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Research paper

Active rotordynamic stability control by use of a combined active magnetic bearing and hole pattern seal component for back-to-back centrifugal compressors

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ABSTRACT

Active control methods of rotordynamic stability for rotordynamic systems have been developed for many years, however effectively implementing these methods in real machines remains a significant challenge. With the goal of improving the performance of a back-to-back centrifugal compressor, a new integral electromagnetic actuator that combines the functions of an active magnetic bearing with a hole pattern seal is designed and used to replace the original balance piston of the machine. The structure design and assembly in the compressor are presented and an investigation on the seal performance and magnetic bearing forces is carried out. The results show that this innovative integral actuator can provide both sealing and vibration control, with two vibration feedback control methods experimentally validated for the elimination of oil whip, improving the rotordynamic stability of the machine.

1. Introduction

The operational requirements of high flow rates, heavy bearing loads, and large bearing spans lead to increasingly flexible rotors in centrifugal compressors, and the ability to design a compact structure for the compressor while preventing and controlling potential instability problems becomes an important consideration. Rotordynamic instability problems are usually caused by a lack of damping, a relatively high value of direct stiffness, or large cross-coupled stiffness forces from seals or impellers, typically causing subsynchronous vibrations with small or even negative values of logarithmic decrement in the case of an instability. To improve the stability of centrifugal compressors, engineers and researchers have commonly replaced traditional seals with hole pattern seals (HPS) and honeycomb seals (HCS) to reduce the significant cross-coupled stiffness forces generated by traditional seals [1,2], used tilting pad journal bearings to eliminate these forces in bearings [3,4], and implemented squeeze film dampers to increase the damping of the rotor-bearing system [5].

Traditional methods to improve rotordynamic stability involve simply replacing existing components with new components that have different stiffness and damping characteristics and are therefore not actively controllable. Thus, if the stiffness and damping of the component can be actively controlled, the stability of the entire rotor system is controllable. In or-

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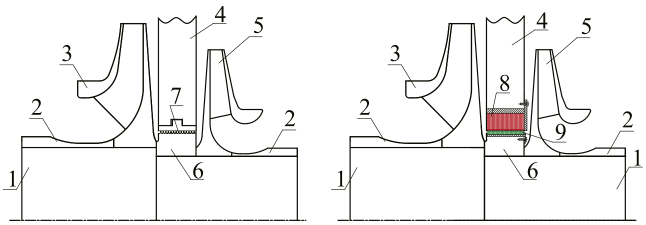

Fig. 1. Seal structure of a balance piston for a back-to-back compressor.

der to actively control the damping of the rotor system, active squeeze film dampers [6], magneto-rheological fluid dampers [7], and active elastic support/dry friction dampers [8] have been adopted. The damping effectiveness of these dampers was verified theoretically and experimentally, with an increase in the rotordynamic stability demonstrated. Cavalini et al. [9] presented a semi-active vibration control method by using a patented intelligent spring which indirectly suppressed the vibration by simultaneously altering the stiffness and damping of one or more bearings through a piezoelectric stack actuator. Active magnetic bearings (AMB) have also been used for actively improving rotordynamic stability [10–12]. Control strategies such as linear feedback controllers [13], fuzzy controllers [14], and μ-synthesis controllers [15] have been applied to improve the stability of rotordynamic systems with AMBs. Numerical and experimental validation of these approaches has also demonstrated the ability of AMBs to eliminate oil whip.

Despite the various control methods that have been developed, the effective implementation of actuators in rotor systems remains a significant challenge. To avoid introducing new components to the system, the actively lubricated tilting pad bearing is one technology designed to improve rotordynamic stability by controlling the lubricating oil injection parameters of existing support bearings [16–18]. Another approach is to combine the functions of multiple components into one. For example, El-Shafei and Dimitri [19,20] developed a fluid film bearing integrated with an AMB to control the rotordynamic stability of the system. In this combined structure the fluid film bearing supports the load of the shaft with the AMB acting as the controller to stabilize the system.

In this study, an original structure with multiple functions was designed for use in a back-to-back (B2B) centrifugal compressor. The multi-function structure consists of an AMB integrated with a HPS, combining sealing functionality with electromagnetic control capabilities at the center of the shaft where destabilizing forces typically occur. The basic force and seal performance of the AMB-HPS actuator is investigated and the control theory is derived. Since the control strategies for the AMB-HPS were numerically investigated in previous work [13], the purpose of this study is to experimentally validate this technology and associated control methods. Two vibration feedback control methods are investigated for their use in eliminating oil whip for the improvement of the rotordynamic stability of the machine.

2. Actuator design and analysis results

2.1. Structure description

Due to the use of small balance piston drums and axial thrust bearings, back-to-back centrifugal compressors are more efficient than through-in-line compressors. A typical balance piston structure for a centrifugal compressor is shown in Fig. 1(a). A large pressure differential across the balance piston labyrinth seal generates excitation forces and destabilizes the rotor system with the generation of cross-coupled stiffness. In order to control these potential instabilities, a compact and multi-function balance piston that combines the original seal function with a new AMB function has been designed which can apply controlling forces to the rotating system to increase the stability. The assembly of the innovative seal structure is shown in Fig. 1(b), requiring no change to the original rotor and impellers when compared to the original structure in Fig. 1(a); thus, this modification solves the traditional problem of integrating an actuator in a compact compressor. The rotor of the AMB consists of silicon-iron sheets, fixing bolts, and retaining rings of stator-iron-core. The stator component is a combination of AMB and HPS components.

The assembly details of the stator component of the AMB-HPS actuator are shown in Fig. 2(a) and (c), consisting of three main parts - the AMB, seal body, and HPS as shown in Fig. 2(b). The seal body is inserted into the pole spaces of the original AMB and is made of aluminium, which is soft and has a low magnetic permeability when compared to that of silicon iron. The seal body and poles of laminated silicon-iron sheets form a continuous surface on the inner surface of the actuator, and electro-discharge machining or CNC drilling can be used to produce the counterborings on the inner surface to form the HPS as shown in Fig. 2(c).