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Analytic expressions for the Lorentz force and torque on a line current with arbitrary orientation due to a cuboidal permanent magnet

J.M.M. Rovers, J.W. Jansen, E.A. Lomonova

Department of Electrical Engineering, Eindhoven University of Technology

P.O. Box 513, 5600 MB, Eindhoven, The Netherlands

j.m.m.rovers@tue.nl

Abstract— This paper concerns the analysis of the force and torque between a rectangular coil with arbitrary orientation and a cuboidal permanent magnet. An analytic solution for the Lorentz force and torque on a line current is presented and the results for a rectangular coil are obtained by meshing the cross-section of the coil. The method presented will be used in the design of a planar actuator.

I. INTRODUCTION

Single-stage magnetically levitated ironless planar actuators are being researched for use in the lithographic industry (e.g. wafer stages). Such actuators consist of a stator with coils and a plate with permanent magnets mounted on it (the translator). These actuators require a positioning accuracy in the nanometer range. To achieve such accuracies, the deformation of the translator has to be limited. Therefore, expressions for the force acting on each PM in the array are needed, since these forces cause the deformation. An analytic solution of the Lorentz force integral on a rectangular coil due to a cuboidal magnet where the current direction is parallel or orthogonal to the magnetization direction is presented in [1]. However, the planar actuator as presented in [2] makes use of coils rotated 45° around the z-axis with respect to the magnets. Also, expressions for the torque on the coil are not given.

This paper presents a semi-analytic method to determine the force and torque between a cuboidal magnet and a rotated rectangular coil.

II. LORENTZ FORCE ON A LINE CURRENT

Consider the line current in Fig. 1. The magnetic flux density \vec{B} due to the cuboidal magnet is determined using analytic expressions [4]. The force and torque on the line current is then given by:

$$\vec{F} = \int_{-L}^{+L} \vec{I} \times \vec{B}(x_0 + \alpha l, y_0 + \beta l, z_0 + \gamma l) dl,$$

$$\vec{T} = \int_{-L}^{+L} (x_0 + \alpha l - r_x, y_0 + \beta l - r_y, z_0 + \gamma l - r_z) \times (\vec{I} \times \vec{B}(x_0 + \alpha l, y_0 + \beta l, z_0 + \gamma l)) dl, \quad (1)$$

where $\vec{r} = (r_x, r_y, r_z)$ is the point around which the torque is calculated. The orientation of the line current is specified by (α, β, γ) , i.e. a line rotated 45° around the z-axis corresponds to $\alpha = \beta = 1$ and $\gamma = 0$.

III. MODELING OF THE RECTANGULAR COIL

In previous research [2,3], the force on a (rotated) rectangular coil is determined by numerically integrating over

the total coil volume using a cuboidal mesh. This is shown for bundle A in Fig 2. The rest of the coil is meshed in a likewise manner. This is time consuming and the accuracy is dependent on the mesh size. Instead, the results of (1) are used. This means that the coil will be modeled by line currents as shown for bundle B in Fig. 2, which is modeled as $j \times k$ line currents.

The force and torque acting on bundle B is given by:

$$\vec{F}_B = \sum_j \sum_k \vec{F}_{B,j,k}, \quad (2)$$

$$\vec{T}_B = \sum_j \sum_k \vec{T}_{B,j,k},$$

where $\vec{F}_{B,j,k}$ and $\vec{T}_{B,j,k}$ are the solutions to the integrals in (1) for line current $I_{B,j,k}$, which will be presented in the final paper. The same method can be applied to the other segments of the coil, including the corners as indicated by corner C in Fig. 2. The advantage is that this method speeds up the design process and the accuracy is less dependent on the mesh size.

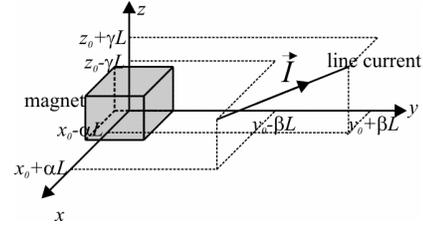


Fig. 1. Cuboidal permanent magnet and a line current

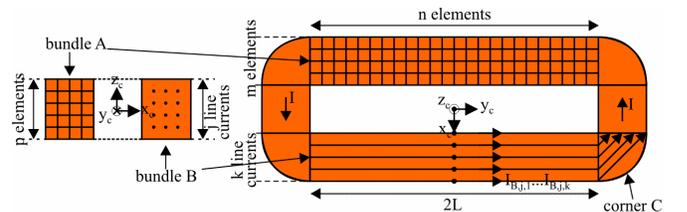


Fig. 2. Side view (left) and top view (right) of a rectangular coil

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