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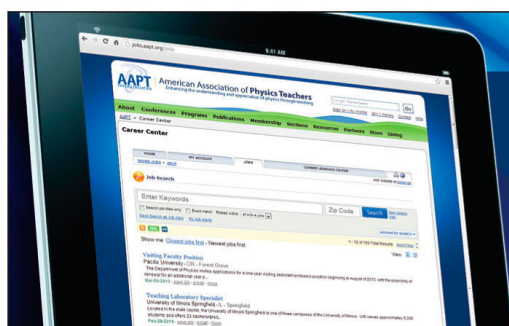
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Magnetic suspension for lecture and classroom demonstrations

W. R. Towler and J. W. Beams

School of Engineering and Applied Sciences and Department of Physics, University of Virginia, Charlottesville, Virginia 22903

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In lecture demonstrations and in the laboratory classroom it is sometimes convenient to suspend a mass freely (without mechanical contact) in a vacuum, in air or in a liquid. Although the literature contains descriptions of many types of magnetic suspensions,¹⁻⁴ in this paper, a servo-controlled magnetic suspension is described which we have employed for a number of years and which has been found useful for the above purposes. The apparatus was designed to operate on the 110-V lines, to be rugged and simple to operate, to be easily portable, to weigh less than 15 lb, to cost less than a total of \$100 (parts alone 1975) and to stably suspend masses up to 100 g a few millimeters below the lower end of the electromagnet.

Figure 1 shows a schematic diagram and Fig. 2 a photograph of the apparatus. The support solenoid consists of 300 turns of No. 18 enameled copper wire wound on a bare plastic spool (solder wire). The core of the solenoid consists of an iron rod $\frac{3}{4}$ in. in diameter and 3 in. long. As shown in Fig. 1, the solenoid is mounted with aluminum sheet stock which also supports the lamp, lenses, and photodiodes that serve as the height sensor. The aluminum box at the bottom houses both the support circuit and the controls.

Figure 3 is a circuit diagram of the magnetic suspension system and its power supply. The vertical displacement of the suspended object is converted into voltage variations by means of an optical pickup system which consists of a photoresistive diode and field-effect transistor (D_1, Q_1). This voltage variation is converted into a current variation in the supporting electromagnet by the remainder of the amplifier circuit, consisting of the trans-

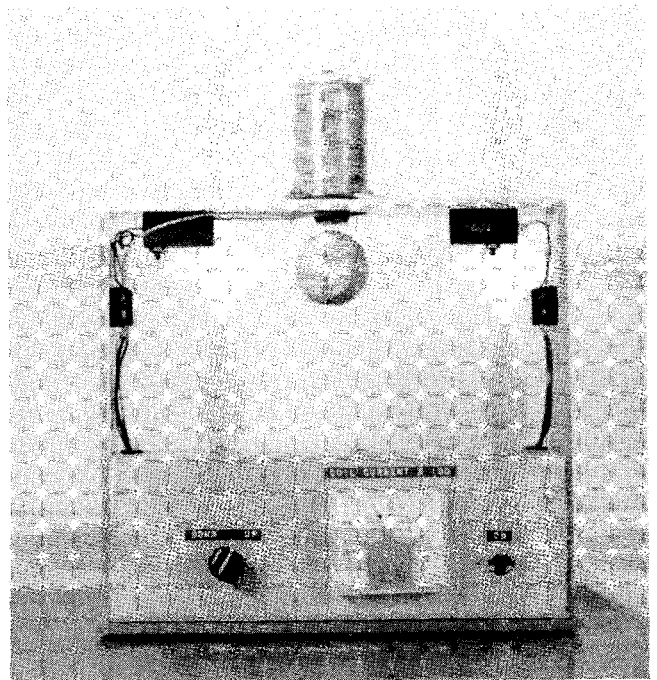


Fig. 2. Photograph of suspension system with small hollow iron globe suspended.

istors $Q_2, Q_3, Q_4, Q_5,$ and Q_6 . Thus, the current in the supporting electromagnet is controlled in such a way that the magnetic attraction exceeds the gravitational force on the suspended object if it moves downward from the equilibrium position, whereas the pull of gravity exceeds the magnetic pull if the supported object rises above equilibrium. Around the equilibrium point the supported object experiences an essentially linear restoring force. The restoring constant K can be determined by defining a distance over which we wish the suspended object to be operative; for instance, a range of 4 mm. At the top of this range all current is to be cut off, leaving only the force of gravity acting on the suspended object (if the effect of the permanent moment of the solenoid core is neglected). At the center of this range we wish to have the equilibrium point where the magnetic attraction equals the gravitational attraction; while at the bottom of this 4-mm range the magnetic attraction should equal twice the gravitational attraction. Therefore, the elastic, or vertical restoring constant K over this range can be written

$$K = 2mg / (z_2 - z_1) \text{ dyn/cm}, \quad (1)$$

where m is the mass of the suspended body, g the acceleration of gravity, and z_1 and z_2 refer to the end points of the linear range. This constant K can be expressed in amperes per millimeter for a suitable solenoid designed to match the load of the object to be suspended. The

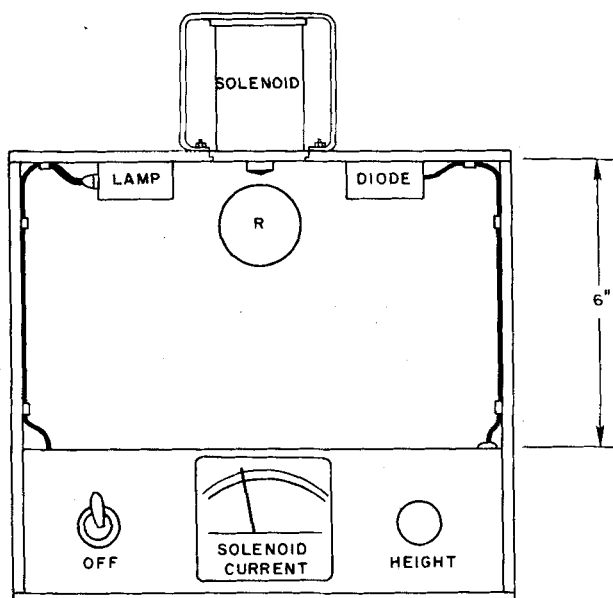


Fig. 1. Schematic diagram of apparatus.

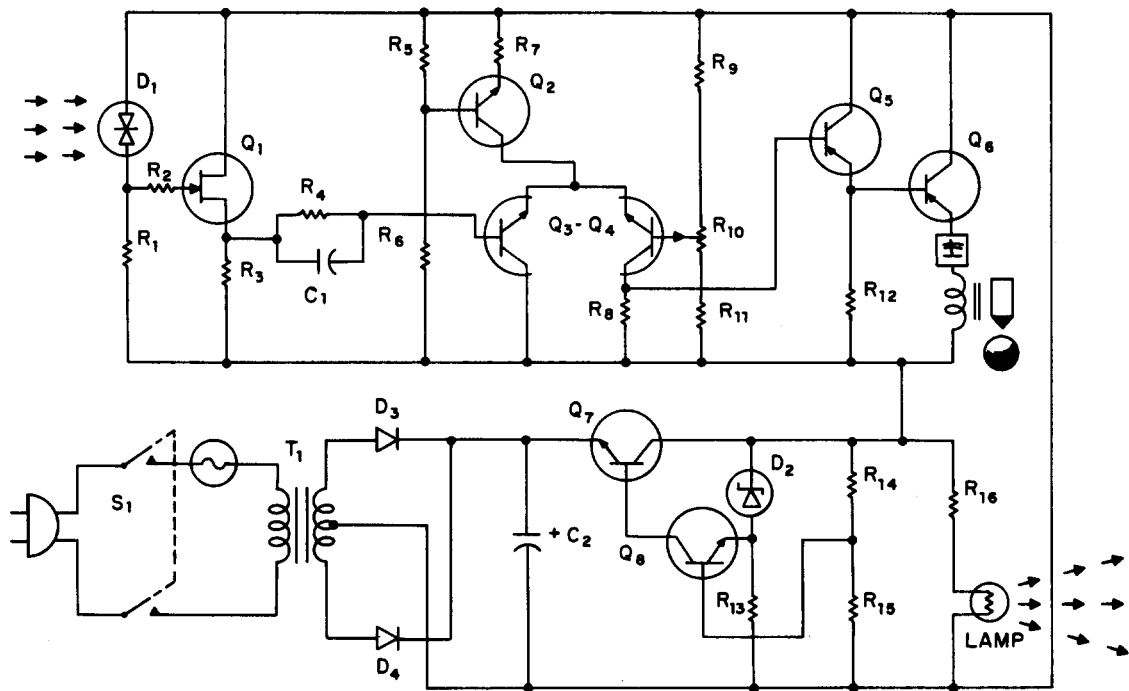


Fig. 3. Circuit diagram of magnetic suspension: R_1 , 1 M Ω ; R_2 , 100 k Ω ; R_3 , 12 k Ω ; R_4 , 150 k Ω ; R_5 , 220 Ω ; R_6 , 1.5 k Ω ; R_7 , 56 Ω ; R_8 , 680 Ω ; R_9 , 220 Ω ; R_{10} , 500 Ω ; R_{11} , 220 Ω ; R_{12} , 2 k Ω ; R_{13} , 330 Ω ; R_{14} , 470 Ω ; R_{15} , 560 Ω ; R_{16} , 60 Ω ; C_1 , 0.15 μ F; C_2 , 1000 μ F; D_1 , 1N2175; D_2 , $24 \times L6.2$; D_3 and D_4 , 1N5061; lamp, CM20-1; Q_1 , MPF161; Q_2 , 2N3392; Q_3 , $\frac{1}{2}$ 2N2480; Q_4 , $\frac{1}{2}$ 2N2480; Q_5 , 2N404A; Q_6 , 2N1358A; Q_7 , 2N2158A; Q_8 , 2N3392; T_1 , stancor; RT202.

amplifier circuit is then designed to be compatible with the solenoid. To prevent the suspended object from oscillating along the vertical axis a stabilizing network C_1R_4 is introduced into the signal path (Fig. 3). The value of the product of the capacity C_1 and resistance R_4 can be easily calculated if the assumption is made that the system is linear. The characteristic equation for a linear harmonic oscillator may be written

$$m\ddot{z} + h\dot{z} + Kz = 0, \quad (2)$$

where h is a damping constant. In terms of the circuit parameters, (2) becomes

$$[(z_2 - z_1)/2gR_4]A(\ddot{z}) + C_1A(\dot{z}) + (1/R_4)Az = 0, \quad (3)$$

where $A(z)$ is the current gain of the power amplifier A , multiplied by the transfer function of the position sensor and that of the suspended mass m . In Eq. (3), K has been replaced by $1/R_4$, which is equivalent to stating that the current $A(z)$ per unit distance is equal to a normalized voltage divided by R_4 , a valid relationship if $A(z)$ is chosen suitably. It will be observed that the support solenoid current is proportional to $i_{R_4} + i_{C_1}$, where i_{R_4} is directly proportional to the distance of the suspended mass from the top cutoff point and i_{C_1} is proportional to the rate of change of this distance. For critical damping in Eqs. (2) and (3), $h = 2(mK)^{1/2} = C_1$ and $K = 1/R_4$, so that from (1)

$$R_4C_1 = 2[(z_2 - z_1)/2g]^{1/2}. \quad (4)$$

If one chooses a value of $R_4 = 150$ k Ω , $g = 980$ cm/sec², and 4 mm for $z_2 - z_1$, then $C_1 \approx 0.15$ μ F. Although this

is close to the optimum value, it is usually advisable to make either R_4 or C_1 adjustable.

As the characteristics of the photodiode vary from unit to unit and also since it is difficult to predict the light level from a given lamp, the design approach was first to construct the position sensing circuit. Then from the measured V/mm, as determined at the output from Q_1 , A was calculated and the power amplifier circuit was designed for this specific gain. The equilibrium position is adjusted by the potentiometer R_{10} on the base of Q_4 . If buoyant forces of the surrounding medium are neglected, then $mg = M\partial H/\partial z$, where M is the magnetic moment of the suspended body and $\partial H/\partial z$ is the vertical gradient of the magnetic field acting at the suspended body's center of permeability. If the ferromagnetic part of the mass m is highly permeable, $M = K'H$, where (below saturation) K' is a constant, while if it is a hard permanent magnet, M is almost independent of H below the coercive value. The magnetic properties of most ferromagnetic substances fall within these two limits and if they are known the required values of H and $\partial H/\partial z$ can be estimated. For example, if M is independent of H , it, of course, can be measured by the well-known laboratory methods and the value of $M\partial H/\partial z$ found. If $M = K'H$, then $mg = K'H\partial H/\partial z$. For example, suppose m is a soft iron sphere with infinite permeability in a field of intensity H , then $M = r^3H$ and $M\partial H/\partial z = r^3H\partial H/\partial z = mg$, hence $H\partial H/\partial z = (m/r^3)g = (4/3)\pi gd$, a constant independent of the radius where the densities d of the spheres are the same. For iron the constant is 3.23×10^4 . The calculated value of this constant is not greatly changed if instead of assuming that the permeability is infinite if it is only say 10^4 or even as low as 10^3 . Consequently the above method of calculation gives a realistic estimate of $H\partial H/\partial z$ which in

turn gives a useful guide line for the design of the support electromagnet. It should be noted that a ferromagnetic body will always seek the strongest part of the magnetic field where the potential energy is a minimum so that in a properly designed system there should be no motion either vertically or horizontally which can be observed with a microscope focused on the rotor scratches. One can see this from a very qualitative consideration. The distance S that a body moves in a time t with an acceleration a is $S = \frac{1}{2} at^2$. For a properly designed circuit, mg is balanced by $M\partial H/\partial z$ to one part in 10^5 and the motion of the rotor is corrected in 10^{-3} sec, then $S = \frac{1}{2}(g/10^5) \times (10^{-6}) \approx 10^{-11} \approx 10^{-8}$ cm. The actual variation of this is larger than this but still very small. However the damping is small for motion in the horizontal direction and when the suspended body is rotating horizontal damping should be provided or built into the circuit. One simple means is to hang the core of the support electromagnet as a pendulum in a dash pot of oil. Since no magnetic flux is cut when the suspended body rotates, there are no induced currents in the spinning rotor so that the magnetic suspension bearing is essentially friction free for rotation about the vertical axis. Also, if the axis of M is precisely on the axis of the magnetic field of the support solenoid, the rotor experiences no observable restoring torque when given a small angular displacement. From the above discussion it will be noted that with the same current in the solenoid, much larger masses can be suspended by placing a strong permanent magnet on top of the core of the electromagnet, by installing an iron flux return jacket around the electromagnet or by having a large permanent magnetic moment in the suspended body.

The magnetic suspension has been used in a number of demonstrations. The suspended hollow steel globe shown in Fig. 2 may be used to demonstrate the principle of the servo-circuit, the fact that the suspended body seeks the

position of minimum potential energy, the low axial friction as well as the use of the suspension of measuring forces. If the magnetic moment of the suspended body is made not to coincide with magnetic axis of the support, then the body will experience a restoring torque when it is given a small angular displacement from its position of equilibrium. Since this restoring torque can be made adjustable from comparatively large values down to zero, the suspension may replace the usual suspension fiber in experiments involving torsional (oscillation) experiments. In many cases it has the advantage over a fiber in that large masses may be suspended and still maintain an extremely small restoring constant. When the restoring constant approaches zero the low axial friction makes the device suitable for demonstrating the conservation of angular momentum. If the iron core of the solenoid is removed, the suspension may be used as an accurate method of weighing bodies. For example a modification of the magnetic support has been used for showing the presence of absorption and of small density changes in gases and liquids; also in determining the partial specific volumes of dissolved substances, in measuring very small osmotic pressures, etc. The device of course makes an ideal supporter for a high-speed rotating mirror in a vacuum or as a support (bearing) for an ultracentrifuge rotor which spins in a vacuum.

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Transmission of normally incident light through transparent dielectric plates

A. Kshatriya

Physics Department, British Columbia Institute of Technology, Burnaby, British Columbia V5G 3H2, Canada

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This note describes a laboratory project designed to impress the following on technology students taking a course in physics: (i) experimental data coupled with appropriate graphical analysis can produce an empirical law; (ii) perfectly transparent materials reflect light; (iii) there is a good agreement between the theoretically calculated value of the transmission coefficient of light treated as electromagnetic radiation and that obtained from an analysis of laboratory data.

When a beam of light strikes a "perfectly" transparent dielectric medium at normal incidence, the reflection coefficient R and transmission coefficient T are given by¹

$$R = \frac{\text{intensity of reflected light}}{\text{intensity of incident light}} = \left(\frac{n_{12} - 1}{n_{12} + 1} \right)^2, \quad (1)$$

$$T = \frac{\text{intensity of transmitted light}}{\text{intensity of incident light}} = \frac{4n_{12}}{(n_{12} + 1)^2},$$

where n_{12} is the refractive index of the dielectric with respect to air.

A straightforward derivation establishes the following relation between the incident intensity I_0 and the transmitted intensity I_m through m perfectly transparent and parallel dielectric plates. If conservation of energy is assumed