Research and Experiments on Electromagnetic Field Induced by Two Coaxial Solenoid Coils of Axially Mag-lev Driving Needle

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Abstract: The movement of mag-lev driving needle depends on the interaction of magnetic fields between two solenoid coils and magnet. Inside single cylinder, two solenoid coils are placed vertically and coaxially while the magnet is laid at the bottom of the needle base. Based on magnetic-levitation theory and Biot-Savart Law, this paper taking into account the impacts of mutual inductance caused by double coils analyzed and computed magnetic force when these two coaxial coils were separated into different air-gap heights. By using Gauss meter to measure the magnetic field induced by two coils, we attains that the measuring data accords well with computing results. Besides, the electromagnetic-permanent driving model has been built through electromagnetic coupling module in ANSYS, and through FEM simulation, the curve of electromagnetic force exerted on the magnet as the air-gap height was achieved, and the magnetic field distribution map of this model was also attained.

Introduction

Among mag-lev devices, whatever radial levitation or axial levitation, it's essential to precisely understand the interrelations of magnetic force between magnetic objects. The coupling problem of electromagnetic fields has recently been one of the research focuses both at home and abroad, and such relevant studies can be seen in power electronic system as study on coupling mechanism of transmission line system and magnetic field, study on coupling property of electro magnetism of MRF (Magnetorheological fluid) damper, and magnetic analysis of electromagnetic system for AC contactor, etc. According to reference[1], by use of Newman formula and complete elliptic integral, it derived the mathematical formula to calculate magnetic force between two parallel-placed rings which are coaxial and have the same radius. This paper applied the conclusion presented in reference[1] into two coaxial and equivalent solenoid coils, analyzed and calculated the electromagnetic force existing between them, verified the results through numerical calculation and practical experiments, and finally simulated the magnetic field distribution affected by the coils and magnet by means of finite-element simulation.

Magnetic field distribution of single electrified coil on its axis

When a piece of metal wire was powered on, it generally will produce a kind of circular magnetic field around itself and the principles is, the larger the current, the more intensified the magnetic field, and the direction of which can be determined by Ampere's spiral rule of right hand. In the same manner, after curling the original electrified wire into hollow cylindrical coil around a fixed axis, the direction of magnetic field induced by a single-turn coil can also be ascertained through the same rule[2]. Thus, the total magnetic field on the axis of the solenoid coil can be seen as the result of superposition on magnetic fields of N single coil.

According to Biot-Savart Law, supposing there is a coil of radius a and it is electrified with current I, the magnetic induction intensity of any point on the axis distancing from the coil center x is

$$B = \frac{m_0}{2}\frac{Ia^2}{\left(a^2 + x^2\right)^{3/2}} \quad . \qquad (1)$$

Based on Eq.1, integrating along the axial path of the coil, the magnetic induction intensity of any point P on the axis of solenoid coil is given.

$$B' = \int dB = \int \frac{m_0}{2}\frac{I{r_m}^2 ndx}{\left({r_m}^2 + x^2\right)^{3/2}} = \frac{m_0 nI{r_m}^2}{2}\frac{x}{{r_m}^2\left({r_m}^2 + x^2\right)^{1/2}}\Bigg|_{-l_1}^{l_2} \quad , \qquad (2)$$

therein, I is coil current, r_m is coil radius, n is the number of turns of coil per unit length, l_1 and l_2 are the distances from the point to the two ends of the coil, μ_0 is permeability of vacuum.

Electromagnetic force induced by two solenoid coils

Numerical calculation and experiments. From Eq.2 it can be seen that, magnetic field intensity caused by single coil decreases very quickly near the two ends of the coil. So in order to strengthen magnetic field on the axis of the coil, two solenoid coils need to be in vertically coaxial arrangement[3], this way, due to the effects of mutual inductance produced by the upper and lower coils, both magnetic fields will be superposed. When exerted the same current on them, the upper and lower coils will generate magnetic fields of the same direction. With the assist of repulsion and attraction induced by these two solenoid coils, there would be a superposition on the magnetic fields, which can also strengthen the magnetic field on their axis.

When two equal and coaxial circular current loops are separated from each other with distance h in air, their electromagnetic interacting force can be calculated by

$$F = \frac{m_0 I_1 I_2 h}{\sqrt{4r^2 + h^2}}\left[K(k) - \frac{1 + k'^2}{2k'^2}E(k)\right] \quad , \qquad (3)$$

therein, $k = \dfrac{2r}{\sqrt{h^2 + 4r^2}}$, $K(k) = \displaystyle\int_0^{p/2} \frac{dx}{\sqrt{1 - k^2 \sin^2 x}}$, $E(k) = \displaystyle\int_0^{p/2} \sqrt{(1 - k^2 \sin^2 x)}dx$

Matlab numerical calculation. According to Eq.3, with the application of Matlab numerical research method and substitution of practical values of parameters, the electromagnetic interacting force F induced by two solenoid coils when they are separated within different distances h has been worked out, and its fitting curve can be seen in Fig 1.

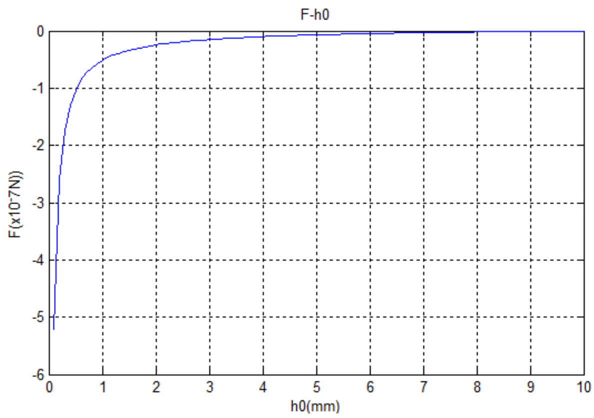

Fig 1. Calculating results

In Fig 1, the negative values of *F* indicate magnetic attractions between two solenoid coils (when both coils were electrified with currents of the same direction and value). It can be seen that *F* induced by these two coils diminishes as the distance h_0 between them increases. When distance h_0 goes to infinity, the magnetic interaction between these two coils tends to zero, that is, there is almost no magnetic distraction between the magnetic fields caused by two coils. However, when distance h_0 gradually reduced to a situation in which the two coils reach contact, the electromagnetic force will go up very high, which indicates an intense magnetic interaction.

Experimental data. Applying equal but reverse current to two solenoid coils, the experimental voltage is *+12V*, electric resistance is *38W*, the length of single coil is a fixed value, *L=16mm*, the number of coil turns *n* is approximate to *1050*. The experiment uses the *CH3600* three channels Gauss meter to measure magnetic field on the axis of two solenoid coils. In this experiment, the Gauss meter probe whose permeability can be up to thousands high need to be put into these two vertical coils, with the help of highly magnetic sensibility of the probe, it can easily get the accurate values of magnetic field at any point in the field. Based on that, we read the data on the Gauss meter each 0.5mm along the axis of the coils. Respectively measuring the magnetic induction intensity for different air-gap heights, Table 1 has been achieved, which shows the magnetic distribution at the center of the axis of the coils when they are at different air-gap heights.

Table1 Experimental data for different air-gap heights

h(mm)	1	2	3	4	5	6	7	8	9	10
B(mT)	15.39	14.04	11.74	9.635	7.75	6.94	5.927	5.11	3.93	3.61

Fitting curve of Table 1 can be easily got in Matlab, Fig 2 shows the variation trend of magnetic induction intensity with the air-gap heights.

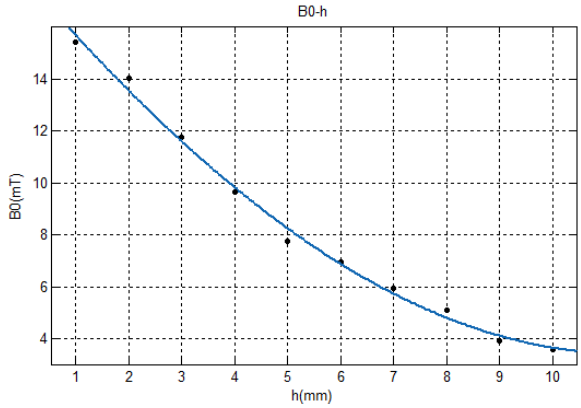

Fig 2. Fitting curve of experimental data

Compared Fig 1 with Fig 2, it can be seen in Fig 1 that the magnetic induction intensity *B* at the midpoint of the axis reduces as the air-gap height *h* increases. Because the weaker the magnetic field, the smaller its magnetic force, just as in Fig 2, when distance *h* reaches zero, the magnetic attraction between two coils tends to be infinite, but as *h* increases, *F* decreases rapidly, approximate to zero. Thus, it shows that theoretical calculation accords with experimental results.

ANSYS electromagnetic simulation and analysis

Electromagnetic-permanent magnets FEM model. The software package of ANSYS Multi-physics supports magnetic-structural analysis, it can be used to determine the magnetic force imposed on electric conductors or magnetic material, and the resulting structural deformation. It has wide applications such as computing magnetostatic and transient-magnetic force, structural deformation and stress, so that to understand their influences on structure design. Because dual-coil driving needle model belongs to axisymmetric element[4], using half of the single needle cylinder to build FEM model could be a proper way to do the simulation in ANSYS. According to design parameters of the magnet and solenoid coils, the FEM models of magnet suspended at different air-gap heights were established, and therefore, the force exerted on the magnet by electromagnetic field can be respectively simulated and analyzed. One of the models that describes the situation of height h=4mm is presented in Fig 3.

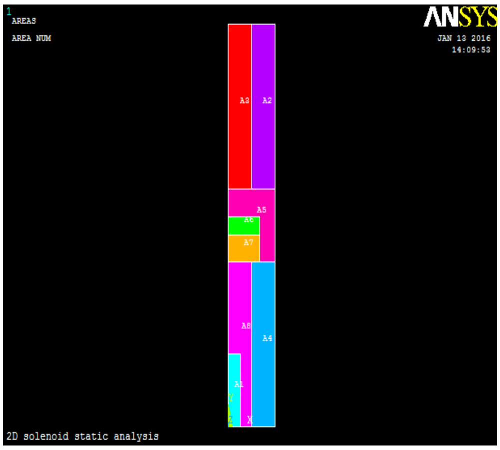

Fig 3(a). Geometric model

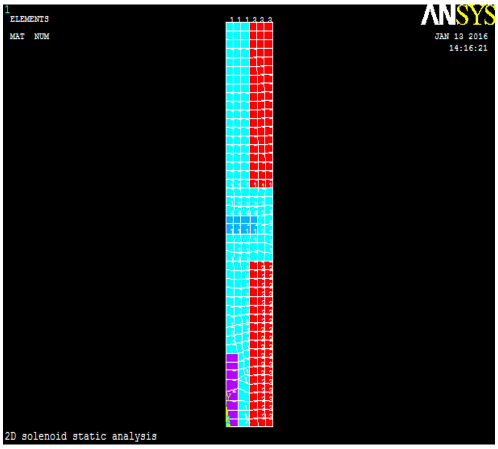

Fig 3(b). Meshing

Fig3. Analytical model

Simulation results. The simulation results can be seen in Fig 4 and Table 2. Fig 4(a) presents the distribution map of magnetic lines when the magnetic field induced by two solenoid coils were interfered with other magnetic fields produced by magnet and the lower iron bar. It can be observed that the magnetic field of the iron bar settled in the center of the lower coil interferes with the original magnetic lines more than that of the magnet did, there are only a few magnetic lines passing through the magnet. Fig 4(b) presents the axonometric map of nodal magnetic induction density *B*. It can also be observed that the magnetic fluid density *B* approximate to the iron bar inside the lower coil is much stronger than that of the magnet which is settled between two coaxial coils. Fig 4(c) and Fig 4(d) display the fitting curves of simulation results.

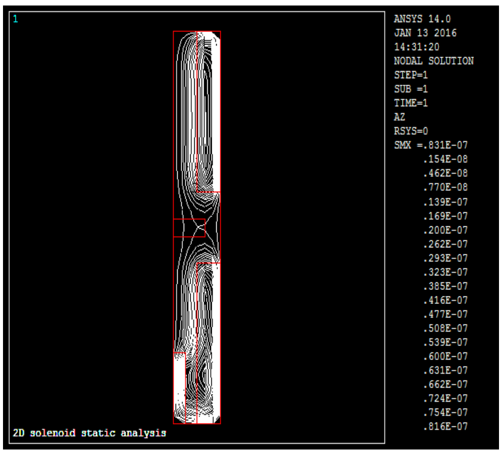

Fig 4(a). Magnetic lines of h=3mm

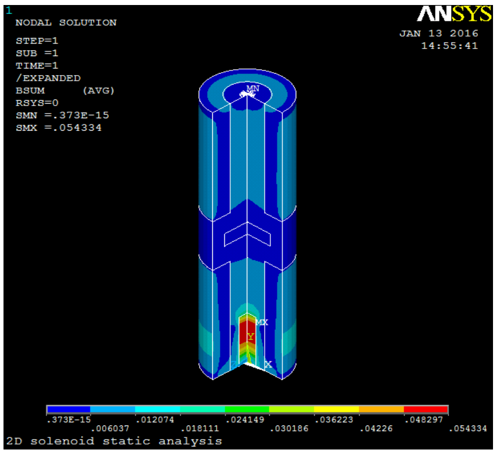

Fig 4(b). Magnetic fluid density B

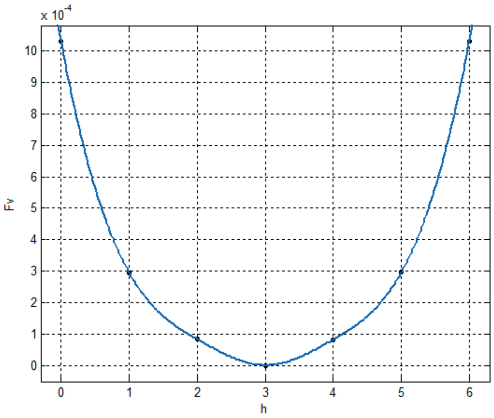

Fig 4(c). Curve F_V vs *h*

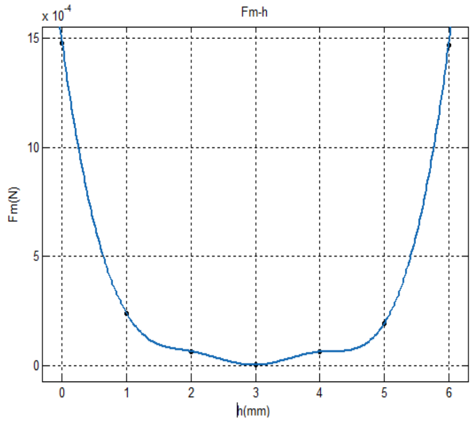

Fig 4(d). Curve F_M vs *h*

Fig 4. Simulation results

Table2 Magnetic force exerted on magnet

h(mm)	0	1	2	3	4	5	6
Fv(N)	-0.103* 10^-2	-0.295* 10^-3	-0.838* 10^-4	0.382* 10^-6	0.827* 10^-4	0.296* 10^-3	0.103* 10^-2
FM(N)	-0.148* 10^-2	-0.239* 10^-3	-0.638* 10^-4	-0.793* 10^-6	0.613* 10^-4	0.193* 10^-3	0.147* 10^-2

therein, F_V represents the force was calculated based on virtual work principle, while F_M is the force calculated through MAXWELL equations.

Conclusions

In conclusion, this paper applies the computing principle used to determine the magnetic force induced by two electric loops into analyze two coaxial solenoid coils driving needle model, to examine its electromagnetic properties.

(1).The consistency between theoretically numerical calculating and experimental data validates the accuracy and reliability of the analytical mode.

(2).The distribution map of magnetic fluid density and the results of magnetic force exerted on magnet attained by FEM simulation offer important design basis and theoretical support for control optimism and structure design of two-coil drive and axially mag-lev needle device.

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