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Magnetic Suspension Balance*

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An analytical balance is described in which the materials to be weighed are attached to a ferromagnetic body that is freely suspended by the axial magnetic field of a solenoid. The vertical position of the suspended mass is maintained by the automatic regulation of the current through the solenoid by means of an electronic servo-circuit actuated by a light beam and photomultiplier tube arrangement. The horizontal position of the supported mass is maintained by the symmetrically diverging field of the solenoid. Changes in the nonferromagnetic masses of the suspended bodies are determined by the resulting changes in the current through the solenoid necessary to keep the bodies freely suspended. Masses ranging from 10^5 grams to 2×10^{-6} gram have been suspended. The precision of the balance is limited only by the natural fluctuations in the circuit, the photomultipliers and the support system. This balance is especially useful where it is necessary to weigh materials inside of sealed chambers which contain gases, vapors or liquids, or which are evacuated. A method is described for accurately calibrating the balance.

In the course of some experiments in which high speed rotors were suspended by the axial magnetic field of a solenoid, it was observed that under certain conditions the current in the solenoid could be made to vary rapidly with the nonferromagnetic mass of the rotor.[1] This suggested that the magnetic suspension might be used as a sensitive analytical balance for weighing materials inside vacuum chambers, in liquid, vapors, or gases, and in general under conditions where standard balances are difficult to use. Preliminary results[2] indicated that such a magnetic suspension balance could detect changes in mass of from 10^{-8} to 10^{-9} gram when the total mass was of the order of 10^{-3} to 10^{-4} gram. The purpose of this paper is to describe improvements and modifications of this balance, its calibration, and some of its applications

Figure 1 shows a schematic diagram of the suspension. The material to be weighed is attached to a ferromagnetic body A (a steel sphere in Fig. 1) which is freely supported inside of a vacuum tight chamber made of nonferromagnetic material (glass) by the magnetic field of the solenoid situated above the chamber. The vertical position of the ferromagnetic body A is maintained by the automatic regulation of the current through the solenoid while its horizontal position is determined by the symmetrically diverging magnetic field of the solenoid. Light from a narrow horizontal slit is focused on and just above the suspended body A in such a way that A reflects or scatters light up through the hollow solenoid into a 1P21 photoelectron multiplier tube. The output from this tube actuates an electronic servo-circuit which in turn regulates the current through the solenoid in such a manner that the suspended body A is held at the desired vertical position in the light beam. If now the mass attached to A is increased or decreased, the circuit can be so adjusted that A will move down or up in the light beam, respectively. At the same time the current in the solenoid will increase or decrease. Consequently it is usually convenient, although not necessary, to maintain A at a given vertical position by adjusting the current in the solenoid. The increase or decrease in current in the solenoid required to bring A back to its original position then gives a measure of the mass added to or subtracted from A. The change in mass also may be determined from the change in current in the solenoid directly without bringing A back to its original height, but this requires more careful calibration and adjustment. The vertical position of A is determined by focusing its magnified shadow on a masking slit placed in front of a photoelectron multiplier tube as shown in Fig. 1. The output of the 6291 photomultiplier tube gives a very precise measure of the height of A. When the circuit is properly adjusted no motion of the suspended body A can be observed with a 100 power microscope focused on the scratches on A.

Several different types of solenoids have been used. The one shown in Figs. 1 and 2 consists of 26 000 turns of #32 AWG enameled copper wire wound on a Bakelite frame. The solenoid has an i.d. of 1.5 in., and an o.d. of 3.5 in., and is 2.25 in. high. Its resistance is 2617 ohms and its inductance 41.7 henries when it contains a tubular cold rolled steel core 4.5 in. long with

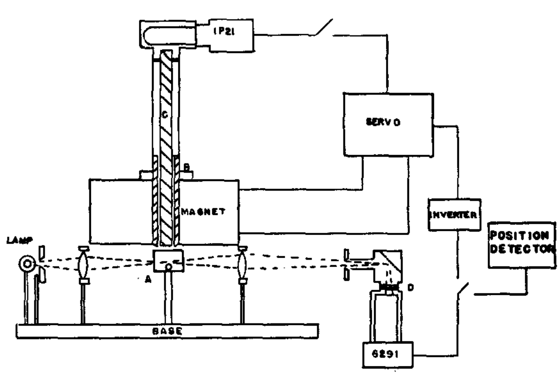

Fig. 1. Schematic diagram of magnetic suspension balance.

* Supported by Navy Bureau of Ordnance and the Office of Ordnance Research.
[1] J. W. Beams, Rev. Sci. Instr. 21, 182 (1950).
[2] J. W. Beams, Phys. Rev. 78, 471 (1950).

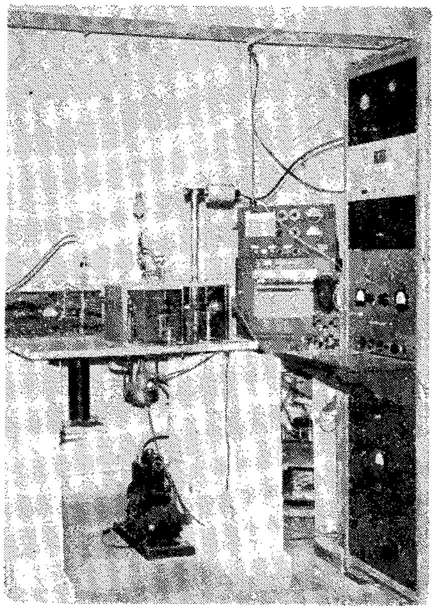

FIG. 2. Experimental arrangement of the components of the magnetic suspension balance.

an i.d. of 0.69 in. and an o.d. of 1 in. This core is positioned by the screw adjustment B. The optical system consists of a Westinghouse 1 AT 5/7 sound track lamp followed by an adjustable horizontal slit and a corrected lens of at least 75-mm focal length. The glass vacuum chamber preferably should have plane parallel sides although good results have been obtained with ordinary cylindrical Pyrex glass tubes. It is, of course, necessary to take account of the effects of any changes in refractive index along the light path. The second lens also is of good optical quality, and at least 75 mm in focal length. The positions of the light source, the two slits and the lens were accurately adjustable in both the horizontal and vertical directions. The solenoid and optical parts were mounted on a heavy soap-stone slab supported by cement blocks, as shown in Figs. 1 and 2. This is necessary to prevent warping and vibrations of the optical and support systems. The light reflected and scattered upward by A reaches the 1P21 photomultiplier tube through a $\frac{5}{8}$-in. Lucite "light pipe" C which is 18 in. long. It is necessary to remove the phototube from the vicinity of the magnetic field as there is an adverse interaction between them.

Several different types of support servocircuits have been used successfully. Figure 3 shows an arrangement that has proven to be easily adjustable and stable. The negative signal from the 1P21 photomultiplier is applied to the grid of a 6J5 which serves as an amplifier. The 6J5 output signal is then fed through the derivative or phase shift network to the grid of a 6SJ7. The variable resistances in the network make it possible to change the phase until maximum stability is obtained. For the solenoid described above the 500 K variable resistor is set at about 200 K and the 50 K resistor at about 30 K. The 6SJ7 serves primarily as an inverter for giving the correct phase relationship at the 5881 beam power tubes. The 330-ohm resistors in the grids and the 100-ohm resistors in the screens and plates of the power tubes are to eliminate parasitic oscillations between the parallel tubes. With a 0.25-mm steel sphere supported roughly 1.5 cm below the solenoid the plate current through the 6SJ7 tube was about 0.01 milliampere and the current through the support solenoid about 50 milliamperes.

The change in potential across the 200-ohm resistor in the support solenoid circuit is used to measure the current changes through the solenoid due to changes in the supported mass A. This voltage across the 200-ohm resistor is balanced out by a potentiometer circuit consisting of a Leeds and Northrup Model 7551 potentiometer coupled with a Brown continuous recording potentiometer Model 153x12V–X30. The L and N potentiometer is used for the large adjustments necessary to bring the recorder on scale. A standard cell is used with the L and N potentiometer so that accurate current measurements can be made. Figure 4 gives a diagram of the measuring circuit. The 200-ohm resistor in the measuring circuit of Fig. 4 is the same as that marked "measure" in Fig. 3. When $S1$ is in position 1 and $S2$ is open the L and N potentiometer is calibrated using the standard cell $S1$ in position 2 with $S2$ open is the arrangement for measuring the support current when accurate values are desired. $S1$ in position 3 and $S2$ closed is the arrangement used to obtain a continuous recording of the variation in voltage across the 200-ohm resistor as a function of the change in mass of the supported system.

The circuit which supplies the potential for the 1P21 photomultiplier is shown in Fig. 5. This circuit is the same as that described by Flagge and Harris[3] except for the changes necessary to adapt their circuit to the 1P21. The circuit used with the 6291 photomultiplier is identical to that devised by Flagge and Harris. The voltage regulators between the stages were G.E. Ne–2 tubes and the resistors had a power rating of 0.25 watt. This arrangement greatly reduced fluctuations and increased the reliability of the photomultipliers over that of a battery supply used in earlier work. The voltage across the photomultipliers was about 1500 volts and was supplied by a high-voltage, low-power type source with RC filters and variable input as described by Braddick.[4] The other power supplies used

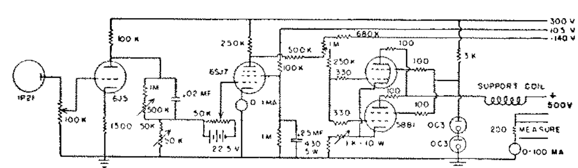

FIG. 3. Support circuit for the magnetic suspension balance.

[3] B. d'E. Flagge and O. R. Harris, Rev. Sci. Instr. **26**, 619 (1955).
[4] H. J. J. Braddick, *Physics of Experimental Method* (John Wiley and Sons, Inc., New York, 1954).

were standard regulated types with low ripple. The light source was supplied by 6 volts of heavy-duty batteries continuously charged with 1.2 ampere. However, if fluctuations are troublesome, they may be approximately balanced out with a third photocell circuit.

It is sometimes desirable to use the 6291 photomultiplier shown in Fig. 1 both as a means of determining the position of the suspended body A and for regulating the current through the support solenoid. This is accomplished by feeding the output of the 6291 tube into the circuit of Fig. 3 in the proper phase. For example, if the movement of the shadow of the suspended body A is utilized then it is necessary to put in or take out one amplifier or 180° phase inverter stage in the circuit.

As will be shown later, the sensitivity of the magnetic balance may be increased by removing the iron core. On the other hand, such an air core solenoid requires a larger support current. We have used an air core solenoid with 40 300 turns of #25 copper wire which required a support current of 170 milliamperes to support the sphere mentioned above. In order to provide additional current, it is only necessary to add additional 5881 power tubes in parallel with the two shown in Fig. 3 and to increase the power of the power supplies. We also have used a solenoid consisting of two concentric windings. A steady direct current is passed through the inner (larger number) windings almost sufficient to support the ferromagnetic body A. A regulated current is then passed through the outer windings which stably supports A. A permanent magnet may of course be substituted for the inner solenoid. In practice, it is found that by decreasing the gradient of the light intensity above the suspended body A the sensitivity of the apparatus may be increased. The best value of this is usually determined by trial. Also, when the shadow on the 6291 photomultiplier is used for regulating the current in the solenoid the light beam, of course, may be positioned below A, as well as above it if desired.

At first sight it might seem that ac amplifiers should be used instead of the dc amplifiers in Fig. 3. In some experiments[5] a 1000-cycle frequency was introduced into the 1P21 photomultiplier output and then removed after the requisite amplification; but, in practice, this was less reliable than the circuit of Fig. 3. Also a small pickup coil, either above or below A, which is in the grid circuit of a tuned-grid-tuned plate oscillator has been used instead of the light beam as a means of regulating the current in the magnetic suspension circuit. This type of circuit has been described in detail previously and is usually used for the suspension of high speed rotors.[6] However, in most experiments the method of Fig. 3 is better adapted to the magnetic balance problem.

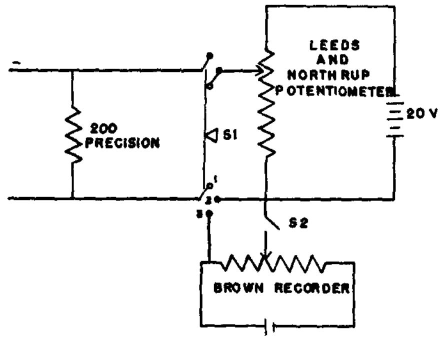

FIG. 4. Measuring circuit for determination of the change in support currents as a function of a change in weight.

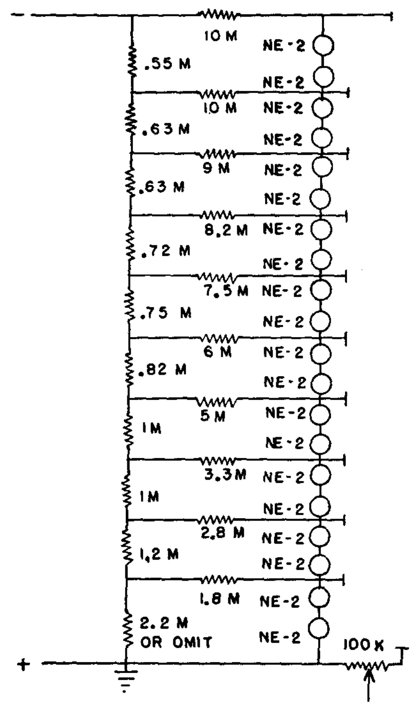

FIG. 5. Voltage regulation circuit for the 1P21 photomultiplier tube.

Although for the case of the air core solenoid, it is possible to calculate the changes in mass of the suspended system A, when the dimensions of the solenoid and the magnitude of the current are known, it is preferable to calibrate the magnetic balance directly. One of the most convenient methods of doing this, when the volume of A is known, makes use of the buoyancy effect of a gas surrounding the suspended body A. Figure 6 shows a graph of the current change through the solenoid *versus* the pressure change of carbon dioxide gas surrounding a suspended 0.182-mm diameter steel sphere. The circles and crosses are points for two consecutive calibrations on different days. It will be observed that a current of 225 microamperes corresponds to a loss in buoyancy of 5.8×10^{-9} gram. The recorder can be read reliably to at least five spaces

[5] W. E. Lotz, Jr., dissertation, University of Virginia (1953).
[6] Beams, Young, and Moore, J. Appl. Phys. **17**, 886 (1947).

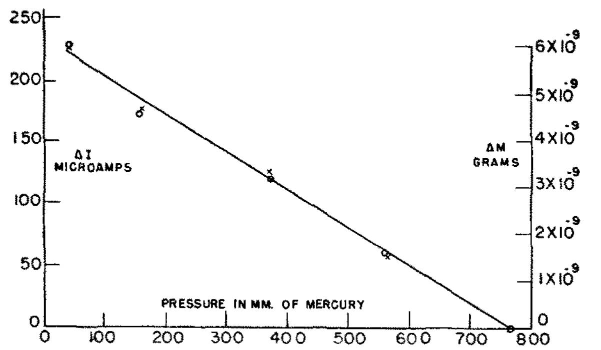

FIG. 6. Calibration curve for the magnetic suspension balance obtained from the buoyancy effect of carbon dioxide gas on a steel sphere.

and each space corresponds to 6.4×10^{-11} gram so that the change in mass of the suspended sphere could be determined to 3.2×10^{-10} gram. The smallest absolute mass changes that we have recorded were the order of 5×10^{-11} gram with a suspended weight of 2.3×10^{-6} gram. This method of calibration, as will be shown later, is reliable only when the gas pressure surrounding A is above 30 mm Hg and when no condensable vapors are present. The calibration of the magnetic balance remains constant from day to day if care is used in lowering and raising A and if the suspension system is not jarred or disturbed. Incidentally, with a comparatively large suspended mass A the above magnetic suspension serves as a good seismograph.

THEORY

The upward force F due to the solenoid on the ferromagnetic body A is $F=\nabla(\bar{M}\cdot\bar{H})=M(dh/dz)$ if the axis of the solenoid is along the vertical z-direction. M is the magnetic moment of A, and H is the magnetic field at A. For a cylindrical air core solenoid of height $2b$, i.d. of $2(r_0-d)$ and o.d. of $2(r_0+d)$, the magnetic field H at a point on the axis below the bottom of the solenoid and a distance z below the center of the solenoid for a current density I is given by

$$H=\frac{2\pi I}{10}\left[(z+b)\ln\frac{r_0+d+[(z+b)^2+(r_0+d)^2]^{\frac{1}{2}}}{r_0-d+[(z+b)^2+(r_0-d)^2]^{\frac{1}{2}}}\right.$$
$$\left.-(z-b)\ln\frac{r_0+d+[(z-b)^2+(r_0+d)^2]^{\frac{1}{2}}}{r_0-d+[(z-b)^2+(r_0-d)^2]^{\frac{1}{2}}}\right]$$
$$=\frac{2\pi I}{10}f_1(z)=K_1I.$$

Assuming that in the use of the magnetic balance the suspended body A will always be at approximately the same position then

$$\frac{dH}{dz}=\frac{2\pi I}{10}f_2(z)=K_2I,$$

where $f_2(z)$ is a slowly varying function of z. If next we assume that the suspended body A is a steel sphere of radius r, permeability μ, mass m_1, that M is proportional to H, and μ is large,

$$m_1g=M\frac{dH}{dz}=r^3\frac{\mu-1}{\mu+2}K_1K_2I^2=K_1K_2r^3I^2$$

or $I^2=4\pi gd/3K_1K_2$, where d is the density of the sphere A. Hence the support current is approximately independent of the radius of the sphere. If now we add a small nonferromagnetic mass Δm

$$\frac{\Delta I}{\Delta m}=\frac{g}{2IK_1K_2r^3}=\frac{I}{2m_1}.$$

Consequently, K_1, K_2, and r should be made as small as possible. The constants K_1 and K_2 may be calculated or their product determined by measuring I before Δm is added. Also it will be observed that the insertion of an iron core into the support solenoid changes the values of K_1 and K_2 in a direction as to decrease the support current required. Similar theory may be used for determining the sensitivity when the suspended body at A is a cylinder or has other shapes by methods similar to that given above for a soft steel sphere. When the added nonferromagnetic mass m_2 is of the same order as the ferromagnetic mass m_1, the change in current is proportional to the square root of the increase in mass. A study of the stability of the support circuit has been made using the Nyquist diagram and attenuation-frequency diagram methods. In brief, the results can be summarized as follows. There are two time constants associated with the phase lead network shown in Fig. 3, following the 6J5 amplifier. Let T_1 be the greater and T_2 the smaller of the two time constants. Let T_3 be the time constant for the supported object in the magnetic field. This is given by $(m/b^2)^{\frac{1}{2}}$ where m is the mass of the supported object and $b^2=dF/dz$ (F is the magnetic force on the supported object and z is the distance from object to solenoid). Finally there is a time constant T_4 for the power circuit which consists of the power tubes, the cathode resistance, and the solenoid.

$$T_4=\left(\frac{R_pLC}{R_L+R_p}\right)^{\frac{1}{2}},$$

R_p is the plate resistance of the power tubes, R_L is the resistance of the solenoid, L is the inductance of the solenoid, and C is the distributed capacitance of the solenoid.

From the Nyquist and attenuation-frequency diagrams, it can be concluded that for stable operation of the support circuit, certain relations should exist among the four time constants. Breazeale[7] has shown that T_1 should be less than or equal to T_3. For the circuit in

[7] J. B. Breazeale, dissertation, University of Virginia (1955).

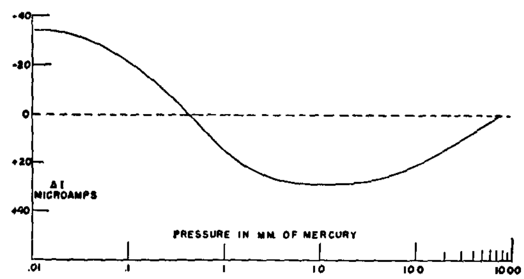

FIG. 7. Buoyancy effect and adsorption of nitrogen on an Armco iron sphere of 0.2-mm diameter.

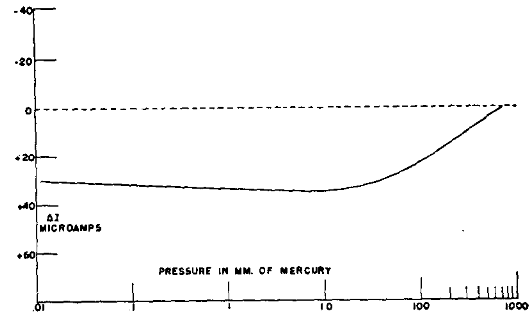

FIG. 8. Buoyancy effect and adsorption of helium on an Armco iron sphere of 0.2-mm diameter.

Fig. 3, T_3 is approximately 0.02 sec. T_1 should be from 5 to 15 times as large as T_2. For the circuit in Fig. 3, $T_1=12T_2$. Also T_4 must be smaller than T_2. Associated with the power circuit there is a damping constant n where

$$n=\frac{1}{2}\frac{R_LR_pC+L}{[R_pLC(R_L+R_p)]^{\frac{1}{2}}}.$$

If n is much greater than 1 it will not be possible to obtain a satisfactory phase margin for the support system. Also, if n is very small, the power amplifier will be underdamped. For best results n should be from 0.25 to 5.0.

The limiting theoretical value for the precision of the magnetic balance is set by the natural fluctuations in the multiplier tubes, the circuits and the suspended body itself. All of these either can be estimated or measured by the usual methods.

Applications

As pointed out above, the magnetic balance described may be used for weighing materials inside of a vacuum chamber, in various gases, vapors, or under liquids. It also has a wide range of sensitivity, and is particularly suited for determining small mass changes. We have suspended masses which vary in magnitude from 10^5 grams to about 2×10^{-6} gram, although these values are by no means the limits of the usable range. It should be noted that when the mass of the suspended body A becomes smaller than 10^{-4} grams, it may stick to the bottom of the glass chamber. This is due to electrostatic charge, and may be corrected by introducing a nonferromagnetic conductor on the bottom of the chamber. When the suspended ferromagnetic body A is subject to attack by corrosive substances it, of course, may be surrounded by glass or other noncorrosive covering to protect it without materially changing the sensitivity. Also, when the optical properties of the surface of A are changed by corrosion the shadow system (6291 tube in Fig. 1) still provides reliable regulation and positioning of A. The balance has proven to be a reliable method of studying the adsorption of gases on surfaces.[8,9] Figure 7 shows the change in current in the solenoid of Fig. 1 when the pressure of nitrogen is varied from 1 atmosphere to 10^{-3} mm of Hg around a supported 0.20-mm Armco iron sphere. The curve was accurately repeatable both when the pressure was increased and decreased. The all glass vacuum chamber and sphere were baked out while the chamber was evacuated through liquid nitrogen traps with an oil diffusion pump. The nitrogen was then passed through liquid nitrogen traps into the vacuum chamber. It will be observed that the increase in current was almost linear with decrease in pressure down to 10 mm of Hg where the curve flattens and reverses, i.e., the sphere gets lighter below 10 mm of Hg. The change in slope of the curve at low pressures is believed to be due to adsorbed gases coming off the sphere at the reduced pressure. It will be noted that this effect becomes fairly large at pressures as high as 0.1 mm Hg. Curves qualitatively similar have been obtained with nitrogen when the sphere was electroplated with copper, silver, or nickel.[9] On the other hand, when helium was used, the adsorption was greatly reduced as shown in Fig. 8. The method has been used for the measurement of the adsorption of a number of different gases on several different metals as a function of pressure.[8,9]

This type of magnetic suspension may be adapted to the measurements of small masses over the temperature range below the Curie point of the suspended ferromagnetic body.[10] When the ferromagnetic body is iron, this range would extend from about 760° C down to liquid helium temperatures.

ACKNOWLEDGMENTS

We wish to acknowledge our indebtedness to Dr. Orville R. Harris and Dr. John B. Breazeale for permission to mention parts of their data before final publication.

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[8] C. W. Hulburt, masters thesis, University of Virginia (1954).
[9] R. M. Montague, Jr., masters thesis, University of Virginia (1955).
[10] J. W. Beams, Science **120**, 619 (1954).