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THE SECOND INTERNATIONAL SYMPOSIUM
ON
ELECTRO-MAGNETIC SUSPENSION

Proceedings of a Symposium held in the Department of Aeronautics and Astronautics, the University of Southampton, England during 12th to 14th July, 1971.

The Symposium organisers were Dr. M.J. Goodyer and Dr. M. Judd. The programme was divided into sessions during which papers were presented which described researches in the following or closely related fields:

Reviews of electro-magnetic techniques which are currently used for the suspension of wind tunnel models, and which are under development for future surface transportation vehicles. Discussions of their characteristics and problems, and examples of application.

Representative aerodynamic data which is currently being obtained with the wind tunnel magnetic suspension and balance systems. Indications of those areas where quality or scope require improvement.

Electrical power supply characteristics, electromagnet design and performance, and the influence of scaling and the use of superconductors on these components.

Position sensing, automatic position control, force and moment calibration techniques, and data acquisition.

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SESSION I. Chairman, Dr. M. Judd (Southampton University)

SESSION II. Chairman, Professor E.E. Covert (M.I.T.)

SESSION III. Chairman, Professor H.M. Parker- (U.VA.)

SOME REMARKS ON SERVO-CONTROLLED MAGNETIC SUSPENSIONS AT THE UNIVERSITY OF VIRGINIA

An Introductory paper by Professor J.W. Beams
of the University of Virginia, U.S.A., relayed by Professor H.M. Parker

I indeed am very highly honoured by the invitation to present a paper at this Symposium on Electro-magnetic Suspension. It has been suggested that I should confine my remarks to some recollections of the early work done at the University of Virginia on the development of the Servo-Controlled Magnetic Suspension. I am very pleased to do this for three principle reasons: first it gives an old man a chance to reminisce, second, it is obvious that I am not in a position to make a really meaningful contribution to the very highly sophisticated modern researches and techniques which are to be discussed in this Symposium and third it allows me to restrict my remarks to the word done at Virginia and relieves me of the responsibility of discussing, in the finite time available for these remarks, the enormous amount of very excellent, important and highly original work done elsewhere.

There is a well known theorem first proven by Earnshaw in 1839 which states that a charged body placed in an electrostatic field cannot be maintained in stable equilibrium under the influence of the electric forces alone. When applied to the magnetic case, Earnshaw's theorem also shows that a ferromagnetic body (permanent magnet) when placed in a magnetic field produced by other stationary permanent magnets will not rest at equilibrium under the influence of the magnetic forces alone. Records show that many amateur experimenters and inventors have amply demonstrated the correctness of this theorem. On the other hand a diamagnetic body such as a superconducting metal or graphite crystal can be stably supported by a proper configuration of stationary permanent magnets or vice versa. This, of course, is not a violation of Earnshaw's theorem. Furthermore the theorem does not apply when the permanent support magnets are continuously moving or when the support magnetic field is made to change with time in the proper way. The same is also true in the electrical case when the charges or electrical fields are moved or varied. Consequently, it is not surprising that the great advances in electronics, servo-circuit techniques, photoelectric and solid state devices, low temperature physics, etc. has made possible many types of practical and useful electric and magnetic suspensions in the last few decades.

My own interest in magnetic suspensions and/or magnetic bearings dates back more than 40 years, when we employed them for partially supporting very high speed rotors. These rotors spun about a vertical axis in a vacuum. A symmetrical vertical axial magnetic field produced by an electro-magnet or permanent magnet placed just above (not in contact) a cylindrical steel rotor supported about 97 percent of the weight of the rotor (weight = 100 lbs). The remainder of the weight of the rotor was supported by an air bearing or oil thrust bearing. Actually the function of the air or oil bearing was only to maintain a stable vertical position of the rotor. If the vertical axis of the magnetic support field and the axis of the spinning rotor coincide no change in flux occurs when the rotor spins so this type of magnetic support bearing has zero friction unless the rotor vibrates or precesses. If the magnetic support is mounted in a damping medium such as an oil dash pot it not only serves as a support but also as a damper. Although the above arrangement greatly reduced the friction of the thrust bearing there still was appreciable drag due to the air and/or oil bearings which were necessary to keep the rotor in a stable position. It was, of course, clear that if the stabilizing thrust bearing could be eliminated by a proper variation of the magnetic field in the support the rotor friction due to the bearings could be made negligible. This problem was undertaken in our laboratory at the University of Virginia by F.T. Holmes and in the latter part of 1936 he succeeded in freely supporting magnetically a small steel rod.

A short time later Holmes and the writer succeeded in freely suspending and spinning a small rotor to above 1000 r.p.s. in a vacuum and observed the expected negligible friction on the rotor. In these early experiments the vertical position of the rotor was sensed by a photoelectric cell that actuated a control circuit which in turn regulated the current through the support solenoid in such a way as to maintain the ferromagnetic rotor at a constant vertical position. Since any free ferromagnetic body will seek the strongest part of the magnetic field, the steel rotor was held automatically on the vertical axis of the axial magnetic field. Consequently the rotor was maintained at a constant position inside the vacuum chamber. It might be interesting to mention that in these early experiments the poor quality and very bad regulation of our power supplies greatly contributed to the instability of the magnetic support. Holmes and the writer were soon joined by L.B. Snoddy and the magnetic support was made somewhat more stable. Simultaneously with the above early work with the magnetic suspension the same principles (servo system) were applied to the successful levitation of bodies in our laboratory by electrical forces but, in general, the magnetic suspension was thought to be better adapted to the suspension of high speed rotors of the kind that were in use at Virginia. Unfortunately World War II was approaching (1939) and our principal efforts were diverted to problems of National defence, but the magnetic support development was continued by a graduate student in our laboratory, L.E. McHattie who succeeded in spinning several steel rotors to destruction.

Following the end of the war the development of the magnetic suspension was again undertaken at Virginia. Fortunately we were able to apply our experience obtained during the war with various kinds of servo-circuits, to the problem and the magnetic suspensions soon became extremely stable and reliable. Rotors with weights from 100 lbs to 10^{-9} lbs were stably supported and spun. Small rotors were spun to 1.5×10^6 r.p.s. in a vacuum and, in general, the mechanical strength set the only limiting factor to the attainable rotational speed. Furthermore experiment showed that when special care was taken the frictional drag on a spinning magnetically supported rotor could be accounted for as due entirely to gaseous friction on the rotor surfaces down to pressures of at least 5×10^{-8} tor in the surrounding vacuum chamber. For several years the magnetic suspension has been used successfully for supporting ultracentrifuge rotors which routinely spin in a vacuum for weeks at constant speed and constant temperature, and in many other problems which require high speed rotors.

It, of course, was clear from the pre-World War II experiments that the servo-controlled magnetic suspension system could be made into a microbalance. Any external forces applied to the magnetically suspended body in any direction produces a change in the current in the supporting solenoid. If the force is applied only in the vertical direction and if the supporting magnetic field is produced by an air core solenoid with its axis vertical, the relation between the solenoid current and the applied vertical force to the suspended body is both simple and exact. Consequently the sensitivity and precision of the servo-controlled magnetic balance is limited only by the noise in the circuits. In the late 1940's after more stable and reliable servo-support circuits had been developed the writer noticed that it was necessary to vary the current in the support solenoid by an appreciable amount in order to maintain the suspended body at a given vertical position as the air was pumped out of the vacuum chamber. At first it was necessary to increase the current due to the reduction of the buoyancy of the air on the suspended body but when a low pressure was reached the absorbed water and gases on the surface of the body started coming off and the current in the solenoid had to be decreased. These observations showed that the servo-controlled magnetic suspension could be used as a very sensitive microbalance which would be of great use in weighing bodies inside of a vacuum chamber, under a liquid, or inside of any sealed chamber where direct connections to the outside would disturb the results.

Further improvements in this magnetic support microbalance showed it to be extremely reliable and could measure 10^{-6} of the mass of the suspended body. Changes in weight of 10^{-11} grams were observed. Masses from 10^{5} grams to 10^{-6} grams were suspended with the same apparatus. Another important characteristic of the servo-controlled magnetic balance is the extreme steadiness of the supported body. For example measurements with an interferometer showed that both the vertical and horizontal motion of the supported body when suspended in a vacuum tight chamber was less than 0.1 the wave length of light. This property of the magnetic balance has greatly contributed to its success as a magnetic densimeter which, in effect, weighs a calibrated buoy beneath the surface of a fluid solution and employs Archimedes principle to determine the density. Consequently the absence of motion of the buoy eliminates all wall and viscosity effects and makes possible precise measurements on small specimens (~ 0.2 milliliters) of material. This is especially important in the determination of densities and hence partial specific volumes of many solutions of biomacromolecules which are so difficult and expensive to purify that they are available only in very small amounts. It might be interesting to note that when the freely suspended body beneath the fluid surface is made cylindrical and coaxial with the cylindrical container, and rotated very slowly by an electromagnetic drive, the viscosity is obtained from the power input by the drive. Consequently measurements of both the viscosity μ and the density ρ are made simultaneously on very small specimens of material. The measurements are very precise both on liquid solutions and on gases. Incidently the magnetic suspension technique has made possible the determination of the mass, volume and shape of biomacromolecules in solution with greatly increased precision. You will recall that the upward force on a magnetically suspended body is

$$F_z = M \frac{\partial H}{\partial Z}$$

where H is the magnetic field and Z is the vertical co-ordinate. In general $M = M_o + f\ (H)$ where M_o is the permanent moment and f(H) is the magnetic moment induced by the field H. For magnetically soft material the permanent moment M_0 approaches zero and for many cases $M \cong f(H) \cong K_1 I$ where K_1 is a constant and I is the current in the supporting air core solenoid.

$$\frac{\partial H}{\partial Z} = K_2 I$$

is an exact relation so for the soft magnetic material $F_z \cong K_3 I^2$ over comparatively small ranges of F_z. In modern densimeters most of the weight of the suspended body is supported by a solenoid with a constant current or by a permanent magnet. A pair of Helmholtz coils connected in series are coaxial with the solenoid or permanent magnet and arranged so that as the current through two coils is varied their magnetic fields at the suspended body cancel while their field derivatives add. Consequently the magnetic moment M remains constant while

$$\frac{\partial H}{\partial Z}$$

produced by the coils is exactly proportional to the current I in the Helmholtz coils over wide ranges. Although in the early work the relations were worked out for the horizontal stability of the magnetic balance and with proper shaping of the field the restoring force in the horizontal direction could be made quite large, there were a number of problems where solenoids with their axes in appropriate directions other than the vertical Z co-ordinate were necessary. It is clear that with such arrangements forces along X and Y as well as Z axes are measurable with the magnetic balance. In 1958 H.M. Parker and his associates at Virginia designed and built a truly 3-dimensional magnetic support system. Since a discussion of the modern version of this balance is on the agenda of this symposium, no attempt will be made to tell you more about it at this time.

As mentioned previously, with a properly designed magnetic suspension, a suspended spinning rotor has a negligible bearing friction as compared to the gaseous friction on the rotor down to gas pressures below 5×10^{-8} tor. On the other hand in the case of a rotor originally starting from rest there is, in most cases, a very slight restoring torque when the rotor is first given a slight angular displacement. This restoring torque can be made to approach zero by spinning the rotor to say one-half its bursting speed and then bringing it to rest. For this reason the magnetic suspension can be used as a super sensitive torsion balance. It was early observed in our laboratory that a beam of light focused on a small spherical suspended rotor (off axis) in a high vacuum caused the rotor to start spinning due to the pressure of the light. In fact some of these observations probably have lead to the most precise measurement of the pressure of light. The angular momentum of circularly polarized light also is measurable. Preparations are being made at Virginia at the present time to use the vanishingly low starting friction of the magnetically suspended body in the determination of the Newton gravitational constant G, etc.

In closing these remarks it might be fitting to compare the magnetic suspension balance with other precision balances now in use. There seems to be no absolute criterion of excellence for balances. Some balances obviously are better adapted to one application than another and some can be used where others cannot. Nevertheless a quantity usually known as the Range of Load to Precision Ratio (L.P.R.) is a popular criterion of excellence by which different balances can be judged. The largest values quoted for the best modern microbalances under the best possible conditions in a recent authoritive review is an (L.P.R.) of 2×10^8 while the L.P.R. of the magnetic balance under comparable conditions approaches 10^{10}.