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ROBUST MAGNETIC BEARINGS FOR FLYWHEEL ENERGY STORAGE SYSTEMS

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Abstract

Magnetic bearings are an essential component of flywheel energy storage (FES) systems because of their very low frictional losses, and their extremely long expected operating lifetimes. In this paper recent work on the development of magnetic bearings for a 500 Wh FES system, which is to be used for low earth orbit space applications and is being constructed at the University of Maryland, is described. In this paper two aspects of magnetic bearings are discussed. The first is the design of bearing control systems which prevent large scale self–sustaining non linear oscillations from being established, while the second is the development of an improved inductive displacement transducer which differentiates between rotor growth and rotor displacement.

1. Introduction

The use of magnetic bearings for flywheel suspension in space–borne flywheel energy storage (FES) applications has been studied by Kirk and Studer [1,2] where they have shown that they are essential for such systems to operate efficiently, because of their very low frictional losses, and their extremely long expected lifetimes.

At the University of Maryland design studies of 300 and 500 Wh FES systems for spacecraft applications have shown it is important to maximize the flywheel specific energy density (SED), and a bench mark system design goal of 20 Wh/kg has been set as it exceeds, by an acceptable margin, the 14 Wh/kg of electrochemical systems [3,4,5]. Because of the required SED advanced fibre–composite flywheels are needed, and it has been shown that these need to operate at high rotational speeds, in the range 33 000 to 66 000 rpm, so as to make effective use of these materials. These operating speeds necessitate placing the flywheel in a vacuum to minimize aero–dynamic drag. Since magnetic bearings operate without physical contact and so require no lubricants, and also have no intrinsic speed limitations they appear to be ideally suited for this application. Experience has shown with the electromagnet/permanent–magnet (EM/PM) bearing designs discussed in this paper that the total power losses can be one or even two orders of magnitude smaller than comparable fluid film or rolling element bearings. Also their non–contact operation precludes tribo–physical degradation which limits the life expectancies of the other bearing types mentioned above.

In this paper recent work on the development of magnetic bearings for the 500 Wh FES system, which is to be used for low earth orbit satellite applications is described. Attention will be focussed upon the two aspects of bearing controller design and position transducer configuration, both of which have a significant impact upon the robustness of bearing operation.

2. Flywheel Design

The 500 Wh energy storage system is based upon a "pancake" magnetic bearing stack as shown in Fig. 1. In this arrangement two magnetic bearings are shown with one positioned at the top of the stack and the other at the bottom. Mounted between these two bearings is the motor/generator which is used for converting mechanical into electrical energy and vice versa. It is a three phase brushless D.C. machine having permanent magnets

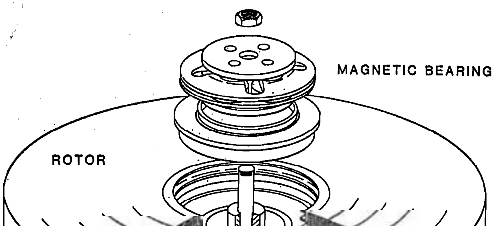

Fig.1. Magetic bearing stack for 500 Wh system.

mounted on the inner surface of the flywheel and a surface mounted winding on the laminated stator core. The design of the motor/generator is discussed in detail by Neimeyer [6] and Neimeyer et.al. [7]. To protect the magnetic bearing actuators and suspension rings as well as the motor/generator when magnetic suspension failure occurs back–up bearings are used. Under normal operating conditions the flywheel is suspended so that there is a uniform clearance of approximately 0.15 mm between the outer ring of the ball bearing and the inner surface of the flywheel. When there is loss of suspension or a large disturbance occurs and the flywheel deflects outside the above range then the flywheel is supported by the ball bearings thus preventing internal damage.

Not shown in the figure, but nevertheless an integral part of the system is the power conditioning electronics for the motor/generator, and the electronic control system for the magnetic bearings. Estimates of the mass of these components has been made and is included when calculating the total system SED.

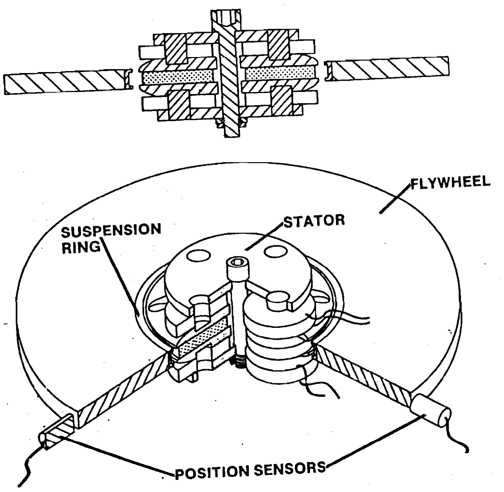

Fig.2. Sectioned view of pancake bearing.

3. Magnetic Bearings

The pancake magnetic bearing used in the 500 Wh energy storage system are EM/PM bearings and a sectioned view of one is shown in Figure 2. In these bearings permanent magnets are used to establish a uniformly distributed bias flux around the airgap between the stator and the suspension ring. In addition electromagnets having controlled currents are used to regulate the magnetic flux in designated quadrants of the pole–faces so as to generate net forces on the flywheel which can be used to control its motion.

These bearings were designed to support a $2g$ axial load without loss of suspension. Based upon experience with earlier designs for the 300 Wh flywheel the static stiffness K_x and current sensitivity K_i for the 500 Wh flywheel bearings were selected to be 981 N/mm (5600 lb/inch) and 249 N/amp (56 lb/amp) respectively. From these values and the estimated flywheel mass the mechanical and electrical design of the actuators was carried out using a suite of computer design programs written at the University of Maryland. In all cases the flux density in the magnetic components was limited to 1.5T.

The design methodology followed involved the iterative computation of the magnetic flux densities in various components for a set of trial physical dimensions. The coil design, which was also performed iteratively, was determined from K_i, and the maximum amplifier output current and voltage. A deficiency of this approach becomes evident when it is realized that the current sensitivity K_i together with the magnetic design determines the required magneto–motive force of the coils. This can be achieved by many combinations of number of coil turns and magnitude of coil current; however it is not clear from static analysis what the optimum choice is for the number of coil turns and the concomitant coil current.

It should be noted though that the coil inductance also increases rapidly with increased number of coil turns, which means that the applied coil voltage must increase significantly if the coil current is to be able to change rapidly under dynamic conditions. Because of uncontrollable oscillation and other difficulties experienced when commissioning the magnetic bearings for the 500 Wh flywheel an investigation of the effects of coil inductance on their operation has been undertaken. The results of this work are discussed below.

The flywheel excursion range was limited to ± 0.15 mm by the touchdown bearings. Theoretical analysis, confirmed by subsequent measurement, showed that the values of K_x and K_i vary as the flywheel traverses from one extreme of the excursion range to the other. It will be seen that these variations in the above parameters as a function of flywheel position can under injudicious circumstances have a profound effect upon the bearing control system robustness.

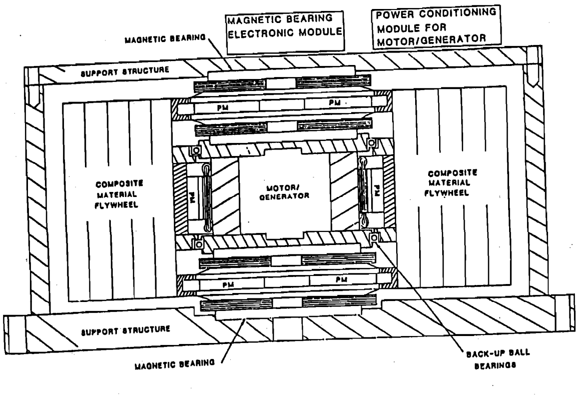

Fig.3. Cross–sectional view of 500 Wh flywheel energy storage system.

4. Robust Magnetic Bearing Control System Design

In the design of the magnetic bearing control systems for the University of Maryland flywheel energy storage system difficulties have arisen from two independant sources. The origin of the first difficulty which appeared quite early in the development phase arose from vibrations of the structure supporting the pancake bearings. Analysis [8] has shown that structural vibrations within the bandwidth of the bearing control systems can seriously affect their operation with the potential risk of instability. These vibrational effects were overcome by progressively improving the mechanical design of the central bearing stack shown in Fig. 1, and by increasing the stiffness of the flywheel support structure, illustrated for the 500 Wh system in Fig. 3. Extensive modal analysis of the final design by Lashley [9] showed that the structural modal frequencies were all well outside the bearing control system bandwidth.

Nevertheless during the commissioning of the bearing control systems for the 500 Wh flywheel great difficulty was experienced in initially suspending the rotor, and any slight disturbance was found to cause the system to break into violent oscillations. In addition, in spite of careful adjustment of the controller time constants and gains it was impossible to make the system self–suspend when the power was first connected. The results of careful investigation has shown that unless the bearing actuator parameters are carefully chosen at the design stage then the control system is likely to break into limit cycle oscillations which cannot be easily controlled by control system parameter adjustment.

The origin of these oscillations has been discussed by Zmood et. al. [10, 11]. They have been found to be due to the combined effect of the power amplifier saturation voltage, the bearing actuator parameter K_x, and the physical constraint of the flywheel displacement. A good understanding of these oscillations can be obtained from studying the operation of the simplified block diagram given in Fig. 4.

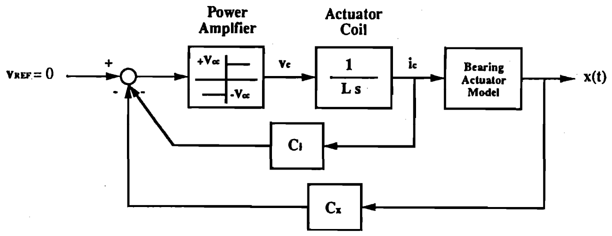

Fig.4. Simplified bearing control system block diagram.

To understand the mechanism of these oscillations imagine for the moment the flywheel mass is zero. In this case the flywheel will move from one physical limit to the other instantaneously, once the threshold current $i_{crit} = \pm K_x x_m / K_i$ is reached. Here K_x and K_i are the magnetic bearing static stiffness and current sensitivity repectively, while x_m is the maximum rotor excursion. Since the coil inductance limits the rate of change of the coil current, the flywheel will oscillate between the physical limits, $\pm x_m$, at a frequency determined by the amplifier supply voltage, the coil inductance, and the current i_{crit}. When the mass is zero the system will oscillate irrespective of the values of the control system parameters C_x and C_i, or the coil inductance L.

In practice, the flywheel mass cannot be neglected. In this case it is shown by Zmood [11] that the control system given in Fig. 4 can be stabilized provided the parameters C_i and C_x are selected correctly. The conditions that need to be satisfied are

$$(1) \qquad \frac{K_x}{K_i} < \frac{C_x}{C_i} < \frac{K_x}{K_i}\left[\frac{1}{2} + \sqrt{\frac{1}{4} + \frac{K_i\alpha'}{K_x x_m}}\right],$$

where the current $\alpha' = V_{cc}/\omega_m' L$, $\omega_m' \approx \sqrt{K_x/M}$, V_{cc} is the amplifier supply voltage, and M is the flywheel mass. Even though the system shown in the above figure is a simplification of the physical bearing control system, the results of experiment and of detailed simulation compare very favourably with the limits given by the above inequalities.

The inequalities given in Eq. (1) are plotted in Fig. 5 using the parameters for the experimentally tested bearing. It will be noted from this figure that the bearing can, in principle, be stabilized by an appropriate choice of the gain parameters C_x and C_i for all coil inductance values. In particular it will be observed that the current gain parameter C_i must be non–zero for stability to be possible. The most important observation to be made from this diagram, however, is that as the coil inductance increases the range of the ratio C_x/C_i for which the system is stable gets narower and narrower. Thus for large values of inductance the values of C_x and C_i need to be selected very carefully.

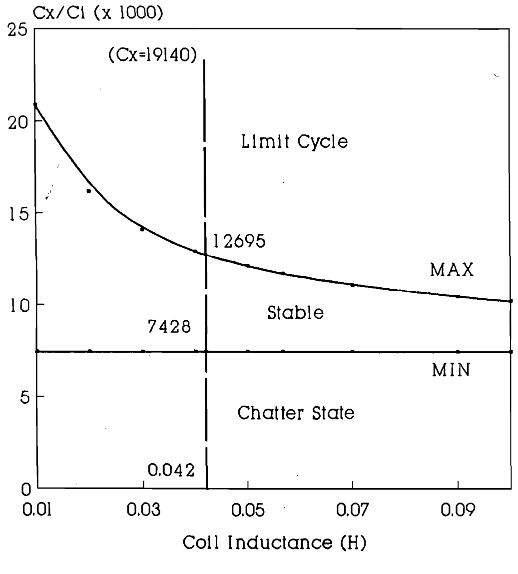

Fig.5. Stability diagram showing variations of C_x/C_i as a function of coil inductance.

Conversely, suppose C_x/C_i is chosen to stabilize the bearing control system for some nominal values of the parameters K_x and K_i. It will be observed from the diagram that if the coil inductance is large then we can only tolerate very small variations of K_x and K_i about their nominal values if stability is to be maintained. Unfortunately, as we have observed above, the uncertainty in the values of these parameters is quite large and varies as a function of the flywheel displacement, so if the coil inductance is too large then it may be impossible to stabilize the rotor. For the bearings tested in the laboratory this was indeed initially the case as self–suspension was impossible, and even when the flywheel rotor was suspended and stabilized by using locking screws it was found that small transient disturbances caused oscillations to develop. When the coil inductance was decreased by a factor of 1:4 by re–winding the coils a marked improvement in bearing robustness was observed, and in particular it was found that it could easily self–suspend when power was applied.

5. Position Transducers and Sensor Positioning

An essential component, of magnetic bearings for use in flywheel energy storage systems, is the non–contacting position transducer which is used to measure the translational displacements of the rotating flywheel relative to the magnetic bearing stators. These transducers convert physical displacements into electrical signals which are fed to the bearing control system. While many techniques are available for non–contact sensing of displacement, to date, no completely satisfactory method has been found which satisfies all requirements. Plant [12,13] has closely examined a number of competing transducers, utilizing inductive, capacitive, and optical techniques. He has also experimentally investigated the performance of a number of commercially available transducers, but has found them all wanting in some respect. It is for this reason that effort has been devoted to developing suitable position transducers for flywheel applications at the University of Maryland, which meet fairly stringent requirements of: reliability, simplicity of concept, robustness, and ease of application.

Of the many techniques considered we have concentrated our attention on those using inductive, capacitive, and optical methods, and in the following we will consider them under the headings:

- Sensitivity
- External disturbing effects
- Packaging

Sensitivity

Both the inner and outer bores of the flywheel grow significantly as it spins from zero to a maximum speed of 66 000 rpm. In the case of the inner bore the radial growth has been estimated to be 0.5055 mm at a speed of 52 000 rpm. On the other hand the rotor translational motion is limited by the touchdown bearings to ±0.15mm about its nominal centre position, which it is observed is significantly less than the radial growth. Consequently any rotor position measuring system which senses the position, of either the flywheel outer rim or its inner bore, must be able to differentiate between displacements due to these two sources.

Currently available commercial transducers, whether of the inductive, capacitive, or optical type, having a single sensor head are incapable of achieving this differentiation, as they sense only at one radial position on, say, the flywheel inner bore. In this case the airgap will be held constant in the region of the sensor and all radial growth will be accommodated by airgap growth in the region diametrically opposite. The nett results of this type of control is that the flywheel geometric axis of symmetry will be displaced away from the bearing stator magnetic centre, so that considerable current will need to be supplied to the control windings to balance the destabilizing forces of the permanent magnets. This situation is highly undesirable as the power consumed by the suspension system will increase considerably.

To overcome this difficulty differential transducers need to be used. In the case of inductive devices this can be achieved by using two inductive elements positioned to sense on diametrically opposite sides of the flywheel inner bore. If these inductors are connected in an electrical bridge circuit the bridge balance will be unaffected by radial growth, and will only sense changes in inductance due to translational motion. A similar situation will occur with differentially connected capacitive and optical sensors. In practice a radial growth to translation rejection ratio of 1:1000 may be achieved with inductive transducers, but the same cannot be said for either capacitive or optical devices. Under worst case conditions for inductive transducers a radial growth of 0.51 mm will only appear as an equivalent 0.00051 mm translational motion, which is less than 0.3 percent of the full scale translational displacement.

Experience has shown that sensitivities in the range 2 to 40 V/mm are achievable with acceptable output signal–to–noise ratios for all of the above transducer types, but the sensitivities are usually limited in applications to the range 2 to 4 V/mm. Commercially available inductive and capacitive transducers appear to operate with carrier frequencies of 1 to 2 MHz, and with low pass output filters having bandwidths of about 10 kHz. The optical transducers which operate on either reflective or interruptive principles are generally of the baseband type and their operating bandwidth is essentially determined by response characteristic of the photo–detector, which can be as high as 100 kHz. Again, in practice this is likely to be limited to approximately 10 kHz to limit the output signal–to–noise ratio.

External Disturbing Effects

Since inductive transducers rely upon magnetic effects they are particularly prone to interference from external magnetic fields generated by the magnetic bearings actuators. Plant [12] has investigated a number of commercially available inductive transducers and has found them to all be sensitive to the presence of external magnetic fields even when sensing displacements relative to aluminium targets. This being in spite of advice to the contrary from the manufacturers. Subsequent experimental investigation of one commercial transducer has shown the probable cause to be due to the transducer sensor casing. This casing is manufactured from a stainless steel which is mildly, but sufficiently, ferromagnetic so that the transducer calibration is affected by changes in the saturation level of the steel when it is immersed in an external magnetic field. It seems likely that the manufacturer could correct this problem by using a truly non–ferromagnetic material, such a brass. Radio frequency interference can also affect these transducers, but because of the low impedance levels at which they operate this problem can be easily overcome.

Capacitive transducers are totally insensitive to magnetic fields, so they would seem to offer good prospects in this application. However their very high impedance levels, the effect of stray capacitances, and the very small changes in capacitance which needs to be sensed make it quite difficult to achieve satisfactory operation. In addition the high operating impedance levels can lead to serious problems from power frequency and radio frequency interference. Methods of overcoming these problems need to use active guarding and specially shielded cables. Commercial transducers are available but the bulkiness of the sensors together with the high cost has discouraged their use in magnetic bearings.

Two types of optical transducers have been considered. In the reflective type the target must have constant reflectivity, and be preferably a plane surface held at a constant angle to the transmit/send head. For the flywheel the reflective surface is obviously curved and it is extremely difficult to retain constant reflectivity around either its inner or outer perimeter. Experience has shown this method to be highly unreliable in this application. The interruptive optical transducer has been shown to work extremely well with good linearity and sensitivity using commercial light emitting diodes and phototransistors. However strong doubts exist about the stability of the photo transistor sensitivity which is known to drift with time for many devices.

Packaging

Both capacitive and inductive transducers require a metallic target, and if they are to sense displacement on the flywheel outer rim then it must have a metallic surface attached by some means. The limited strength of metals combined with the very high surface speed of the flywheel makes this a difficult task. Interruptive optical transducers on the other hand can operate on the flywheel outer rim because they do not require a metallic target.

While the difficulty of attaching a metal surface to the outer rim may possibly be overcome, mounting the position transducers so as to sense displacement on the outer rim of the flywheel is not recommended for other reasons. Firstly, there are problems in maintaining concentricity between the flywheel outer rim and its inner bore, both during manufacture and especially when it is running at high speed. The latter situation arises due to the effects of large rotor growth with increase in rotor speed, and the inhomogeneity of the composite structure causing an eccentricity to develop between the flywheel outer rim and the inner bore which changes as a function of speed. Secondly the transducer sensors need to be rigidly and accurately fixed to the flywheel outer support structure which in turn must be accurately positioned with respect to the bearing stator; a complicated manufacturing problem. Thus for both manufacturing and operational reasons it is sensible to mount the position sensors internally so as to measure the displacement of the flywheel inner bore relative to the magnetic bearing stators.

Apart from the desirability of mounting the transducer sensors internally it is desirable that they sense along the plane of symmetry of the pancake magnetic bearing actuators, and yet at the same time they must not interfere with the assembly of the flywheel during construction. Neither the inductive nor capacitive types of position sensors need interfere with the flywheel assembly, but the interruptive optical type will, by the nature of its construction and operation, do so. The best mounting position for the inductive and capacitive sensors would be between the two pole faces of each actuator, Fig. 6(a), so that they sense the distance to the suspension rings. However because of restricted space and the presence of strong magnetic fields it is not practical to mount them in this location. Alternative locations which overcome the collocation problem will be discussed below.

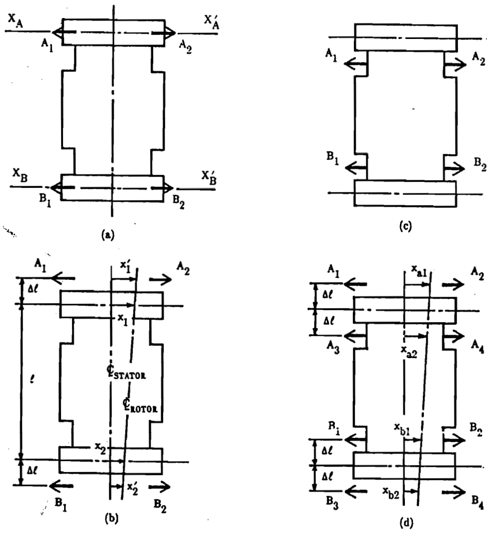

Fig.6. Alternative positions for displacement sensors. Sensor positions indicated by arrowed blocks.

Sensor Positions

The remainder of this discussion will centre on the application of inductive sensors and how they may be used in electrical bridge networks to solve the collocation problem by ensuring the effective displacement sensing planes are along the bearing actuator planes of symmetry, and also to cancel the effects of rotor growth.

Four possible arrangements for the inductive sense coils of the transducers are shown in Fig. 6. The most ideal arrangement is shown in Fig. 6(a) where the coils are mounted between the pole faces, as this enables direct displacement measurement in the bearing planes $X_A X_A'$ and $X_B X_B'$. For practical reasons this arrangement is difficult to implement and so will not be considered further.

The remaining possible arrangements can measure the displacments in the bearing planes of symmetry provided it is assumed that the bearing actuators and the motor/generator are rigid bodies. For example, let us consider the alternatives shown in Figs. 6(b) and (c) where the inductive sense coils are shown by the arrowed bars in each case. From simple geometry the displacements x_1 and x_2 can be calculated from measurements x_1' and x_2' and for the case shown in Fig. 6(b) are given by

$$x_1 = x_1'\left[\frac{\ell + \Delta\ell}{\ell + 2\Delta\ell}\right] + x_2'\left[\frac{\Delta\ell}{\ell + 2\Delta\ell}\right], \tag{2}$$

and

$$x_2 = x_1'\left[\frac{\Delta\ell}{\ell + \Delta\ell}\right] + x_2'\left[\frac{\ell + \Delta\ell}{\ell + 2\Delta\ell}\right]. \tag{3}$$

When the sensors are inboard of the bearings the errors in the computation of x_1 and x_2 due to uncertainties in $\Delta\ell$ will be larger than for the corresponding outboard case. However as long as $\Delta\ell/\ell$ is small the error in either case can be neglected and the computed values of x_1 and x_2 can be used in place of their exact values in the respective bearing controllers.

If the motor cannot be considered to be rigid then the arrangement shown in Fig. 6(d) needs to be used. Here the sense coils A_1, A_2, coils A_3, A_4, coils B_1, B_2 and coils B_3, B_4 are separately connected in series. Since these coils are symmetrically displaced about the bearing planes of symmetry the transducer outputs will be x_1 and x_2, where

$$x_1 = \frac{x_{a_1} + x_{a_2}}{2}, \tag{4}$$

and

$$x_2 = \frac{x_{b_1} + x_{b_2}}{2}. \tag{5}$$

The Inductive Sensor

In Fig. 7 is shown a simplified schematic of the experimental inductive bridge transducer, which can be used in any of the mechanical arrangements shown in Fig. 6. The sensor inductors are connected in a Maxwell impedance bridge whose ouput is fed to a synchronous demodulator. The output of the demodulator passes through a low pass filter which filters the residual high frequency modulation products as well as any extraneous noise induced into the circuitry. The filter output is an analog signal whose magnitude is proportional to the displacment x. To ensure good balance of the bridge circuit special care needs to be taken to retain symmetry in all parts of the circuit; especially in the wiring of the inductors.

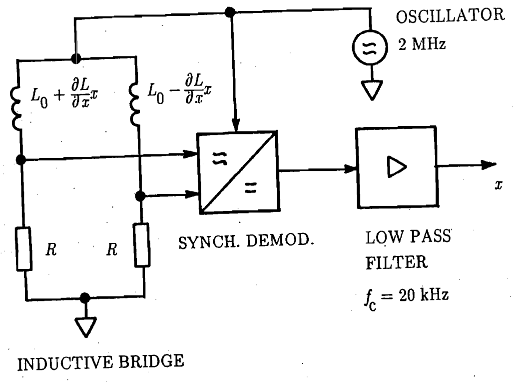

Fig.7. Simplified schematic of inductive bridge transducers.

Heeding the observations made above about the use of stainless steel in the bodies of commercial inductive transducers, care was taken to only use non–ferrous materials, such as aluminium, in the construction of the experimental sensors. Aluminium was also used for the transducer target. Experiments showed that using this construction made the transducers insensitive to changes in external magnetic fields.

6. Concluding Remarks

Two aspects of magnetic bearings for flywheel energy systems which contribute to their robust operation have been considered.

Firstly it has been shown that bearing control systems experience limit cycle oscillations if the actuator coil inductances are too large. The analysis above shows that for the control system to be stable the control gain ratio C_x/C_i must lie within upper and lower bounds which are determined from the characteristics of the bearing actuator. These bounds are particularly sensitive to actuator coil inductance. These considerations profoundly influence the design methodology of the actuators. In the new approach the coil ampere–turns for the actuator are determined as before from static force considerations. Now however the coil inductance is determined from Eq. (1) so as to ensure adequate control system robustness, and from this the number of turns for the control winding can be calculated. From the above information the peak actuator drive current is calculated and the sizing of the control winding amplifiers determined. This approach should be contrasted with the one previously followed, where the winding specifications and the amplifier sizes were largely determined from static considerations. Using the above approach we have found that bearings operates quite robustly, can withstand large transient disturbances, and are easily able to self–suspend.

Secondly it has been shown that the use of differential position transducers enables the rotor displacement to be differentiated from rotor radial growth. As a consequence the bearing control system operation will be markedly less sensitive to disturbances due to rotor growth than when single–sensor displacement transducers are used. Although inductive transducers can be sensitive to external magnetic field, in most other regards they are much less sensitive to extraneous effects than capacitive and optical transducers. Experience has shown that if care is taken to avoid using ferro–magnetic materials (including stainless steel) in their construction then magnetic effects can be minimized. These types of transducers are currently being included in the design of the 500 Wh flywheel energy storage system.

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