod. Thereby, the effects caused by the gravity can be neglected.

In this paper, we clarify the nonlinear relationship in AMC by means of electromagnetic field numerical simulation. And a compensation stage based on displacement feedback is developed to linearize the control system. Then we introduce conventional PID regulators into a closed 3-loop control system. Hereinto, the rod velocity closed-loop, to be more exact, the derivative feedback of displacement, is introduced to increase the robustness of the control system especially. The modeling procedure of the AMC system and parameter designs of the regulators are given in great detail. The simulated results based on the model are in comparison with the experimental. In the end, an optimal robust controller based on H-infinity (H∞) theory is introduced for the comparison with the proposed PID controller.

2. Design of the AMC system

2.1. Structure and characteristics of the labyrinth piston compressor and its simplified experimental platform

The simplified structure of the conventional labyrinth piston compressor is depicted in Fig. 1a. And the improved structure of the labyrinth piston compressor with an AMC system is shown in Fig. 1b. In this structure, the piston rod runs through the piston and the cylinder. And the electromagnetic guiding sleeve is installed on the top of the cylinder, surrounding the guiding rod. Besides, the displacement sensors are fixed on the pedestal that is isolated from the other parts of the compressor to prevent the sensors from vibration. And the two sensors are along the axes of a rectangular coordinate system to monitor the radial eccentricity of the piston rod. The sensors, the electromagnetic guiding sleeve, and the guide rod are sealed by a shell to avoid the gas leakage. In the new structure, the running of the piston is guided by the crosshead and the electromagnetic guiding sleeve. Therefore, the guide bearing under the cylinder can be removed and the inner structure of the labyrinth compressor will be simplified.

In the labyrinth piston compressor, the running of the piston will be disturbed by an intrinsic force owing to its mechanical characteristics. Referring to our earlier work in [18], the typical spectrum of the force disturbance to the piston is shown in Fig. 1c. It is obvious that the frequency of the force disturbance ranges from 10 Hz to 75 Hz. Affected by the force, the route of the eccentric running of the piston is shown in Fig.1d. The electromagnetic guiding sleeve is designed to provide an electromagnetic force for the guiding rod to overcome the intrinsic force disturbance and keep it running centrally. Owing to the rigidity, as long as the guiding rod is centric, the piston will be also at the central position.

An experimental platform simplified by a real labyrinth compressor is built and shown in Fig. 2. It contains the piston rod, the electromagnetic guiding sleeve and the displacement sensor. It is mainly used to verify the electromagnetic centering control of the guide rod. At the bottom is a giant pedestal that can ensure the stability of the whole experiment platform. The piston rod is only supported by a much smaller ball, which is installed inside a hole dug on the surface of the pedestal. And the electromagnetic guiding sleeve is installed on the top of the cylinder which is concentric with the rod. Its relevant parameters are listed in Table 1.

The vertical running of the piston cannot be implemented on the experimental platform, because it has no motor driving system. Even so, the eccentric running can be simulated as long as the radial force disturbance can be exerted on the rod. Based on the simplified experimental platform, we build a displacement control circuit including the signal conditioning circuit, power amplifier, and the digital signal processor (DSP), etc. And the accurate mathematical model of the whole AMC system is built. The proposed control strategy is carried out for the system, and the regulators are optically designed. The data of the actual force disturbance given in Fig. 1c will be input into the AMC system to verify its validity in a real labyrinth compressor by simulation.

The 3D model of the piston rod and the electromagnetic guiding sleeve is depicted in Fig. 3a. The layout of the electromagnetic coils and magnetic poles in the electromagnetic guide sleeve is shown as Fig. 3b. Taking the center of the guiding sleeve as the origin, a displacement coordinate system with x- and y-axis is created as shown in Fig. 3b. The guiding sleeve has four pairs of magnetic poles with the central line along the x- and y-axis of the coordinate system. Fig. 3c shows the