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FORCE CALCULATION IN ELECTROMAGNETIC DEVICES

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ABSTRACT

In this paper the authors show how the Maxwell stress tensor can be used, in practice, in order to determine local magnetic forces distribution in an electromagnetic system. An experimental set-up has been designed in view of comparing the theoretical results with the measurements.

INTRODUCTION

In electrical machines and actuators, the magnetic force is an important quantity which should be determined with precision. Generally this force is applied to a moving part of a system. Under this global aspect, it constitutes the main useful quantity, like the torque of an electrical motor. But this force presents also a local aspect, and can then be the cause of vibrations in actuators and electrical machines. In fact the rotor rotation and the variations of currents passing through conductors which are usually placed in the slots produce fluctuations of the magnetic forces applied to the different parts of the electromagnetic structure.

The first step in the study of vibrations of magnetic origin is therefore the knowledge of the distribution of these forces within the machine, in the space and time domains.

In this paper, the authors present an approach which leads to the determination of this distribution. First they recall the different methods which allow the magnetic force calculations in an electromagnetic structure. Then they show how the Maxwell stress tensor, which is usually used for global force calculations[1], can be employed in order to determine local forces applied to a specific part of the device. Finally, they illustrate the possibility of using the Maxwell stress tensor, by setting up an experimental device and comparing the theoretical results with those obtained from the measurements.

MAGNETIC FORCE CALCULATION

In pratice three methods are available for the calculation of magnetic forces[2,3,4] :

- Laplace's law for the calculation of forces applied to a current carrying conductor :

$$F = \int_V J \wedge B \, . \, dv$$

- The coenergy derivative with respect to the space coordinates[5] :

$$Fm = \delta/\delta x \int_V \int_0^H B.dH \, . \, dv$$

- The integration of Maxwell stress tensor over the surface enclosing that part of the device over which the forces are applied :

$$Fm = \int_S T_m \, . \, ds$$

where T_m is a column vector of the Maxwell stress tensor :

$$T = 1/u \, . \begin{vmatrix} B_1{}^2 - B^2/2 & B_1 . B_2 & B_1 . B_3 \\ B_1 . B_2 & B_2{}^2 - B^2/2 & B_2 . B_3 \\ B_1 . B_3 & B_2 . B_3 & B_3{}^2 - B^2/2 \end{vmatrix}$$

B_i (i=1,2,3) are the components of the induction vector B.

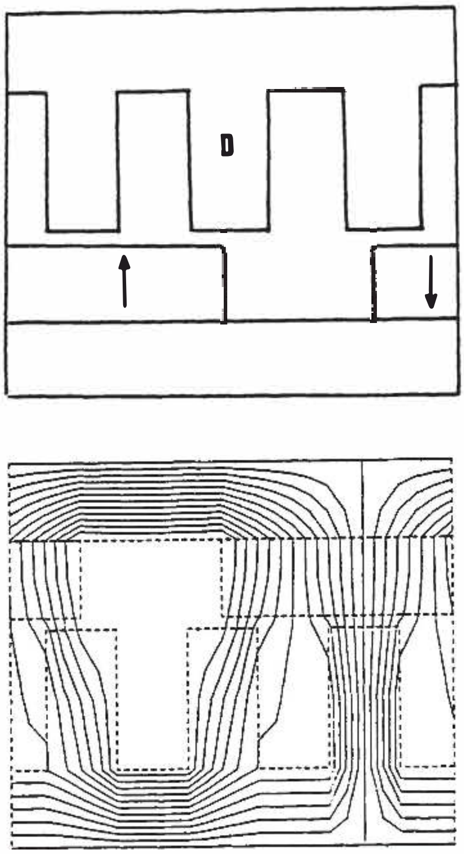
Among these methods, only Laplace's law allows theoretically a local force calculation, when it is applied on conductors. On the other hand the local aspect of the force obtained by the coenergy derivation can be easily underlined since it is derived from a volume integration. It seems therefore interesting to associate to the volume element dV the force dF calculated on it. In contrast, the force calculation by this method needs usually for each force component two successive solutions of the electromagnetic field equations, for two adjoining positions. Finally when the force is calculated by Maxwell stress tensor, it should be noted that even if only one solution of the field equations is sufficient for the determination of the different force components, the integration is carried out over a surface which passes in the air and encloses the considered device part, so that, theoretically, it allows only the calculation of the global force applied to this part.

It is now shown that it would be possible, in practice, to determine a local force by means of Maxwell's tensor.

LOCAL ASPECT OF THE MAXWELL'S TENSOR

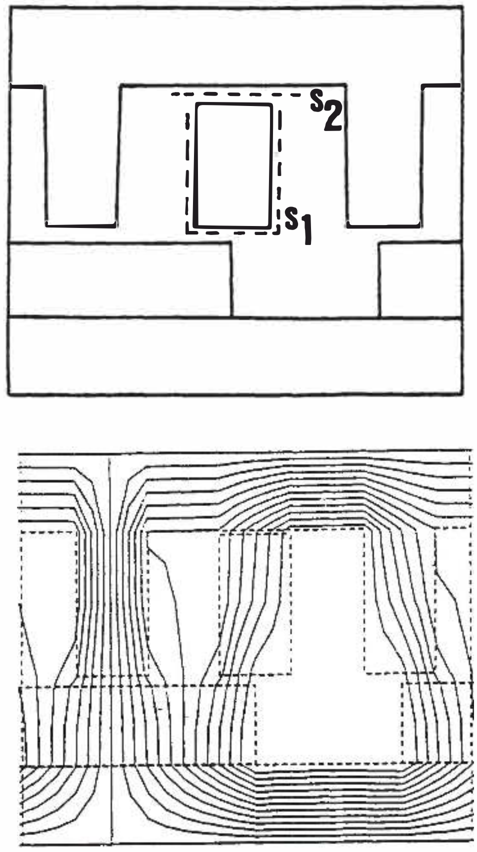
Let's consider the periodic structure in figure 1 in which the force applied to the tooth D is to be calculated. It is theoretically impossible to calculate the force applied to this tooth since it cannot be enclosed by a surface passing in the air. However if we solve the electromagnetic field equations for the structure of figure 1 and then for an identical structure in which the tooth D is slightly separated (figure 2) the obtained results are in practice very similar.

In this latter case Maxwell's tensor integration over the surface S is carried out over the surface S_1 and S_2 separately, giving the following results :



$\Delta A = 0.936\ 10^{-3}$ Wb/m
$A_m = 0.127\ 10^{-1}$ Wb/m

Fig. 1. Considered device.



$\Delta A = 0.927\ 10^{-3}$ Wb/m
$A_m = 0.126\ 10^{-1}$ Wb/m

Fig. 2. Sticking out a tooth.

- integration over S_1 : $F_x = -\ 312.$ N, $F_y = -\ 540.$ N

- integration over S_2 : $F_x = 0.$ N, $F_y = 670.$ N

These results can be compared to those obtained for the original structure in which the tooth D is attached to the device body :

- integration over S_1 : $F_x = -\ 312.$ N, $F_y = -\ 540.$ N

This comparison shows that the integration over S_1 yields practically to the same result in the two cases : it can be considered as being the force applied on D by the magnet. The integration over S_2 does not involve any x components which would correspond to a magnet attraction. This force is applied in the y-direction corresponding to the attraction force which tends to stick back the tooth to the body device.

Experimental device

The above example has allowed us to demonstrate that the integration over a surface which encloses partially a device part should lead to the determination of the force applied to it. This result should now be verified on an experimental device. The model used for this purpose is represented in figure 3.

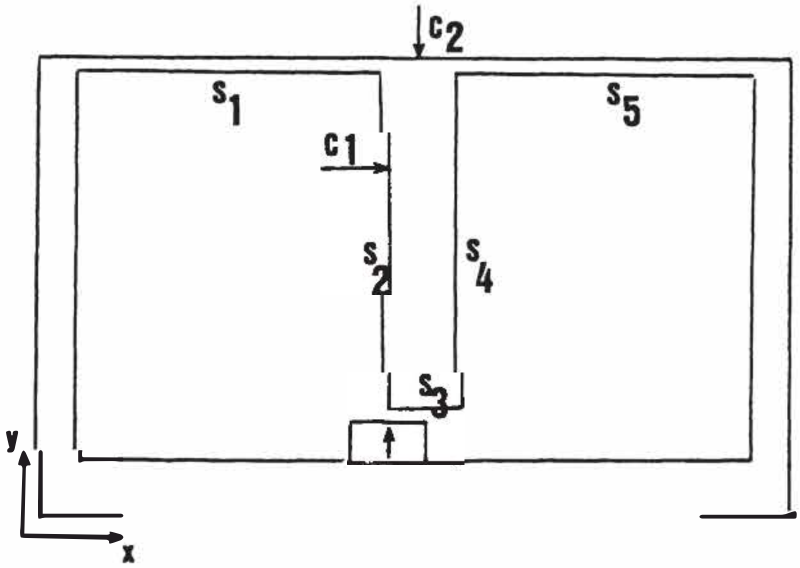
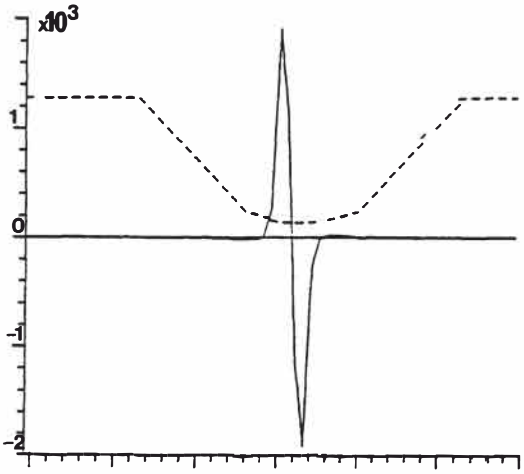
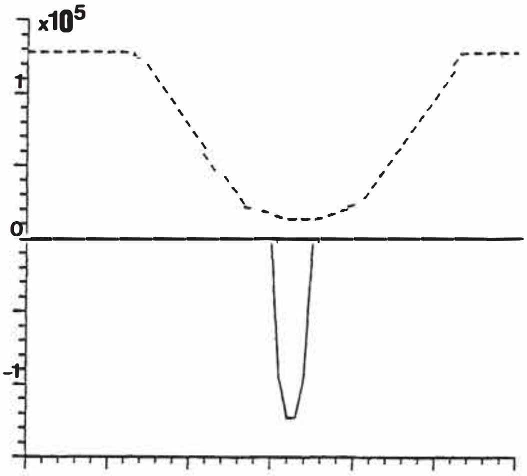


Fig. 3. Experimental device.



Force density in x-direction



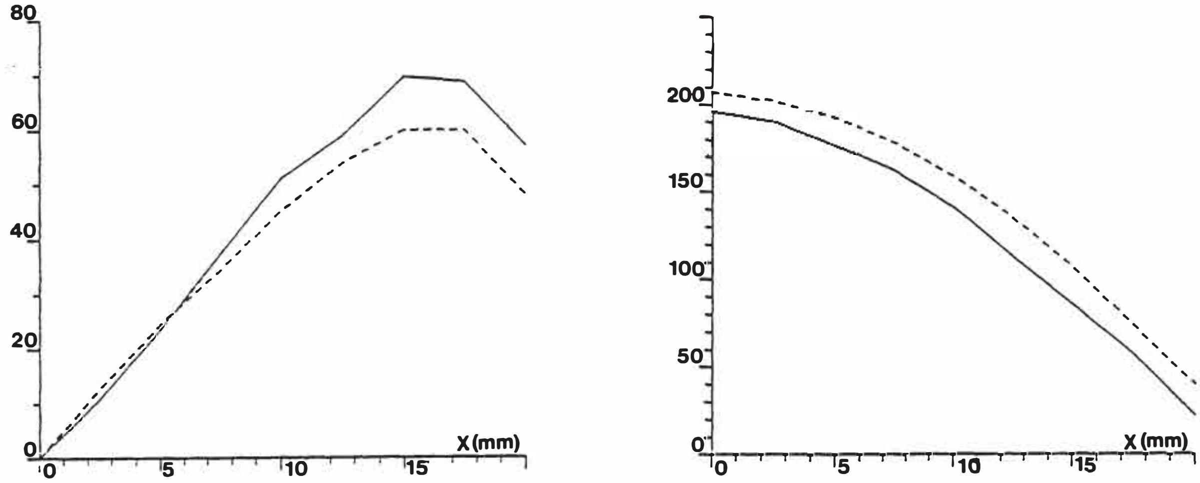
Force density in y-direction

Fig. 4. Force densities along the tooth (N/m^2)

It is composed of a closed magnetic circuit, including a tooth, in front of which a magnet can be displaced. The tooth has been intentionally very long in order to permit simple measurements of components Fx and Fy of the force applied to the tooth by the magnet. The upper part of the magnetic circuit is composed of a thin plate so that it could suffer measurable deformations under the electromagnetic forces.

The force applied to the tooth is obtained numerically by integrating the Maxwell's tensor along the surface S_1, S_2, S_3, S_4 and S_5. Figure 4 illustrates the computed force density distributions over these surfaces for one magnet position. The force densities are decomposed into DF_x and DF_y. The dashed curves correspond to the developed integration surfaces and allows one to locate the point where the force density is applied. It can be observed that the magnetic force is pratically applied only on the surface S_3.

The force has been experimentally measured from the displacements measurement by means of comparators C_1 and C_2, which have been already calibrated by applying known forces to the tooth end along x and y axes.



Force in x-direction   Force in y-direction

Fig. 5. Force versus magnet displacement (N).

The results obtained experimentally : the values of forces as a function of the magnet position with respect to its equilibrum position are compared in figure 5 with the results obtained from numerical analysis.

The deviation between the different results is less than 10 % and principally due to the dispersion of the characteristics of the different magnet bars, whereas a mean value has been taken for the numerical calculations.

CONCLUSION

The two examples of electromagnetic structures presented show that the integration of the Maxwell's tensor over a surface enclosing partially a device part allows the calculation of electromagnetic forces applied to this part. The calculation is considered accurate since the stresses are applied especially to the end parts. It would be therefore possible to make use of the Maxwell stress tensor, in spite of its global character, for the evaluation of magnetic forces applied to the teeth of an electrical machine.

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