Robust control of active magnetic bearing systems for helium centrifugal cold compressors

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Abstract. Centrifugal cold compressors, now being developed at Technical Institute of Physics and Chemistry, Chinese Academy of Sciences, are used to pump gaseous helium from saturated liquid helium tank to obtain super-fluid helium in cryogenic refrigeration systems. Active magnetic bearings (AMB) are replacing traditional oil-fed bearings as the optimal supporting assembly for cold compressors because of their many advantages. In this paper, five degrees of freedom AMBs are developed for the centrifugal cold compressor application. Considering the rotational speed is high, causing the nominal plant model to deviate materially from the precise mathematical model, robust $H\infty$ control methods are proposed to control AMB systems. Experimental results show that $H\infty$ controllers guarantee good dynamic and steady state performance in the closed-loop system at the rotation speed of 50 000 rpm.

1. Introduction

Many large scientific experiments around the world -- Tore Supra in France, Continuous Electron Beam Accelerator Facility (CEBAF) in America, Large Hadron Collider (LHC) for European Council for Nuclear Research (CERN) in Switzerland, Experimental Advanced Superconducting Tokamak (EAST) in China, are all equipped with helium refrigeration systems [1-4]. In the refrigeration system, using cold compressors to pump gaseous helium from saturated liquid helium tank is the most common method to obtain super-fluid helium [5]. In previous applications, ceramic ball bearings, aerostatic bearings and active magnetic bearings are commonly used to support the centrifugal compressor rotor in cryogenic refrigeration systems [6]. However, active magnetic bearings are regarded as the best support assembly than other bearings because of its multitudes of advantages, such as zero frictional wear and working in harshen environment like ultra-speed rotating, elimination of the lubrication and low-pressure systems [7].

The centrifugal cold compressors, as shown in figure 1, are used to compress pure gaseous helium from 2.8 kPa to 42 kPa with mass flow rate of 30 g/s. Based on preliminary fluid simulation and calculation of compressors impeller runner, there are three-stage centrifugal compressors in series form. The pressure ratios of those three-stage compressors are designed to be 0.65, 0.7 and 0.75 respectively [8]. The biggest rotational speed, corresponding to the biggest pressure ratio of compressors, is of 50 000 rpm, which is the maximum continuous rated revolution of active magnetic bearings.
Figure 1. Structure components of the helium cold compressor.

2. AMB system description
The laboratory experimental AMB system is shown in figure 2. The main components of the AMB system are AMBs, controllers, displacement sensors, host computers, power amplifiers and so on. The controllers use a digital signal processor (DSP/OMAP-L138). The A/D converter AD7357 has two channels with 4.25MSPS rate and fourteen-bit precision, while the D/A converter AD5644R has four channels with fourteen-bit precision. The monitoring system was based on host computer and LABVIEW (NI). Transverse flux sensors are used here to detect the displacement of the rotor. Its' sensitivity is 50 V/mm and resolution is 20 mV, which means that the minimum identifiable displacement can reach 0.4 µm; the time response of the displacement sensor is 3.5 µs. Those meet the detection accuracy and fast response requirements of magnetic bearings. Switch mode amplifiers are applied to reduce loss and increase efficiency. In addition, the type of auxiliary bearings are ceramic bearings from SKF [9]. The system can monitor five channels displacement signals, ten current signals and speed signal acquisition, processing and display, the calculation of current control and amplification signals, diagnosis of the states of the AMB operation and fault monitoring and control.

Figure 2. AMB system (a) The laboratory AMB setup. (b) The rotor and stator of AMB.
It’s usual to linearize mathematical model of the AMB, whose analytical equation is quadratic and nonlinear in engineering application [10]. The linearized electromagnetic force equation is shown in equation (1), where the force is given by \( f \). There, electromagnetic force labels \( f \). In addition, the two important constants \( k_i \) (N/A) and \( k_x \) (N/m), are called current stiffness and displacement stiffness respectively:

\[
f = k_i i + k_x x
\]  

(1)

Take one of the radial magnetic bearings for an example, the transfer function form of the AMB mathematical model can be shown as (2):

\[
G = \frac{k_i/m}{s^2 + k_i/m} = \frac{10.3571}{s^2 - 96428.5714}
\]  

(2)

3. Robust \( H_\infty \) controller design

Robust \( H_\infty \) control does not depend on the accurate mathematical model of the system, and could achieve better performance and stability than simple PID controller, in the presence of bounded modelling errors, especially when the rotor speed is high.

The mixed-sensitivity \( H_\infty \) control problem is cast into a general control configuration, as shown in figure 3, where \( r \) is the reference input, \( e \) is the tracking error, \( u_1 \) is the controller output, \( z_1, z_2, z_3 \) are the evaluation signals, \( y \) is the system output, \( d \) is the interference input, \( n \) is the measurement noise, and \( w_1, w_2, w_3 \) are the sensitivity function, linear function and the complementary sensitivity function respectively.

![Figure 3. Configuration of \( H_\infty \) controller and augmented plant.](image)

After repeated iterations, these three weighting functions are selected as follow:

\[
W_i = \frac{375}{s + 2}
\]  

(3)

\[
W_e = 2.5 \times 10^7
\]  

(4)

\[
W_i = \frac{s}{0.025s + 1250}
\]  

(5)

Based on the robust control toolbox of MATLAB, the generalized controlled object \( P \) of the radial AMB system can be listed as follows:

\[
P = \begin{bmatrix}
0 & 964286 & 0 & 0 & 0 & 0 & 4 \\
1 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 1 & 0 & 0 \\
0 & -10.3571 & -2 & -50000 & 0 & 0 & 0 \\
0 & 10.3571 & 375 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 2.5 \times 10^{-7} & 0 & 0 \\
0 & 414.2856 & 0 & -2000000 & 0 & 0 & 0 \\
0 & -10.3571 & 0 & 0 & 1 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & -\infty
\end{bmatrix}
\]  

(6)
The MATLAB function ‘hinflmi’ is used to compute an internally stabilizing controller. Bode diagram of controller is shown in figure 4 and its transfer function is:

\[
K(s) = \frac{4.124s^5 + 1.021s^4 + 4.538s^3 + 4.225s^2 + 4.286s^3 + 6.872s^2 + 4.678s + 8.439}{s^3 + 1.119s^2 + 0.7908s + 0.9101}
\]

The controller can be converted to the discrete pulse transfer function:

\[
K(z) = \frac{1.119z^3 - 1.237z^2 - 0.7908z + 0.9101}{z^3 - 0.7056z^2 - 0.6594z + 0.3651}
\]

Figure 4. Bode diagram of robust controller.

4. Experimental results

Figure 5 shows the step response of the AMB system. It shows that, at the beginning the rotor was stationary on the auxiliary bearing; then at 0.086 s, when input signals were added to the AMB the rotor displacement in the perpendicular direction reached its peak 0.022 mm some 0.01 s later, which is much less than the air gap of the radial auxiliary bearing, 100 µm. After about 0.1 s, the rotor was suspended stably in the centre of the radial bearing. Figure 6 shows the diagram of axis trajectory from the LabVIEW monitoring system. It shows that when the rotational speed reached 833.33 Hz, namely 50k rpm, the max displacement of the rotor centre is about 30 µm. The robust controller can achieve the stable operation at high speed. Experimental results demonstrate that the control method proposed in the paper can not only stabilize the AMB system but also achieve good performance in both transient and steady state.

Figure 5. Step response of the rotor.
5. Conclusions

AMBs have many advantages and are considered as the best support assembly for cold compressors. This brings opportunities and challenges for AMB applications with high-speed rotating machines in low-temperature refrigeration systems. The paper discussed the structure and hardware composition of AMB systems. The design of the mixed sensitivity robust controller is described in some detail. Experimental results demonstrate the $\text{H}_\infty$ controller proposed guarantees that the rotor speed reach 50k rpm, which meet the needs of cold compressors.

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Figure 6. Trajectory of the rotor.