A MAGNETIC BEARING SYSTEM USING CAPACITIVE SENSORS FOR POSITION MEASUREMENT

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Abstract — **A capacitive sensor system for use in a bearingless induction motor is presented. Details of the circuit design are presented. A theoretical step response is calculated and compared with experimental results.**

INTRODUCTION

Previous work on magnetic bearings over the past 150 years has involved both passive and active systems [1 - 3]. Commercial bearings with high effective stiffnesses are now available at high cost with active suspension systems. These are generally used in high speed applications where position control is important. The emphasis of the work described in this paper is an application where position control is of minor importance but the ability to suspend and rotate a shaft without mechanical contact is of prime interest. This paper describes a preliminary investigation to determine the feasibility of controlling the currents in the existing stator coils of a conventional squirrel cage induction motor to achieve a satisfactory levitation effect.

In principle, if the currents in three distinct coils, space displaced by 120 degrees, are controlled independently it is possible to achieve a positive control in any direction in a two dimensional plane. However, since the ultimate intention is to modulate the coil currents to achieve both levitation and rotation it is likely that better results will be achieved through a larger number of independent coils. Partly for this reason, but primarily for conceptual convenience the initial work described in this paper was performed on a four pole induction motor with six independent coils. This paper describes results obtained on the system shown in figure 1. Here only two of the coils on opposite sides of the rotor are excited, to control the position in one dimension.

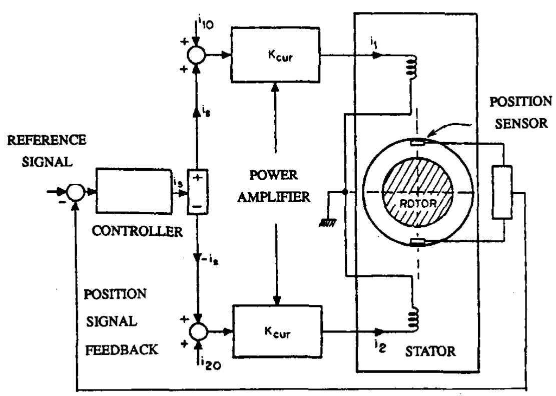

Fig. 1. Experimental System

SYSTEM MODEL

The magnetic circuit of the system consisting of the rotor and the two opposing stator coils may be represented as the lumped reluctance model shown in figure 2. Each coil is represented as an mmf source with a main flux path through the rotor iron $\mathcal{R}_{r1}+\mathcal{R}_{rm}+\mathcal{R}_{r2}$, across two air gaps $\mathcal{R}_{gm1}+\mathcal{R}_{gm2}$ and returning through the stator iron $\mathcal{R}_{s2}+\mathcal{R}_{sm}+\mathcal{R}_{s1}$. There are also secondary paths $\mathcal{R}_{gs1}$ and $\mathcal{R}_{gs2}$ back from the rotor to the stator without linking the second coil.

In an induction motor the relative direction in which the two mmf sources are connected depends on the number of poles in the machine. In the four pole machine described here the sources would be opposed and in a symmetrical system no flux would flow through $\mathcal{R}_{sm}$ and $\mathcal{R}_{rm}$. In a six pole machine the sources would be in the same direction.

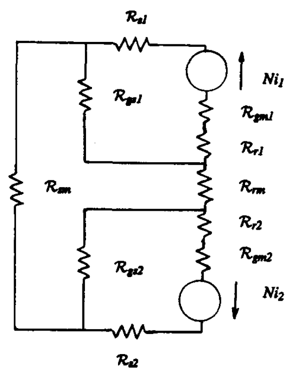

Fig. 2. Approximate Magnetic Equivalent Circuit

Using the concept of Maxwell field stresses it can be seen that there will be a net vertical force on the rotor if the airgap flux densities at the top and bottom of the rotor are different. These flux densities may be approximated by the flux through $\mathcal{R}_{gm1}$ and $\mathcal{R}_{gs1}$ at the top and $\mathcal{R}_{gm2}$ and $\mathcal{R}_{gs2}$ at the bottom. Qualitatively, these fluxes will be different if the airgap reluctances are different due to asymmetry in the rotor position or if the magnitudes of the mmf sources are different. An accurate prediction of this force would require a detailed field analysis but for the work described here the relationship between force and current or position was found empirically.

In a dynamic model of the system the rotor winding should also be included, since voltages will be induced in this by any change of flux linkage. However, as a simplifying assumption the effect of this winding was ignored and only the self inductances of the two stator windings were included. Thus for each winding the force exerted on the rotor at a particular current can be found from the expression:

$$F_y = \frac{1}{2} i^2 \, dL/dy \tag{1}$$

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where L is the self inductance of the coil and y is the vertical displacement. This inductance varies as the reciprocal of the magnetic circuit reluctance, which in turn is approximately proportional to the airgap length. It is therefore assumed that L can be represented by an expression of the form:

$$L = K_1/(G - y) \tag{2}$$

where G is the mean airgap length and y is the vertical displacement of the rotor from the central position.

By symmetry this expression can be applied to both windings except that an increase in the gap on one side produces a decrease in the opposite gap. When eqn. (1) is combined with eqn. (2) the following expression for the net force produced by both windings is obtained:

$$F_y = K_2 \left\{ \left(\frac{i_1}{G-y} \right)^2 - \left(\frac{i_2}{G+y} \right)^2 \right\} \tag{3}$$

This equation can be linearized about the operating point by partial differentiation resulting in the following relationship:

$$F_y = F_{y_o} + 2K_2 \left\{ \left[\frac{i_{10}}{(G-y_o)^2} - \frac{i_{20}}{(G+y_o)^2} \right] \Delta i - \left[\frac{i_{10}^2}{(G-y_o)^3} - \frac{i_{20}^2}{(G+y_o)^3} \right] \Delta y \right\} \tag{4}$$

where the additional zero subscript implies steady state values and F_{y_o} is found from eqn. (3) with this substitution. Δi and Δy represent small deviations from these steady state values. It is assumed that the system control is such that a positive increment in one coil current is accompanied by an equal negative increment in the other coil current.

The mechanical system is represented by the equation:

$$m\frac{d^2(\Delta y)}{dt^2} = F_y - F_c m \tag{5}$$

where m is the rotor mass and F_c represents a steady force in the $-y$ direction. In the system analysed this is simply the gravitational force and under steady state conditions will be equal and opposite to F_{y_o}.

Combining eqns. (4) and (5) and taking Laplace transforms results in a transfer function of the following form for small perturbations about the steady state value:

$$G(s) = \frac{\Delta Y(s)}{\Delta I(s)} = -\frac{K_i/m}{s^2 - K_y/m} \tag{6}$$

This has a pole in the right half plane which requires compensation to produce a stable closed loop response.

The electrical system must also be modelled. This comprises a power voltage amplifier and the L/R time constant of the coil. As an open loop system these both have time constants which are short compared to the mechanical time constant. In the present configuration an additional current loop was used so the electrical system is modelled as a simple transconductance gain K_o.

IMPLEMENTATION OF POSITION SENSOR

The effectiveness of any control system is strongly dependent on the quality of the feedback signals. In this application it was necessary to obtain position information with a minimum of hardware. It was also possible that the shaft might be very short or non existent. This led to the need to sense the radial position of the rotor directly from its outer circumference. The use of a capacitive sensing system offered the possibility of being both rugged and able to operate in the airgap of the machine without any significant magnetic field effects. The configuration used is shown in figure 3. Five electrodes are mounted in the airgap, which are connected to the circuit shown in figure 4.

The principle of operation is that the ring electrode 0 is connected to a reference oscillator. The ring structure is chosen to minimize the variation with position of coupling the reference signal to the rotor iron, although this is not an essential feature. The high frequency (150 kHz) current which is thus injected into the rotor returns through electrodes 1 - 4. A tuned amplifier connected to each of these electrodes produces a voltage which is a function of the value of the capacitance between each electrode and the rotor. With a centralized rotor all the voltages will have the same amplitude and the difference in amplitude between pairs of voltages can be used to produce a position error signal. This is done using a peak detection and filtering circuit.

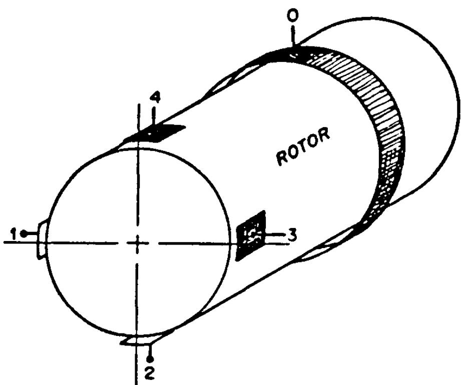


Fig. 3. Location of Electrodes in Capacitive Position Measurement System

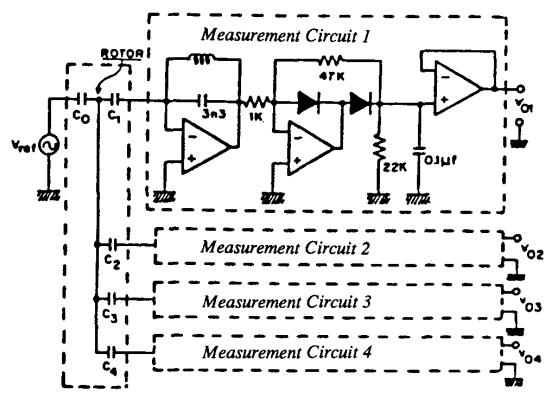


Fig. 4. Signal Processing Circuit

STABILITY ANALYSIS

The block diagram of the complete system is given in figure 5. In addition to the elements already described there is an additional derivative control stage $G_D(s)$. This block also incorporates filtering to reduce high frequency noise problems leading to a relationship of the form:

$$G_D(s) = \frac{K_d s}{(\tau_1 s + 1)(\tau_2 s + 1)} \tag{7}$$

The time constants τ_1 and τ_2 are the filter time constants and are chosen to be small compared to the other system time constants. This allows the transfer function to be approximated as:

$$G_D(s) = K_d s \tag{8}$$

Two additional gain blocks are shown in figure 5. One is the gain of the proportional element K_p. The other is K_b, the effective gain of the position detection circuit. The overall system transfer function can be represented by the relationship:

$$\frac{Y}{Y_{ref}}(s) = \frac{K_p K_i K_o / m}{s^2 + (s K_b K_d K_o K_i + K_b K_p K_o K_i - K_y)/m} \tag{9}$$

It can be shown [4] that the system is stable if $K_d K_i > 0$. The system step response can then be simulated using values appropriate to the real system. This simulation is compared to the experimental response in the next section.

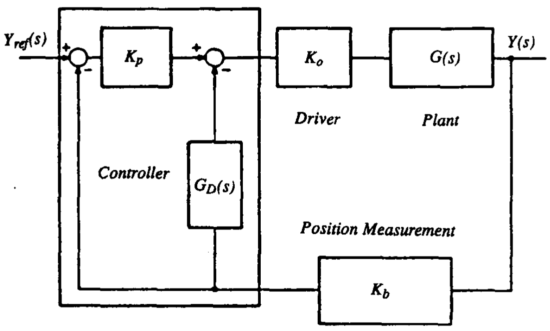


Fig. 5. System Block Diagram

EXPERIMENTAL RESULTS

The time constants of the system elements and other system parameters were determined experimentally. These are tabulated below:

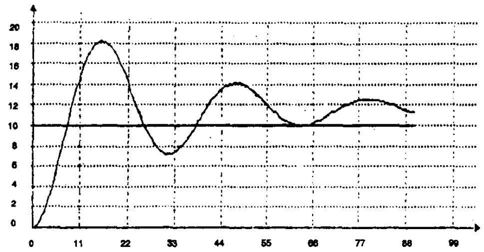
Amplifier and Winding Time Constant	11.8 ms
Measurement System Time Constant	500 μs - 5 ms
Rotor Mass (m)	550 g
Airgap (G)	1.5 mm
Per Unit Steady State Current to Support Rotor	0.33

$K_o = 10$, $K_b = 3000\ V/m$, $K_y = 1114\ N/m$

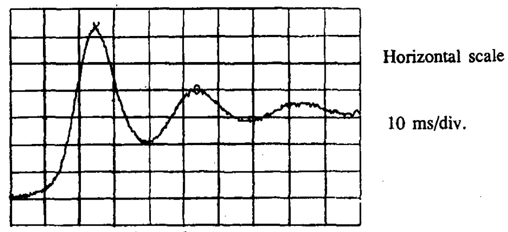
$K_i = 1.67\ N/A$, $K_p/K_d = 40$

The peak detector response is not symmetrical which is reflected in the overall response of the measurement system. However, both this and the electrical system time constants are short compared to the mechanical time constant as assumed in the above analysis.

The simulated and experimental step response of the system is presented in figure 6. It can be seen that these waveforms are very similar, which lends confidence to the various approximations which were made in the model. It should be noted that the experimental response was due to a perturbation of unknown amplitude. No conclusion can therefore be drawn about the absolute amplitude of the response.



a) Simulated response



b) Experimental response

Fig. 6. System Step Response (K_p = 0.5)

CONCLUSIONS

It has been shown that one dimensional position stability of an induction machine rotor can be obtained by controlling the currents in diametrically opposed conventional stator windings. In the case considered the weight of the rotor was supported by a stator current of 33% of the rated value. A margin is therefore available for the addition of a rotating component of current. The rotor of this machine had been reduced during development of the position sensor. It is anticipated that the system could be implemented with a smaller airgap and consequently smaller steady state current. The position signal was satisfactorily obtained using a simple airgap mounted position sensing system. An approximate model of the non-linear system is sufficient for predicting the closed loop step response for small perturbations.

ACKNOWLEDGEMENTS

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