Bearingless Five-Axis Rotor Levitation with Two Pole Pair Separated Conical Motors

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Abstract - In some high performance applications, such as high speed rotating machinery, systems where access for maintenance is limited, or operating environments with extreme temperatures and pressures, motors without mechanical bearings would be preferred.

This paper presents the theory, simulation, and lab results of a new type of fully magnetically levitated bearingless motor. The motors are wound without internally connecting the pole pairs, and force is controlled by varying rotor reference frame d-axis current to each pole pair. This in turn raises or lowers the flux caused by the permanent magnets, creating a flux imbalance on the periphery of the rotor [1], which in turn creates a net force on the rotor. The conical shape of the motor allows forces to be created in both radial and axial directions, allowing these motors full 5-axis levitation.

Index Terms – Bearingless Motor, Conical Motor, 5-axis levitation.

I. INTRODUCTION

Most rotating machinery currently in use today uses some type of mechanical bearing to attach the rotor and the stator. For most machines, where access to the bearings for performing routine maintenance is available and operation does not tax the bearings to the point of failure, this is the most cost effective means of suspension.

However, some applications do not allow the use of mechanical bearings. In high performance applications requiring high speed operation, or extreme operating environments (e.g. high temperature or pressure), or where there is an inherent lack of access for maintenance, bearingless motors are preferred. One example of an application with both high speed and lack of maintenance access is flywheel energy storage used on a spacecraft [2].

An example of extreme environment would be a motor / generator on the shaft of a jet engine. Of course, such extreme environments would also limit the types of motors which could be used, but magnetic circuits have been demonstrated in 1000º F environments [3].

One method of eliminating mechanical bearings is to levitate the rotor using magnetic bearings. For a fully levitated system, assuming the rotor is a rigid body, this would require control of the rotor x and y position in two planes, as well as the axial position of the rotor. This requires two radial magnetic bearings and one axial magnetic bearing. One major disadvantage of this approach is that it requires iron and copper which do not contribute to motor power. Additionally, this approach increases the axial length of the rotor, which lowers the bending mode frequencies of the rotor, causing problems for high speed machines. Allowing the rotor’s synchronous speed to run higher than the first bending mode of the rotor poses considerable control problems.

In order to address these issues, a five-axis levitating rotor where all copper and iron can contribute to either levitation or rotation (depending on system need) is desired. This paper presents a system which accomplishes this goal.

Previous bearingless motor designs require special levitation windings, wound on the motor stator. These designs have been implemented in several different motor types: synchronous reluctance [4], induction [5], permanent magnet [6], and switch reluctance [7]. Note that, in each of these designs, the additional windings have a different number of poles than the motor. The advantage this approach is that it separates the motoring control from the levitation control, reducing the interaction between the motoring function and the levitation function. Using this approach, the
motor and the magnetic bearings share the same iron, which reduces the rotor length and raises bending mode frequencies of the rotor.

With this approach, all of the iron is available for motoring and levitation, but not all of the copper is available for both functions. Although operating scenarios may arise wherein more power is needed for either the motoring or the levitating function, this system does not offer the flexibility to redistribute the needed power.

The rest of this paper describes a new technique of achieving bearingless capability, which does not use separate bearing and motor windings, and thus can use all motor iron and copper for either levitation or torque. A prototype motor demonstrating this technique was designed, built and tested. Although the prototype was an open core permanent magnet motor, the levitation technique presented in this paper can be applied to synchronous reluctance and induction motors as well.

Three different models are used to analyze this new bearingless motor: a magnetic circuit model, finite element analysis, and a Simulink model of the control system.

II. POLE PAIR SEPARATED BEARINGLESS MOTOR

The first innovation presented in this paper is a method of controlling both the motor torque and rotor levitation forces using field oriented control. Traditionally, motors are wound such that no lateral forces are induced in the rotor, which is desired which is so that vibrations are not generated. This is accomplished automatically through the motor design, because the windings comprising pole pairs are connected together, either in series or parallel. Thus the forces induced by each pole pair are the same in magnitude, and due to motor symmetry, the vector addition of these forces always induce a net force of zero on the rotor. A schematic of a standard motor with a series winding connection is shown in Figure 1.

Because of this inherent lateral force balance, motors built with standard windings cannot obtain levitation. However, the prototype motor presented in this paper is wound with the pole pairs left deliberately disconnected. With this scheme, it becomes possible to generate different q-axis and d-axis rotor reference frame currents ($i_{qs}$ and $i_{ds}$) values in each pole pair, thus allowing a net lateral force on the rotor. This new motor winding scheme is seen Figure 2.

The power electronics required to drive a standard 3-phase motor is shown in Figure 3. In this scheme, six switches are required to generate an arbitrary rotor reference frame $q$ and $d$ axis current.
The pole-pair separated bearingless motor requires a more complex power electronics drive, which is shown in Figure 4. In this drive, 18 switches are used to produce arbitrary rotor reference frame d and q axis currents in each of the three individual pole-pole pairs. Although this drive system requires more switches, it should not necessarily require more silicon, because the rating of each switch will decrease. This reduction can be tailored to the needs of the application. For example, if the number of turns per coil is kept the same in bearingless motor as in the standard motor, the voltage of the bearingless motor will be one third of the standard motor, and thus the switches will need only one third of the voltage block capability; and if the turns are increased to keep the voltage of the two motors equal, the current requirement of the switches will be decreased by 3. Although this drive configuration is more complicated, it does have the additional benefit of fault tolerant capability; this will be discussed later in this paper.

A permanent magnet machine was chosen for the prototype motor presented in this paper. It was decided that all pole pairs would be controlled to have the same \( i_{qs} \), which is accomplished by employing a synchronous frame current regulator inner loop on each of the pole pairs. This results in the following torque,

\[
T_e = 6 \cdot \frac{3}{2} \frac{N_m \cdot \lambda_{af-pp} \cdot i_{qs}}{2},
\]

Where \( N_m \) is the number of motor poles, \( \lambda_{af-pp} \) is the magnet flux linkage for one pole pair. This scheme is controlled with an outer-loop controller commanding a desired level of torque.

In the new motor design, forces are induced on the rotor by varying the \( i_{ds} \) to each pole pair; since each pole pair will no longer produce the same force, the net force on the rotor is no longer zero.

A finite element program was used to model the flux density of the prototype machine where the d-axis currents are set to \( i_{ds-1} = 20 \), \( i_{ds-2} = 0 \), and \( i_{ds-3} = 0 \). The results, presented in Figure 5, clearly show that a flux density imbalance is created.

Next, a magnetic circuit model of this machine was developed, including the yoke, backiron, and each gap, tooth, and magnet. The model schematic is shown in Figure 6. Using this model, a positive and a negative constant d-axis current was applied to each pole pair, and the force applied to the rotor was calculated for each tooth, then summed to obtain the net force [8]. The results of these simulations over a motor rotation of 360 degrees, are shown in Figure 7. In all cases, the magnitude of these forces versus the motor...
electrical angle is the same (see Figure 8). Also, the phases of these forces versus electrical angle are plotted in Figure 9.

There are always six possible force vectors that can be applied to the rotor, from the positive and negative rotor reference frame d-axis currents applied to each of the three pole-pairs (Figure 10). These forces bound six distinct regions; a desired force within any region can be produced optimally by using the vectors bordering that region as the basis.

Now a control scheme using this approach will be described. For the purpose of developing the controller, the magnitude of these vectors is assumed to be a constant,

$$F_{pp} = k_i \cdot i_{ds-pp}'$$  \hspace{1cm} (2)

where the constant $k_i$ is the current stiffness of the machine.

Equations for the phase of these vectors as a function of the electrical angle of the rotor were generated by fitting curves to the above force phase data:

$$\beta_1 = 22.04 \cdot \cos \left( 2 \cdot (\theta_e + 105) \frac{\pi}{180} \right) - 150$$  \hspace{1cm} (3)

$$\beta_{1-negative} = \beta_1 + 180$$  \hspace{1cm} (4)

$$\beta_2 = \beta_1 - 120$$  \hspace{1cm} (5)

$$\beta_{2-negative} = \beta_2 + 180$$  \hspace{1cm} (6)

$$\beta_3 = \beta_1 + 120$$  \hspace{1cm} (7)

$$\beta_{3-negative} = \beta_3 + 180$$  \hspace{1cm} (8)

During rotor levitation, the phase of the desired force is calculated and compared with the six available force vectors, and the two force vectors bordering the region containing the desired force are then chosen as the basis. Next, the desired force is transformed from the x, y basis to the basis containing the two vectors to be used, $\beta_{boundary-1}$ and $\beta_{boundary-2}$. The transformation is performed using the following matrix:

$$P = \begin{bmatrix}
\text{real} \left( e^{j \beta_{boundary-1} \frac{180}{\pi}} \right) & \text{real} \left( e^{j \beta_{boundary-2} \frac{180}{\pi}} \right) \\
\text{imag} \left( e^{j \beta_{boundary-1} \frac{180}{\pi}} \right) & \text{imag} \left( e^{j \beta_{boundary-2} \frac{180}{\pi}} \right)
\end{bmatrix}$$  \hspace{1cm} (9)

This allows the two currents that make up the boundary to the region, $i_{ds-boundary1}'$, $i_{ds-boundary2}'$, to be defined as follows.
\[
\begin{bmatrix}
  i_{d_{\text{boundary 1}}} \\
  i_{d_{\text{boundary 2}}}
\end{bmatrix}
= P^{-1} \cdot
\begin{bmatrix}
  F_{x_{\text{com}}} \\
  k_i \\
  F_{x_{\text{com}}} \\
  k_i
\end{bmatrix}
\]

(10)

proportional to the difference between the sums of the rotor reference frame d-axis currents in the top motor and the bottom motor.

Now the magnetic circuit model is run with arbitrary force commands, which are converted to required rotor reference frame d-axis currents according to (10). Several different force commands were applied, and the rotor was rotated 360 electrical degrees in simulation. The developed rotor force using this technique is presented in Figure 11.

III. CONICAL AIR-GAP

The next innovation presented in this paper is the use of a conical air gap in the prototype motor, as shown in Figure 12. The conical gap allows a component of the force to be directed in the axial direction as well the radial directions. In the prototype motor, two conical motors were combined on a single rotor with cones in opposite directions, as seen in Figure 13. In this configuration, the net z-directed force is proportional to the difference between the sums of the rotor reference frame d-axis currents in the top motor and the bottom motor.
Axial force generation is accomplished using the scheme shown in Figure 16. First, the \( d \)-axis rotor reference frame current required to provide the desired radial forces is found using the process described above. As discussed above, if left uncompensated, these \( d \)-axis currents will cause an undesired axial force in addition to the intended radial force. Correction for the unintended axial force is done via the \( z \)-force block.

The \( z \)-force block calculates the axial force generated by the radial force blocks by summing all of the \( d \)-axis currents in the top and bottom motors, and then multiplying the difference (which is the net axial current) by the axial stiffness. As mentioned above, an axial force which does not affect the radial force can be created by adding a constant \( d \)-axis command to the top motor, and subtracting the same constant from the bottom. When an axial force command is passed to this block from the position controller, the undesired axial force created by the radial control is subtracted from this command, then the required constant current to prevent radial impact is added from the top motor and subtracted from the bottom motor.

IV. RESULTS

Figure 17 shows the test setup for the pair of prototype conical motors. The motor controller is a dSPACE system with a 0.3 ms sample time.

The prototype motor was successfully levitated and spun at a variety of speeds. During a 300 RPM operation, data was taken on the rotor position in 5 axes, as well as the motor currents. The x-y plots of the top and bottom radial positions during operation are presented in Figure 18 and Figure 19, and the axial position during operation is shown in Figure 20. The rotor reference frame \( d \)-axis currents for the top rotor are presented in Figure 21.
Next, the system response to a step function is measured. While the rotor was levitated but not rotating, a step of 1 mil was commanded in the x1 (top x axis) position. The step response of the rotor along the x1 axis is shown in Figure 22. Note that, although there is some overshoot, the rotor position does settle in at the commanded position.

Next, the loop gain of the x1 controller was measured in hardware, and compared to the loop gain obtained through simulation. The comparison is shown in Figure 23. Note that the measured loop gain matches the simulated loop gain fairly well except for around 32.5 Hz.
To try to understand the origin of the extra mode seen in the experimental data, a standard rap test was performed on the motor. The accelerometer was attached in the center of the mounting plate, and the hammer was struck close by. The transfer function of the hammer input to the accelerometer output shows a clear dip in magnitude at 32.5 Hz (Figure 24), which is consistent with the experimental loop gain data. Based on the rap test results, it was concluded that the extra 32.5 Hz mechanical mode was likely a rigid body mode of the motor baseplate interacting with the mounting isolation dampers.

Finally, the experimental loop gain data was used to generate a transfer function, which represents the open loop system, and is useful in stability analysis.

First, the experimental loop gain data was fit to a ratio of complex polynomials [9], [10]. Since the controller has a known sample time of 0.3 ms, this delay was first divided out of the loop gain data, then the delay free data was curve fit. This process yields the following:

\[
T(s) = T_{\text{no-delay}}(s) \cdot e^{-s \cdot \text{delay time}} \tag{11}
\]

\[
T_{\text{no-delay}}(s) = \frac{N_{\text{no-delay}}(s)}{D_{\text{no-delay}}(s)} \tag{12}
\]

\[
N_{\text{no-delay}}(s) = -6.06e^{-11}s^5 + 5.12e^{-8}s^4 + 1.88e^{-5}s^3 + 2.28e^{-3}s^2 + 1.31s + .392 \tag{13}
\]

\[
D_{\text{no-delay}}(s) = 2.37e^{-14} \cdot s^6 + 1.32e^{-10} \cdot s^5 - 1.41e^{-8} \cdot s^4 - 7.60e^{-6} \cdot s^3 - 5.22e^{-5} \cdot s^2 - s \tag{14}
\]

Using (13) and (14), the zeros and poles of the open loop transfer function were calculated. The transfer function has the following zeros:

\[
s = 1.16e3 \tag{15}
\]

\[
s = -3.33e2
\]

\[
s = 1.11e1 \pm j \cdot 2.37e2
\]

\[
s = -3.00e-1
\]

And the following poles:

\[
s = 0 \tag{16}
\]

\[
s = -5.65e3
\]

\[
s = 3.78e2
\]

\[
s = -3.20e2
\]

\[
s = 1.86e1 \pm j \cdot 2.48e2
\]

Also using (13) and (14), a Nyquist stability plot was generated, and is shown in Figure 25. Although the open loop transfer function has three poles in the right hand plane, the Nyquist stability plot shows that -1 is encircled three times in the counter clockwise direction, which guarantees that the closed loop system is stable.
V. CONCLUSIONS

A new type of bearingless motor was described. A prototype motor was simulated, built and tested. Five axis levitation and rotation of the rotor using only motors was demonstrated, and experimental results were compared to the simulations. This new bearingless motor design approach has multiple advantages. It minimizes the axial length of the rotor, lowering the frequency of the rotor bending modes and making control much easier. Also, unlike in previous bearingless designs, this approach allows all of the copper to be used for both levitation and rotation, making less copper necessary, lowering the total system weight. In addition, this topology provides inherent fault tolerance.

ACKNOWLEDGMENT

The authors would like to thank Ronald Storozuk for mechanical design work on the prototype machine, Erhard Hartman for fabricating the prototype machine, and Walter Santiago for work on the instrumentation.

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