Abstract

This paper provides the development of an axial suspended active magnetic bearing (AMB) experimental bench for load and disturbance tests. This test bench must be capable of levitating a 2 kg steel disc at a stable working distance of 3 mm and a maximum attraction distance of 6 mm. The suspension is accomplished by two electromagnets producing upward and downward attraction forces to support the steel disc. An inductive sensor measures the position of the steel disc and relays this to a PC based controller board (dSPACE® controller). The control system uses this information to regulate the electromagnetic force on the steel disc. The intent is to construct this system using relatively low-cost, low-precision components, and still be able to stably levitate the 2 kg steel disc with high precision. The dSPACE® software (ControlDesk®) was used for data acquisition. In this paper, an overview of the system design is presented, followed by the axial AMB model design, inductive sensor design, actuating unit design and controller development and implementation. The paper concludes with results obtained from the dSPACE® controller and evaluation of the axial suspended AMB experimental bench with load and disturbance tests.

Keywords: Active magnetic bearings; Control systems engineering; dSPACE® control; Electromagnetics; Inductive sensor; Magnetic levitation

1. Introduction

The project objective is the development of an axial suspended active magnetic bearing (AMB) experimental bench for load and disturbance tests. The system must be constructed by using relatively low-cost, low-precision components and the test bench must provide information on the load and disturbance tests. The development of the experimental bench is the first phase of a larger project on the development of a high performance axial AMB jackhammer for soft use in the residential and industrial sectors. Cases have been reported where cardiac contusion (caused by repeated, less severe blows, over a prolonged period) is caused by the use of jackhammers (Chapman & McEachen, 1957). AMBs in generators, pumps, turbo-machinery, compressors and motors has grown over the last couple of years, because users expect machines to operate at high efficiency and high availability and to be safe and reliable at all times (Gouws, 2012). An AMB provides the advantage of low maintenance cost and high life time, due to the avoidance of lubrication systems and absence of material deterioration and minimal friction losses (Khoo et al., 2010; Ritonja et al., 2006; Schweitzer et al., 1993). It is therefore important to investigate the use of AMBs in jackhammers, in order to improve safety and increase the life span of jackhammers. An introduction to magnetic bearings and electromagnetic design of a magnetic suspension system is provided by (Allaire & Maslen, 1997; Hurley et al., 1997). It is necessary to perform the following designs to develop the axial suspended AMB experimental bench: (1) axial AMB model design; (2) inductive sensor design; (3) actuating unit design, and (4) controller design. Each of these designs is discussed in detail in this paper.

2. System Development

This project can be divided into four stages as shown in Figure 1. Stage 1 focuses on the axial AMB model design. The model consists of a 2 kg steel disc and two electromagnets. The one electromagnet will be placed above the steel disc and the other one beneath the steel disc. The steel disc will be connected to a steel rod and will be able to freely move in the axial direction. Stage 2 focuses on the terminal board (which receives signals from the computer and sends them to the actuating units and vice versa) and actuating units (which provides the electromagnets with the correct potential to suspend the disc). The purpose of the terminal board is to isolate the computer from the actuating units and to scale the input and output signals
the dSPACE® DSP DS-1104 controller board and the control scheme is designed using the pole placement technique (Sawant & Ginoya, 2010).

### 3. Axial AMB Model Design

When starting an axial AMB model design, it is important to know the specifications of the model. The model must be designed to suspend a 2 kg steel disc at a working distance of 3 mm with a maximum attraction distance of 6 mm. Next, it is important to obtain the core dimensions, since the model specifications together with the core dimensions will be used to obtain the theoretical design parameters of the model. A layout of the core can be seen in Figure 3.

The gravitational force \( F \) required to lift the rotor is provided by:

\[
F = mg
\]

The purpose of the electromagnet is to apply a force on the rotor to maintain a constant air gap, between the rotor and the stator (Kasarda, 2000; Gouws, 2013). The air gap flux \( \phi \) required to lift the rotor is determined by using Eq. (2):

\[
F = mg = F_g + F_o
\]

\[
= \frac{\phi^2}{2 \cdot \mu_0 \cdot A_g} + \frac{\phi^2}{2 \cdot \mu_0 \cdot A_o}
\]

\[
= \frac{\phi^2}{2 \cdot \mu_0 \left[ \frac{1}{A_g} + \frac{1}{A_o} \right]}
\]

\[
\therefore \phi = \sqrt{2 \cdot F \cdot \mu_0 \left[ \frac{1}{A_g} + \frac{1}{A_o} \right]}
\]
The inductance \( (L) \) of the electromagnet is determined by using Eq. (10):

\[
L = \frac{N^2 \mu_0 A_i}{l}
\]

The potential, current and inductance at different air gaps can then be determined. Table 1 provides a summary on the steady state values.

The design process is done iteratively until the desired value for the force, number of turns in the coil and dimensions of the electromagnet have been reached. Table 2 provides a summary of the model specifications showing the length \((h_1, h_2)\) and diameter \((r_1, r_2)\) of the disc and shaft.

More information on electromagnetic model design and magnetically suspended flywheel energy storage devices are provided (Ahrens et al., 1996).

### 4. Inductive Sensor Design

The inductive sensor measures the size of the air gap and provides position feedback. The sensor must be designed to show a linear response between the position and the output voltage at the operating point of the AMB. Furthermore, it must have low noise susceptibility and low temperature dependence.

The inductive sensor configuration used to measure the position of the steel base is shown in Figure 4. The inductances \(L_1\) and \(L_2\) are functions of the air gap size, where (Pretorius, 1982):

\[
L_1 = L_0 \frac{d}{d - x}
\]

and

\[
L_2 = L_0 \frac{d}{d + x}
\]

Table 1
Summary of the steady state values.

<table>
<thead>
<tr>
<th>Air gap (mm)</th>
<th>Potential (V)</th>
<th>Current (A)</th>
<th>Inductance (mH)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.00</td>
<td>6.59</td>
<td>0.60</td>
<td>639.48</td>
</tr>
<tr>
<td>6.00</td>
<td>10.99</td>
<td>1.00</td>
<td>319.74</td>
</tr>
</tbody>
</table>

Table 2
Summary of the model specifications.

<table>
<thead>
<tr>
<th>Specifications</th>
<th>Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rotor disc diameter</td>
<td>(2r_2 = 140) mm</td>
</tr>
<tr>
<td>Rotor shaft diameter</td>
<td>(2r_1 = 10) mm</td>
</tr>
<tr>
<td>Length of disc</td>
<td>(h_1 = 15) mm</td>
</tr>
<tr>
<td>Length of shaft</td>
<td>(h_2 = 260) mm</td>
</tr>
<tr>
<td>Mass of rotor (disc + shaft)</td>
<td>(m_{\text{rotor}} = 2) kg</td>
</tr>
<tr>
<td>Working distance</td>
<td>(l = 3) mm</td>
</tr>
<tr>
<td>Maximum attraction distance</td>
<td>(l_{\text{max}} = 6) mm</td>
</tr>
<tr>
<td>Axial disturbance force</td>
<td>No specific force</td>
</tr>
</tbody>
</table>
to have as flat as possible frequency response in the pass-band. A Butterworth band-pass filter is obtained by inserting an inductor in parallel with each capacitor and a capacitor in series with each inductor to form a resonant circuit. Each new component resonates with the old component at the selected frequency (Bianchi & Sorrentino, 2007).

The active rectifier functions as an ideal peak detector and provides a DC output. A low pass filter (\(f_a \approx 1\) kHz) and difference amplifier can be used to filter out any high frequencies and to centre the output on zero. The typical transfer characteristic of the inductive sensor is shown in Figure 6. The linear area can be improved by using a full-wave active rectifier instead of a half-wave active rectifier and obtaining the optimum inductance for the desired air gap. This optimum inductance can be obtained from Eq. (11-12).

5. Actuating Unit Design

A linear voltage amplifier is used as an actuating unit. The circuit in Figure 7 controls the current in the electromagnetic levitation coil \(L\). It is driven by an op-amp, which is specified to source up to 40 mA of current. The 2N3055 transistor has a beta of more than 50, which is sufficient to drive loads of up to 2 A without any additional circuitry.

The base resistor (\(R\)) provides current protection and limits the output current demand on the op-amp. The supply voltage of the op-amp is 12 V and the base terminal voltage is 0.7 V. Therefore the maximum base current (\(I_b\)) is 37.67 mA. The actual maximum value of the base resistor that can be used de-
The equivalent damping constant ($b_{eq}$) and stiffness ($k_{eq}$) is thus (Scherpen, 1998):

$$b_{eq} = 2k_p k_i$$
$$k_{eq} = 2k_s k_i - 2k_r$$  \hspace{1cm} (16)

The linearized AMB system with a PD controller can be represented by the block diagram in Figure 8. The parameters $k_{sl}$ and $k_{sz}$ are current to voltage gains, while the parameters $k_{i}$ and $k_{a}$ are the attraction force to current gains. The parameters $k_{s1}$ and $k_{s2}$ are the attraction force to air gap gains. The constants of the PD controller can be calculated by using Eq. (16). The parameter for the open loop stiffness ($k_s$) of the model can be determined by using Eq. (17) (Sinha, 1987; Gouws, 2013):

$$k_s = \frac{\partial F}{\partial x}$$  \hspace{1cm} (17)

where $F$ is the attraction force of the electromagnet and $x$ is the air gap size.

The value of the proportional gain ($k_p$) is adjusted to realize the required stiffness, then the value of derivative gain ($k_d$) is adjusted to realize the required damping. Finally the integrator is implemented such that $\tau_d < \tau/10$. An integrator is implemented in the experimental system to obtain a smaller steady state error. A real time model can be created after the constants of the controller have been determined. Figure 9 shows the real time Simulink® model.

It was decided to choose the sample time ($T_s$) of the real time interface (RTI) at least 7 times the bandwidth of the sensor. The bandwidth of the sensor is $\approx 1$ kHz, therefore $f_{\text{S real-time}} > 7$ kHz. The sample time was chosen at $T_s = 0.0001$ s ($f_{\text{S real-time}} = 10$ kHz).

The sensor signal enters the dSPACE® controller at ADC port 5 as can be seen in Figure 9. Upper and lower limits of -10 V and +10 V are placed on the signal and the signal is then passed onto the sensor calibration block, where the gain and level of the sensor signal is adjusted.

The signal “sensor2” is subtracted from the position reference of the model. The steel disc can be moved up and down by changing the value of the position reference. This signal is then passed onto a discrete PID controller, from where it is sent to the different actuator stages.

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The development of HIL setup for collision avoidance of an under-actuated flat-fish type AUV using ControlDesk® experiment software and the dSPACE® DS1104 R&D controller is presented by Subramanian et al. (2012). The results show that the developed collision avoidance algorithm can be used in real-time for the flat-fish type AUV and dSPACE® HIL setup is an effective tool for the verification of control algorithms (Subramanian et al., 2012).

7. Evaluation of the System

The following three tests were performed on the experimental AMB system: (1) load test; (2) disturbance test, and (3) system output with variation in input step response.
7.1. Load Test Performed on the Model

The load test was conducted by placing different size weights on top of the steel rod of the model and to observe what impact the downward force \( F_{down} \) of the weights has on the amount of current necessary to keep the steel disc in suspension.

For this test, the reference air gap \( x \) is chosen between the steel disc and the bottom electromagnet (as seen in Fig. 11). Four 1.25 kg weights and one 500 g weight were placed on the model. Table 3 provides the data obtained with the load test.

From this table, it can be seen that the steady state error stays zero for all the controllers up to an added mass of 0.5 kg. The steady state error for the PID controllers stays zero up to an added mass of 2.5 kg. When the weight increases to 5 kg, the steady state error increases to 3 mm. The steel disc at this stage lies on top of the bottom electromagnet.

7.2. Disturbance Test Performed on the Model

In Figure 12, the system is evaluated by applying disturbance forces on it. A 500 g ball falling from different heights is used as disturbance on the system to see if the system can recover from the disturbance force and stably suspend the disc again.

7.3. System Output With Variation in Input Step Response

In this section, the AMB system will be evaluated as a spring-mass-damper system. The following equations were used to determine the natural frequency \( \omega_n \), settling time \( T_s \) and time-to-peak \( T_p \):

\[
\omega_n = \frac{\pi^2}{T_s^2} + \left( \frac{4}{T_p} \right)^2, \quad T_s = \frac{\pi}{\omega_n \sqrt{1 - \zeta^2}}, \quad T_p = \frac{4}{\zeta \omega_n}
\]

where \( \zeta \) is the damping ratio.

![Fig. 11. Load test performed on the axial AMB model.](image1)

![Fig. 12. Disturbance test on the axial AMB model.](image2)
The damping constant \( b_{eq} \) and stiffness \( k_{eq} \) of the model can be determined by using Eq. (19):

\[
2\zeta \omega_n = \frac{b_{eq}}{m} \quad \omega_n^2 = \frac{k_{eq}}{m} \quad (19)
\]

\[
\therefore b_{eq} = 2\zeta \omega_n m \quad \therefore k_{eq} = \omega_n^2 m
\]

The results of the system output with variation in input step response amplitude can be seen in Table 5. This table provides information about the system output for the different controllers.

### Table 4
Data obtained with the disturbance test.

<table>
<thead>
<tr>
<th>Ball Height</th>
<th>Maximum Deviation ( x_{down} ) (mm)</th>
<th>Steady State Error ( e_s ) (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Analog Lead</td>
<td>Discrete Lead</td>
</tr>
<tr>
<td>1-2</td>
<td>0.50</td>
<td>0.50</td>
</tr>
<tr>
<td>5</td>
<td>1.00</td>
<td>1.25</td>
</tr>
<tr>
<td>10</td>
<td>1.70</td>
<td>1.50</td>
</tr>
<tr>
<td>15</td>
<td>2.20</td>
<td>2.00</td>
</tr>
<tr>
<td>20</td>
<td>2.70</td>
<td>2.40</td>
</tr>
<tr>
<td>25</td>
<td>3.00</td>
<td>3.00</td>
</tr>
</tbody>
</table>

### Table 5
System output with variation in input step response amplitude.

<table>
<thead>
<tr>
<th>Step Response Input Amplitude (mm)</th>
<th>Time-to-peak ( T_p ) (ms)</th>
<th>Settling Time ( T_s ) (ms)</th>
<th>Percentage Overshoot P.O. (%)</th>
<th>Natural Frequency ( \omega_n ) (rad/s)</th>
<th>Damping Ratio ( \zeta )</th>
<th>Damping Constant ( b_{eq} ) (Nm s(^{-1}))</th>
<th>Stiffness ( k_{eq} ) (N/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Analog Lead</td>
<td>40.0</td>
<td>45.0</td>
<td>180.0</td>
<td>230.0</td>
<td>41.0</td>
<td>46.0</td>
<td>81.6</td>
</tr>
<tr>
<td>Discrete Lead</td>
<td>30.0</td>
<td>40.0</td>
<td>130.0</td>
<td>190.0</td>
<td>40.0</td>
<td>43.0</td>
<td>109.0</td>
</tr>
<tr>
<td>Analog PID</td>
<td>60.0</td>
<td>55.0</td>
<td>190.0</td>
<td>220.0</td>
<td>28.0</td>
<td>37.0</td>
<td>56.4</td>
</tr>
<tr>
<td>Discrete PID</td>
<td>37.5</td>
<td>50.0</td>
<td>100.0</td>
<td>160.0</td>
<td>22.0</td>
<td>29.0</td>
<td>92.8</td>
</tr>
</tbody>
</table>

8. Physical System

A photo of the complete AMB system showing the actuating units, AMB model, inductive sensor box, dSPACE® 1104 controller and ControlDesk® software interface can be seen in Figure 13.

A photo of the complete axial AMB model showing the steel disc, electromagnets, inductive sensors, sensor unit and actuating unit can be seen in Figure 14.

Various other papers on active vibration control in a rotor system, vibration analysis of rolling element bearings defects and mechatronic design and dynamic modeling provides interesting further reading (Arias-Montiel et al., 2014; Saruhan et al., 2014; Mendoza-Bárcenas et al., 2014).

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![Fig. 13. Axial suspended AMB experimental bench.](image-url)
Higher values of the damping ratio and natural frequency results in higher damping constant values for that specific controller. This can be seen from the values of the discrete PID controller, which has the highest damping constant value for a 2 mm input step response. Higher natural frequency values result in higher stiffness values for that specific controller. This can be seen from the discrete lead controller, which has the highest stiffness value for a 2 mm input step response.

It was necessary to perform the following designs to develop the axial suspended experimental bench:

1. axial AMB model design;
2. inductive sensor design;
3. actuating unit design,
4. controller design. The dSPACE® controller and software makes it easier to establish a real time link between the physical AMB model and the discrete controllers, with the advantage of data acquisition and parameter changing in real time. The performance of the AMB system can further be improved by means of advanced control techniques like fuzzy logic control (Ciocirlan et al., 1998), sliding mode control (Allaire & Sinha, 1998) and $H_{\infty}$ control (Djouadi & Tsiotras, 1999).

One of the most effective and efficient modern custom power devices used in power distribution networks to mitigate power quality problems, such as voltage swell and voltage sag, is dynamic voltage restorer (DVR) (Shitole & Gopalakrishnan, 2012). The implementation of the control and detection algorithm of DVR in the dSPACE® (DS1104) real time simulator is presented by (Shitole & Gopalakrishnan, 2012).

References

9. Conclusions

For this project, an axial suspended AMB experimental bench for load and disturbance tests was developed. This project is the first phase of a larger project on the development of a high performance axial AMB jackhammer for soft use in the residential and industrial sectors. The advantage of this project lays in the results obtained from the experimental developed system which was constructed by using relatively low-cost, low-precision components. The developed system provides results on different load conditions, different disturbance conditions and variation in input step response conditions.

From the load test with the PID controllers, it can be seen that the steady-state error ($e_{ss}$) remains zero up to an added mass of 2.5 kg. From the steady state error obtained during the load test, the conclusion can be made that the PID controller is the better controller, since it has a smaller steady state error. The lead controller also suspends the disc, but has a larger steady state error.

From the disturbance test with the PID controllers it can be seen that the steady-state error remains zero when a ball causing a disturbance at a height of 25 mm. From the data obtained for the disturbance test, the conclusion can be made that the PID controller is also the better controller (in terms of the $e_{ss}$). The lead controller recovers from the disturbance, but has a larger steady state error.

From the input step response test, the analog lead controller provides the advantage of the lowest damping ratio ($\zeta$) and the lowest damping constant ($b_{eq}$) for a 2 mm input step response. The discrete lead controller provides the advantage of the fastest time-to-peak ($T_p$) for a 2 mm input step response. The analog PID controller provides the advantage of the lowest natural frequency ($\omega_n$) and lowest stiffness ($k_{eq}$) for a 2 mm input step response. The discrete PID controller provides the advantage of the fastest settling time ($T_s$) and lowest percentage overshoot ($P.O.$) for a 2 mm input step response.

Fig. 14. Complete axial AMB model.


