Force Characteristics of Solenoid Electromagnet with Ferromagnetic Disc in the Coil

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Abstract. The paper presents the construction and characteristics of a solenoid electromagnet with ferromagnetic disc placed in the coil. The presence of the disc leads to change of the force characteristic compared with conventional solenoid electromagnets – increasing the force at large air gaps and decreasing the force at small air gaps. This could be very useful for some actuators. It has been studied how the force characteristic depend on disc size, position and material. Finite element method has been used for field and force calculations of the electromagnet.

1. INTRODUCTION

Solenoid electromagnets are used in a wide variety of industrial applications, mainly as actuators. The co-ordination between the electromagnetic and the load force and obtaining desired force characteristic is of major importance in the design of these actuators. Usually the change of the characteristics is obtained either by varying geometry, e.g. the shape of the pole pieces, or by external control.

The paper presents a solenoid electromagnet that gives the opportunity of changing the force characteristic by placing a ferromagnetic disc inside the coil.

2. SOLENOID ELECTROMAGNET WITH FERROMAGNETIC DISC

The electromagnet under consideration features a ferromagnetic disc placed in the coil in such a way that the coil is divided in two parts – Fig. 1. It is subject of Bulgarian patent [1,2]. The location of the disc is somewhere in the zone of the air gap of the electromagnet.
The ferromagnetic disc is cut in radial direction in order to avoid its behavior as a secondary winding at dynamic conditions. Only the magnetic field redistribution due to the presence of the disc is thus obtained and its influence on the force has been studied.

3. **FORCE CHARACTERISTICS AT DIFFERENT CONDITIONS**

Inserting a ferromagnetic disc in the coil leads to a change of the force characteristic (electromagnetic force versus air gap). This can be seen from Fig. 2 where force characteristics without and with ferromagnetic disc are shown for an electromagnet of the same magnetic circuit.
All the results in Fig. 2 are experimentally obtained.

When the disc is inside the air gap, i.e. at large gaps, the disc strengthens the working magnetic flux through the armature. These results in increasing the electromagnetic force compared to the case without disc. The flux density in the disc is relatively low, the disc is not saturated and its influence on the force is significant.

When the disc is outside the air gap zone, i.e. at smaller gaps, the disc weakens the working magnetic flux, which leads to lower electromagnetic force in the case without disc. The ferromagnetic disc is saturated and its influence on the force is relatively low.

By varying the position of the disc different force characteristics can be obtained. In Fig. 3 computed characteristics for three different disc positions are shown. The disc thickness in these three cases is \( \Delta d = 0.5 \) mm. The results show that the characteristics are raised in the zone of the disc. The force increases in the area right after the disc.

Other factors that could influence are the disc material and dimensions, in particular its thickness. It is also possible to insert more than one disc. An example of characteristics with disc of different material is shown in Fig. 4. The first curve (disc1) is obtained with simple silicon iron and second curve is for quality iron with higher induction of saturation. Therefore, in second case the disc is less saturated and has stronger influence on the force characteristic.

![Figure 3: Static Force Characteristics for Three Different Disc Positions](image-url)
Figure 4: Static Force Characteristics with Different Disc Materials

Force characteristics for the same disc position and different disc thickness - $\Delta_d$ are given in Fig. 5.
Force characteristics for the same disc position and different disc thicknesses $\Delta_d$ are given in Fig. 5.

The thinnest disc ($\Delta_d = 0.5\text{mm}$) is saturated earlier and thus determines its relatively weak influence on the characteristic variation. At the opposite, the largest disc ($\Delta_d = 2\text{mm}$) stays unsaturated and works like a magnetic shunt. It leads away part of the magnetic flux, thus decreasing the force.

4. **Field Analysis by the Finite Element Method**

For theoretical study, the finite element method has been employed. Axisymmetrical formulation for the modified magnetic vector potential $rA$ is used for the solution of the magnetic field problem governed by the pseudo-Poissonian equation. This is a special (and easier to model) case of the model presented in [3]. Homogeneous Dirichlet boundary conditions are imposed on the boundary of a buffer zone around the electromagnet. The problem has been solved as a non-linear one, taking into account the material characteristics of the core and the disc. The non-linearity is treated by the Newton-Raphson method with relaxation factor.

The electromagnetic force is computed by the Maxwell stress tensor approach. For maintaining similar accuracy at different positions of the armature, the mesh is generated in a way ensuring the same mesh for the armature and for the air surrounding it where the Maxwell integration surfaces are located.

Code developed by the authors is used for the finite element analysis. It is written in FORTRAN and offers some pre- and post-processor features. The static force characteristic of the electromagnet with one disc is computed and compared with the experimental one, both shown in Fig. 6.

![Figure 6: Static force characteristics of solenoid electromagnet with ferromagnetic disc](image-url)
The computed and measured characteristics are in a relatively good agreement. The differences are mainly due to the difference between the real material properties from those used for the modeling.

5. CONCLUSION

Insertion of a ferromagnetic disc in the coil of solenoid actuator could change significantly its force characteristic. The change of the force is in a desired way – increase at large gaps and decrease at small gaps. By varying the position of the disc, its dimensions and material different force characteristics could be obtained.

The finite element method has been used for theoretical analysis. Possible further studies could include more detailed analysis of the influence of other factors on the force characteristic, as well as synthesis of electromagnet of desired characteristic.

References