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OPTIMUM DIMENSIONS OF POWER SOLENOIDS FOR MAGNETIC SUSPENSION

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16. Abstract

Design optimization of power solenoids for controllable and stabilizable magnetic suspensions with force compensation in a wind tunnel is shown, assuming that the model of a levitating body is a sphere of ferromagnetic material with constant magnetic permeability. This sphere, with a radius much smaller than its distance from the solenoid above, is to be maintained in position on the solenoid axis by balance of the vertical electromagnetic force and the force of gravitation. The necessary vertical (axial) force generated by the solenoid is expressed as a function of relevant system dimensions, solenoid design parameters, and physical properties of the body. On the basis of this relation and the relation for solenoid power three families of curves are obtained which depict the solenoid power for a given force as a function of the solenoid length with either outside radius or inside radius as a variable parameter and as a function of the outside radius with inside radius as a variable parameter. These curves indicate the optimum solenoid length and outside radius, for minimum power, corresponding to a given outside radius and inside radius, respectively.

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OPTIMUM DIMENSIONS OF POWER SOLENOIDS FOR MAGNETIC SUSPENSION

B. A. Kaznacheyev

Electromagnetic systems based on compensating the /94*
forces acting on an object (model) with controlled magnetic fields are widely used in many areas of technology. A power magnetic suspension designed to work in conjunction with wind tunnels is an example of this type of system [1]. Figure 1 shows the block diagram of a device which makes it possible to stabilize the position of ferromagnetic model 4 in the direction of axis O_z by varying the current in power solenoid 3. Here the control signal is produced by model position sensor 1 and transformed by power amplifier 2. In these suspensions, the model is placed at a significant distance from the solenoid, and this distance is many times greater than the model's dimensions [2]. Power P consumed by the solenoid is great; it reaches tens and hundreds of kilowatts [2]. Under these conditions, it is necessary to determine solenoid dimensions l, R_1, and R_2 so that the value of power P is smallest at given distance c and external force G.

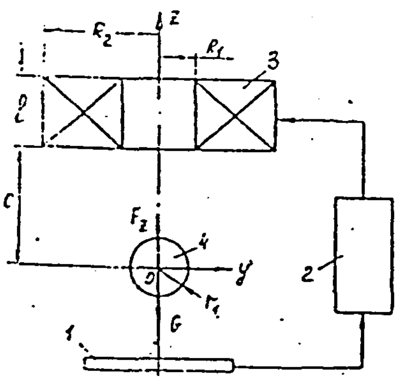

Figure 1. Block diagram of a single-component magnetic suspension.

When optimizing solenoid dimensions, we assume that the model

*Numbers in the margin indicate pagination in the foreign text.

is a solid ferromagnetic sphere with a small radius $r_1 < c$ and constant magnetic permeability μ. The magnitude of electromagnetic force F_z is found using the method given in [3]:

$$F_z = -\frac{VK_m}{1+NK_m} H_z(0;\,0)\,\frac{\partial B_z(0;\,0)}{\partial c},$$

where $K_m = \mu - 1$ is the magnetic susceptibility of model material; $V = 4/3\pi r^3{}_2$ is model volume; $N = 1/3$ is the solid sphere's demagnetizing factor; and $H_z(0;\,0)$ and $\frac{\partial B_z(0;\,0)}{\partial c} = \mu_0 \frac{\partial H_z(0;\,0)}{\partial c}$ are the intensity of the solenoid's magnetic field and its derivative in the center of the model, respectively. Component $H_z(0;\,0)$ on the axis is determined by double integration along the solenoid's copper section:

$$H_z(0;\,0) = \frac{w_0 I K_3}{2}\int_c^{l+c}\int_{R_1}^{R_2}\frac{y^2\,dy\,dz}{(y^2+z^2)^{3/2}}.$$ /95

where ω_0 is the number of solenoid loops in a unit of area; t is solenoid current, and K_3 is the solenoid charge coefficient.

As the result of integration, we obtain:

$$H_z(0;\,0) = \frac{w_0 I K_3}{2}\left\{(c+l)\ln\frac{U_2}{U_1} - c\ln\frac{u_2}{u_1}\right\},$$

where

$$u_1 = R_1 + \sqrt{c^2+R_1^2};\quad U_1 = R_1 + \sqrt{(l+c)^2+R_1^2};$$
$$u_2 = R_2 + \sqrt{c^2+R_2^2};\quad U_2 = R_2 + \sqrt{(l+c)^2+R_2^2}.$$

After several transformations, we find the derivative:

$$\frac{\partial B_z(0;\,0)}{\partial c} = \frac{\mu_0 w_0 I K_3}{2} f,$$

where

$$f = \ln\frac{u_1U_2}{u_2U_1} - \frac{c^2(R_1u_1 - R_2u_2)}{u_1u_2(u_1-R_1)(u_2-R_2)} + \frac{(l+c)^2(R_1U_1-R_2U_2)}{U_1U_2(U_1-R_1)(U_2-R_2)}. \tag{1}$$

Thus, electromagnetic force is

$$F_z = -\frac{K_M V I^2 w^2 \mu_0 K^2_3}{4(1+NK_M)}\left\{(c+l)\ln\frac{U_2}{U_1} - c\ln\frac{u_2}{u_1}\right\}f. \tag{2}$$

The power consumed by the solenoid can be determined using the solenoid's geometric dimensions:

$$P = I^2 w^2_0 \rho \pi K_3 (R^2_2 - R^2_1) l. \tag{3}$$

where ρ is the conductor's specific electrical resistance.

We find current magnitude from (2) and enter it in (3). Finally:

$$P = \frac{4\rho\pi F_z (1+NK_M)c^2}{\mu_0 K_M V K_3}\,\frac{\bar{l}(\bar{R}^2_2 - \bar{R}^2_1)}{\left\{(\bar{l}+1)\ln\frac{U_1}{U_2} + \ln\frac{u_2}{u_1}\right\}f} \tag{4}$$

where $\bar{l} = l/c$; $\bar{R}_1 = R_1/c$, and $\bar{R}_2 = R_2/c$ are relative solenoid dimensions.

It is evident that at a given c and F_z, the solenoid consumes minimum power if the function entered in (4)

$$F(\bar{l}; \bar{R}_1; \bar{R}_2) = \frac{\bar{l}(\bar{R}^2_2 - \bar{R}^2_1)}{\left\{(\bar{l}+1)\ln\frac{U_1}{U_2} + \ln\frac{u_2}{u_1}\right\}f} \tag{5}$$

has its minimum value at selected parameters l, R_1 and R_2. Optimum solenoid parameters thus determined do not depend on the magnitude of (the conductor's) specific resistance, which varies as the result of heating.

Figure 2 shows function (5) as a function of solenoid length l for different outside radii $\bar{R}_2$ and fixed inside radius $\bar{R}_1$ = 0.3. As can be seen from this graph, for each $\bar{R}_2$ there is a solenoid length l_{opt}, at which minimum power is consumed by the solenoid. The increase in power when $\bar{l} > \bar{l}_{opt}$ is due to the fact

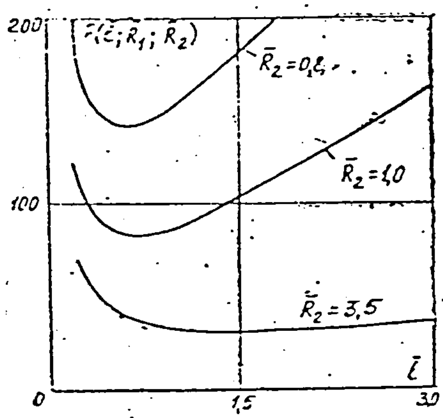

Figure 2. Graphs of function $F(\overline{l}; \overline{R}_1; \overline{R}_1)$ as a function of relative length $\overline{l}$ when $\overline{R}_1 = 0.3$.

that the loops distant from the model contribute very little to electromagnetic force. The increase in power when $\overline{l} > \overline{l}_{opt}$ is due to the sharp increase in solenoid current necessary to create the given electromagnetic force. From Figure 2 it follows that solenoid length must be more carefully selected when $\overline{R}_2$ is smaller since, when $\overline{R}_2$ increases, the minimum value of function $F(\overline{l}; \overline{R}_1; \overline{R}_2)$ becomes ambiguous.

Figure 3 shows graphs of function $F(\overline{l}; \overline{R}_1; \overline{R}_2)$ as a /96
function of $\overline{l}$ for different inside radii $\overline{R}_1$ and fixed outside radius $\overline{R}_2 = 1.1$. Minimum power (whose magnitude depends on the value of $\overline{R}_1$) consumed by the solenoid can be seen on the curves. As opposed to the curves shown in Figure 2, curves in Figure 3 in the $\overline{l}_{opt}$ area are virtually independent of $\overline{R}_1$. This means that solenoid lengths must be more carefully selected for a variable inside radius than for a variable outside radius, especially when $\overline{R}_2$ is large.

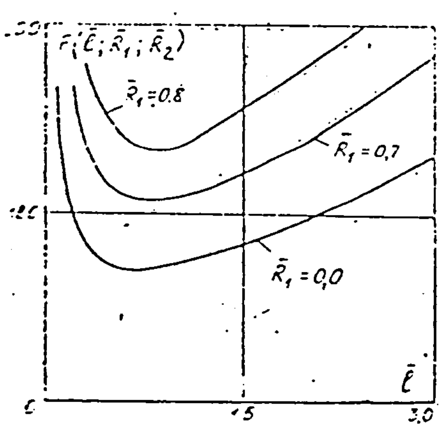

Figure 3. Graphs of function $F(\overline{l}; \overline{R}_1; \overline{R}_2)$ as a function of relative length $\overline{l}$ when $\overline{R}_2 = 1.1$

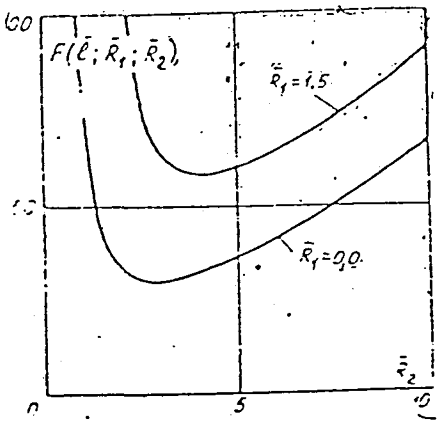

Figure 4. Graphs of minimum values of function $F(\overline{l};\ \overline{R}_1;\ \overline{R}_2$ as a function of $\overline{R}_2$).

Figure 4 shows graphs of the minimum values of function $F(\overline{l};\ \overline{R}_1;\ \overline{R}_2)$ corresponding to $\overline{l}_{opt}$ as a function of outside radius $\overline{R}_2$ for different inside radii $\overline{R}_1$. The absolute minimum value of three-variable function $F(\overline{l}\ \overline{R}_1,\ \overline{R}_2)$ and the optimum solenoid geometric dimensions corresponding to this minimum can be found by using a computer. Calculations give the following values: $\overline{l} = 1.35$; $\overline{R}_1 = 0.10$, $\overline{R}_2 = 2.9$. The minimum value of function F_{min} is 29.994.

Power consumed by the solenoid can be further reduced either by profiling the solenoid [4], or by using superconductive electromagnets [2].

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