ON TRACTIVE FORCE OF PLUNGER - TYPE MAGNET

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Abstract. Using some of early-obtained formulas for corner and constriction permeances, some 2D formulas for the attractive force of a thick plunger type magnet are derived and applied to existing electromagnet. Comparison with 2D, 3D FEM and experimental results are presented

Keywords: Permeance, Force.

INTRODUCTION

In last years some new more exact formulas for 2D permeances and their derivatives were derived, using conformal mappings [1] – [4], which could be used for more accurate magnetic field evaluation in various shape magnets and electromagnetic force calculation.

In the paper the force of a plunger type electromagnet is calculated and compared with the value obtained using Maxwell tensor, evaluated with the two-dimensional FEMM package and early obtained experimental and 3D FEM results obtained with ANSYS.

FORMULAS FOR PERMEANCES EVALUATION

The corner permeance for enough small gaps ($\delta < c$) (Fig. 1a) can be calculated with formula [1] – [3]:

(1) $$\lambda_c(x) = \frac{2}{\pi}\left[x\ \arctan\left(\frac{1}{x}\right) + \frac{1}{x}\arctan(x) + \ln\frac{1+x^2}{4x}\right]; \quad x = \frac{\delta}{b}$$

The derivative of corner permeance, for small gaps is:

(2) $$\lambda'_c(x) = \frac{\mathrm{d}\lambda_c}{\mathrm{d}x} = \frac{2}{\pi}\left[\arctan\left(\frac{1}{x}\right) - \frac{\arctan(x)}{x^2}\right]; \quad x = \frac{\delta}{b}$$

For larger gaps ($c < \delta < a - b$), where $c/\delta \to 0$, the corner permeance is rather given by [3]:

(3) $$\lambda_{c0}(x) = x + \frac{1}{\pi}\ln\left(\frac{2}{\cosh(\pi x) - 1}\right)$$

And its derivative is:

(4) $$\lambda'_{c0}(x) = \frac{d\lambda_{c0}}{dx} = 1 - \frac{\sinh(\pi x)}{\cosh(\pi x) - 1}; \qquad x = \frac{\delta}{b}$$

Notwithstanding the differences between the values of the permeances given by (1) and (3), the derivatives given by the formulas (2) and (4) are practically the same (Fig. 2).

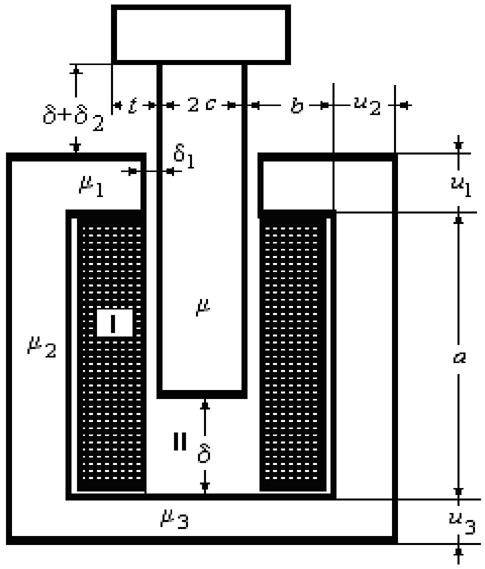

Fig. 1a Plunger type magnet

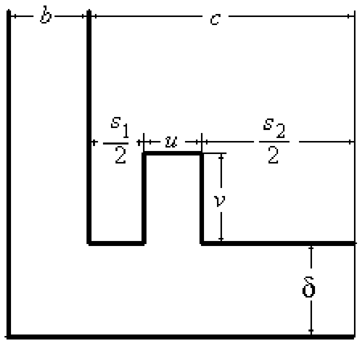

Fig. 1b Pole details

So, both formulas can be used for all the range of the gap.

The constriction permeance, for small gaps and u infinity is given by:

(5) $$\lambda_s(x) = \frac{1}{\pi x}\left[(1 + x^2)\ln\frac{1+x}{1-x} + 2x\ln\frac{1-x^2}{4x}\right]; \qquad x = \frac{\delta}{\delta + v}$$

The derivative of constriction permeance for small gaps is:

(6) $$\lambda'_s(x) = \frac{d\lambda_s}{dx} = \frac{1}{\pi}\left[1 - \frac{1}{x^2}\right]\ln\frac{1+x}{1-x}; \qquad x = \frac{\delta}{\delta + v}$$

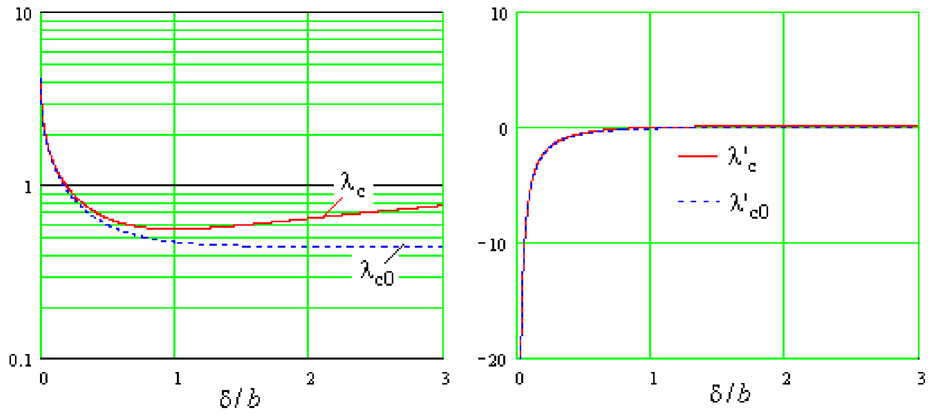

Fig. 2. Corner permeances and their derivatives calculated with (1), (2) (solid) and (3), (4) (dot)

For large gaps, when $s_i/(2\delta) \rightarrow 0$, the constriction permeance can be closer to the exact value for the case $s_i = 0$ [3]:

(7) $$\lambda_{s0}(x) = \frac{1}{\pi}\ln\left(\frac{2}{1-\cos(\pi x)}\right); \qquad x = \frac{\delta}{\delta + v}$$

The derivative of this constriction permeance for large gaps is:

(8) $$\lambda'_{s0}(x) = \frac{d\lambda_{s0}}{dx} = \frac{\sin(\pi x)}{\cos(\pi x) - 1}; \qquad x = \frac{\delta}{\delta + v}$$

We have the limits:

(9) $$\lim_{x\to 0}\frac{d\lambda_{s0}}{d(\ln(x))} = -\frac{2}{\pi} = -0.637; \qquad \lim_{x\to 1}\frac{d\lambda_{s0}}{d(\ln(x))} = 0$$

For deep slots, $u/v \ll 1$, (Fig. 1.b), the following formula for constriction permeance can be derived from [1] or [2], considering that all the flux in the slot emerges from lateral sides:

(10) $$\lambda_{s00}(x) = \frac{1}{\pi}\operatorname{arccosh}\left(1 + \frac{2}{x^2}\right); \qquad x = \frac{2\delta}{u}$$

The derivative of this constriction permeance is:

(11) $$\lambda'_{s00}(x) = \frac{d\lambda_{s00}}{dx} = \frac{-2}{\pi x\sqrt{1+x^2}}; \qquad x = \frac{2\delta}{u}$$

For s_i and d larger than $u/2$, more exact values are given by simple formulas:

$$\lambda_{s01}(x) \approx \frac{1}{x} - \frac{1}{\pi x^2}; \qquad \lambda'_{s01}(x) \approx \frac{d\lambda_{s01}}{dx} = \frac{1}{x^2}\left(\frac{2}{\pi x} - 1\right); \qquad x = \frac{2\delta}{u} \tag{12}$$

Similarly with constriction permeances, despite of any small differences between the values of constriction permeances given by the two formulas (5) and (7), the derivatives of the constriction permeances, given by the formulas (6) and (8), are almost coincident.

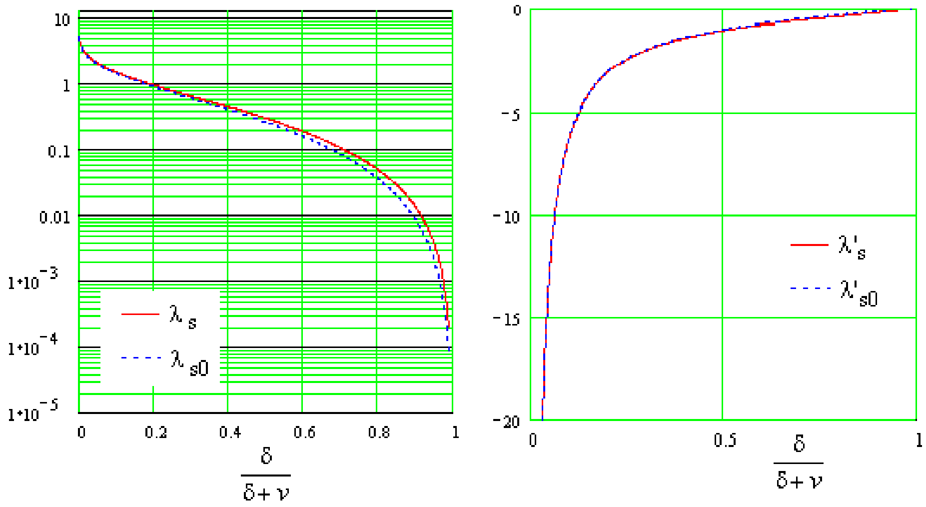

Fig. 3. Constriction permeances and derivatives calculated with (5), (7) (solid) and (6), (8) (dot)

The exact and approximate values of constriction permeances given by formula (12) are shown in fig. 4.

TRACTIVE FORCE OF PLUNGER TYPE MAGNET

The new formulas for 2D permeances were applied to the magnet studied in [4], considering the window width two times larger, because of the coil distribution along the plunger stroke.

The position of the zero magnetic field line can be considered at $k\ a$ distance from the top of the coil window, where k is the ratio of the main and upper gap permeances:

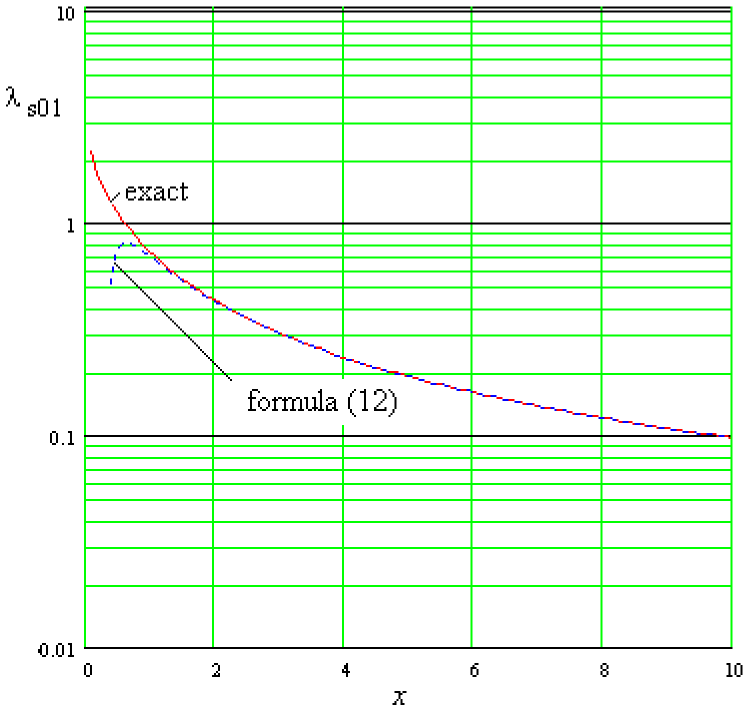

Fig. 4. Constriction permeance for *s* and *v* infinite

(13) $$k = \frac{\lambda_1}{\lambda_2} \approx \frac{\frac{c}{\delta} + 0.88}{\frac{c}{\delta} + \frac{u_1}{\delta_1} + \frac{t - \delta_1}{\delta + \delta_2} + 1.76}$$

Here δ_2 is the difference between the upper and main (bottom) gap and 0.88 is the fringing flux geometric permeance up to flux line, emerging at the distance from the vertex equal to the gap length [5].

The geometric permeance of the main gap and its derivative with respect to the main gap d were evaluated using the eq. (1) and (2):

(14) $$\lambda_1(\delta) = \frac{c}{\delta} + \frac{a(1-k) - \delta}{2b} + \frac{1}{2}\lambda_c\left(\frac{\delta}{2b}\right)$$

(14’) $$\lambda'_1(\delta) = \frac{-c}{\delta^2} - \frac{1}{2b} + \frac{1}{2b}\lambda'_c\left(\frac{\delta}{2b}\right)$$

The geometric permeance of the upper gap and its derivative were evaluated using the eq.

(15) $$\lambda_2(\delta) = \frac{u_1}{\delta_1} + \frac{a\,k}{2b} + \lambda_s\left(\frac{\delta_1}{b}\right) + \frac{t-\delta_1}{\delta+\delta_2} + \lambda_c\left(\frac{\delta_1}{\delta+\delta_2}\right) + 0.88$$

(16) $$\lambda'_2(\delta) = -\frac{t-\delta_1}{(\delta+\delta_2)^2} - \frac{\delta_1}{(\delta+\delta_2)^2}\lambda'_c\left(\frac{\delta_1}{\delta+\delta_2}\right)$$

The equivalent permeance and its derivative were calculated as series connected:

(17) $$\lambda = \frac{\lambda_1\lambda_2}{\lambda_1+\lambda_2}; \qquad \lambda' = \frac{\lambda'_1\lambda_2^2 + \lambda'_2\lambda_1^2}{(\lambda_1+\lambda_2)^2}$$

Considering an average value μ_r of the magnetic permeability of the steel and constant cross-section of the core $c \times g$, the tractive force was calculated for the total ampere-turns wI with the formula:

(18) $$F(\delta) = \mu_0 \frac{(wI)^2}{\left(1+\lambda(\delta)\frac{L_{fe}}{\mu_r c}\right)^2} g\,\lambda'(\delta) \quad [\mathrm{N}]$$

The results are shown in fig. 5. The agreement with 2D FEM results is better than 3%.

CONCLUSIONS

The force can be calculated with proposed formulas for 2D potential magnetic field, considering the window width two times larger along the coil height. The agreement with two-dimensional FEM results is very good. The formulas can be used for accurate force calculation, especially for thick cores.

The influence of the slot on the pole is negligible, especially for large gaps.

The experimental values are close to the calculated for gaps smaller than 5% of the stroke and are lower for larger gaps. This could be explained by three-dimensional character of the magnetic field, which is no considered by proposed formulas.

The given in [4] three-dimensional analysis seems to confirm last conclusion.

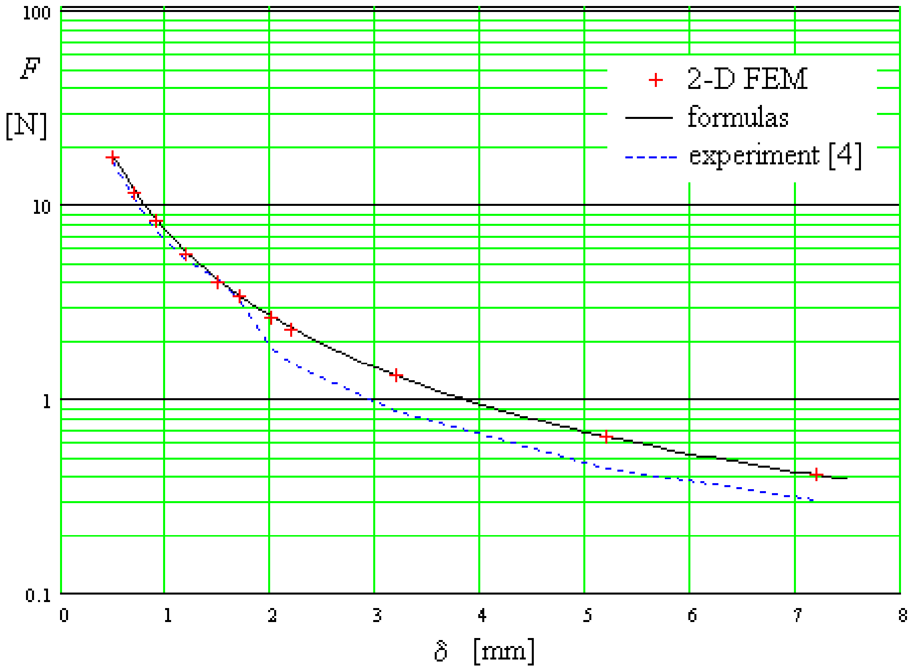

Fig. 5. Tractive force versus stroke

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