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Design of a Linear Eddy Current brake, 3D modeling and optimization

S. Vivier, M. Hecquet, P. Brochet

Abstract—This paper illustrates the use of the Experiment Design technique applied to the optimization of an electromagnetic brake. In order to place this device in rolling stock application, this study shows the influence of particular characteristic dimensions on the braking and attractive forces. The aim is to determine accurately the variations of these forces especially around the optimal point using the 3D finite element method. A comparison with the experimental measurements is realised in order to validate the model.

Index Terms—Eddy current brake, experimental design method, braking and attractive forces, optimization, polynomial model.

I. INTRODUCTION

New developments in braking systems have been initiated recently in order to face new demands for high velocity railway systems. Eddy-current rail brakes have therefore been developed [1], [2], [3]. The aim of such additional equipment is to make the train slow down, and not to stop it completely.

The eddy-current brake can be viewed like the inductor of a linear motor.

Due to the speed of the train carrying the brake, eddy currents are induced in the rail creating so Lorenz forces. Previous studies have demonstrated the relative importance of few characteristic dimensions on braking and attractive forces [4], [5]. But the braking force magnitude is not optimal.

The goal of this study is the research of the best dimensions for each pole, in order to use this structure at medium speed. The braking force must be maximal and in addition, the attraction force must be minimal. In the same time, it is interesting to know how these response functions behave in the neighbourhood of the optimal point.

Analytic computation of the braking force is difficult without major simplifications of the involved phenomena: skin effect, eddy current trajectories, armature magnetic reaction and non-linear materials.

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So the only practical method of computation seems to be the Finite Element Method (F.E.M.), in a cross section or in full 3D. As the induced eddy currents in the rail are stationary in the co-ordinate system of the brake, magnetodynamic solver taking into account the velocity [6] can be used to simulate the braking operation.

In the first part, the braking device is presented and the different parameters are studied. Few simulation results are compared to experimental measurements in order to validate the model.

Then, the response surface methodology is used to optimize this structure in order to obtain a good compromise between the maximum of braking force and the minimum of attractive force. In order to study the response variation, the polynomial expressions for these response functions, braking and attractive forces, are calculated over the validity domain of the design.

II. BRAKING SYSTEM PRESENTATION

The braking system is simple and can be viewed as a linear motor. It can be assembled from simple parts such as coils, poles, and core. The complete geometry is obtained by the repetition of a simple pattern, the pole-pitch. In figure 1, a plane view of one pole is presented, with geometrical parameters defining its shape.

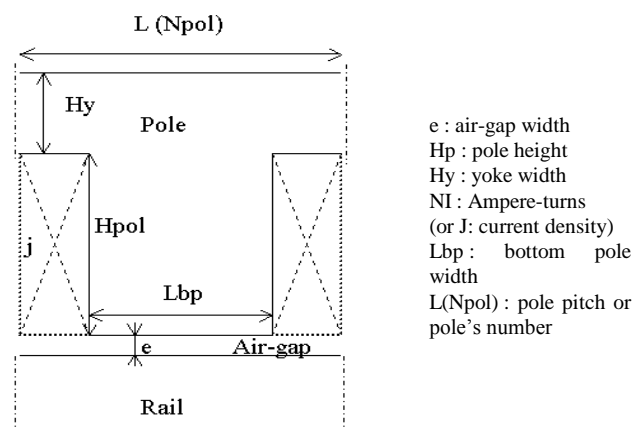


Fig. 1: Plane view of one pole and parameters

The pole pitch L is linked to the number of poles, the total length of this braking system being constant. The coils, supply by a direct current, are placed around the poles.

III. SIMULATIONS AND EXPERIMENTAL COMPARISONS

An experimental bench : a curved model is realized with six poles. It is possible to measure the flux through the bottom and the top of a pole, and also, the attractive and braking forces. The results are obtained with NI (ampere-turns) equal to 10000, 15000 and 20000 AT, with different speed: 0 – 200km/h and different air gaps.

For the simulation, the 3D mesh is defined with six poles, as shown in figure 2, and hence, the extremity effects are taken account. The braking force is obtained by the Lorenz forces and the attractive force by the Maxwell's stress tensor.

For example, the distribution of eddy currents in the rail for v (speed) equal 12.5m/sec are presented for a linear eddy current brake - figure 3 - or the distribution of the induction modified by these currents, as shown in figure 4.

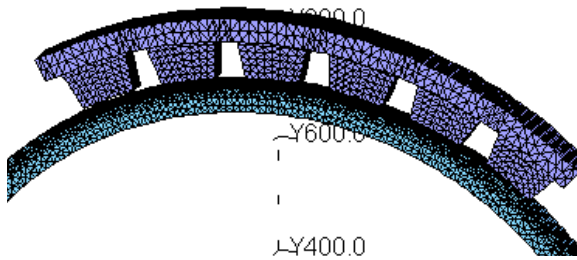


Fig.2. Experimental bench : curved model

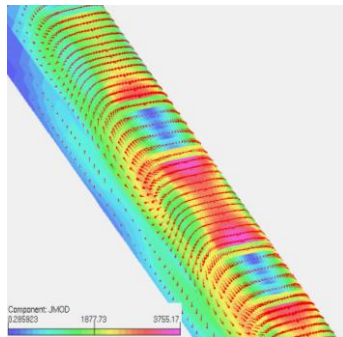


Fig. 3. Eddy current trajectories in the rail ($v=12.5m/s$) for a linear model

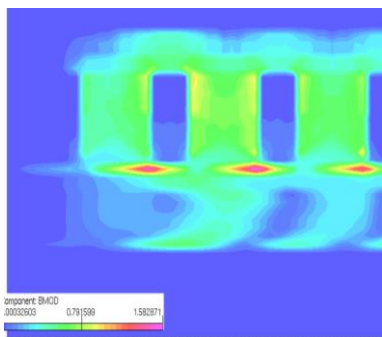


Fig 4. 3D simulation results for $v=12.5m/sec$ (Induction) for a linear model

A comparison between simulation and experimental measurements is realized in order to validate the modeling approach used. The flux at the top and at the bottom of the poles and especially the braking and total attractive forces are compared in figure 5 (NI=10000AT).

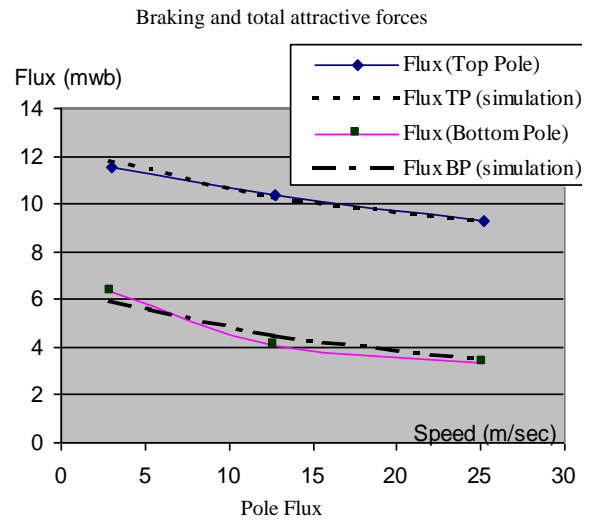
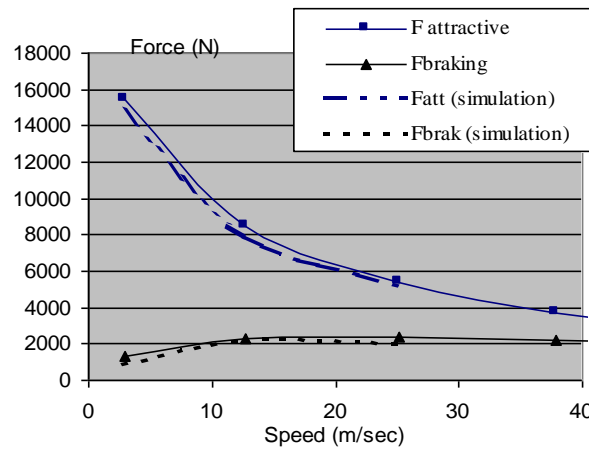


Fig. 5: Experimental and simulation results (NI=10000AT)

These simulation results have proven to be very close to the experimental measurements for different ampere-turns values, and it is possible to simulate a complete 3D model with a reasonable computing time (10 to 15 hours). Hence, the optimization of a 3D linear eddy current brake by this mean is possible.

IV. DESIGN OF EXPERIMENTS METHOD

In this study, classical optimization methods like Steepest Descent or BFGS are not used. The Response Surface Methodology (RSM), a particular application of the Design of Experiments (DoE) Method, has been preferred [7], [8] and [9].

This remains an iterative method; however, at each iteration, N experiments must be carried out so as to deduce information. In a general way, the experimental design method demands N ($N>1$) simulations to be done, from which a modeling of the objective function can be built. Subsequent simulations can then be deduced, leading to optimization techniques.

It is used to determine significant factors on the response values (screening tests), or to build a reliable model of the response (Response Surface Methodology - RSM) [10].

A polynomial expression for the response functions, i.e. the braking and the attractive forces, are then calculated over the validity domain of the design. These models give reliable information about the optimum location, or at least its direction.

The previous methods have been implemented in an optimization manager [11], [12]. Parallel computations are particularly well suited to the design of experiment method. Indeed, since several experiments are needed before deducing information, these simulations can be easily distributed to several computers. The availability of computers in network being more and more common, this solution turns out to be very interesting.

Therefore, according to the number of available computers, 2, 3, and 4 may reduce the time demanded by the problem... The principle of parallelism is based on a master-slave structure. A master computer distributes simulations on available computers that execute their task all at the same time. Results are sent to the master when done, which gathers them afterwards and uses them.

A. Linear model definition:

Different parameters are considered, as shown in figure 1. In references [5], [10], a *screening design* is realised in order to determine significant parameters. For example in Table 1, the effects of the different parameters and their interactions on the braking force are given with the results of the variance analysis (ANOVA). The velocity is equal to 50 km/h.

Factors	Effects	Variance	Residu	F exp.	% point	Significant?
e	0.437	3.06	4.84	26.55	99.9	Yes
Hp	0.062	0.06	4.84	0.54	53.4	No
L	0.937	14.06	4.84	121.9	100	Yes
Hy	-0.656	6.89	4.84	59.75	100	Yes
Lbp	0.093	0.14	4.84	1.22	72.4	No
J	-2.625	110.25	4.84	955.9	100	Yes
L*Hy	0.5	4	4.84	34.68	99.9	Yes
L*NI	0.468	3.51	4.84	30.48	99.9	Yes
L*Lbp	-0.187	0.56	4.84	4.88	96.7	Yes
Hy*NI	-0.625	6.25	4.84	54.19	100	Yes
Lbp*NI	0.062	0.06	4.84	0.54	53.4	No
E*NI	-0.031	0.015	4.84	0.13	28.5	No
Mean	-3.59					

Tab. 1. Effects of factors and interactions on the braking force fy

An obvious objective to study, could be to increase the braking force and essentially to decrease the attractive force for some critical speeds like 50 and 100 km/h. A fractional design 2^{6-2} that defines 16 simulations is used to determine which factors from Hp, Lbp, Hy, e, L and j, the supplied current values, are the sensitive parameters of the braking and attractive forces. The tested effects are the main factors and their interactions of order 2, giving the model below:

$$F_y = \text{mean} + H_p + e + j + L_{bp} + H_y + L + H_p * e + \dots$$

Then, ANOVA, the variance analysis, determines which factors have an effect on the studied response. ANOVA shows

that only 4 parameters are really significant for the braking force: L(Npol), j, e, and Hy.

For this study, two significant factors L and NI have been considered for different speeds. For the Hy parameter, the yoke induction is verified and must be lower than 1.5-1.6T, and the air gap width is constant at 9mm.

Interesting results are the influence of the pole number (Npol) linked to the pole pitch (L) and the speed on the attractive and braking forces (figure 6). In addition, the ratio of the braking force (Fbrake) on the attractive force (Fattr) is determined.

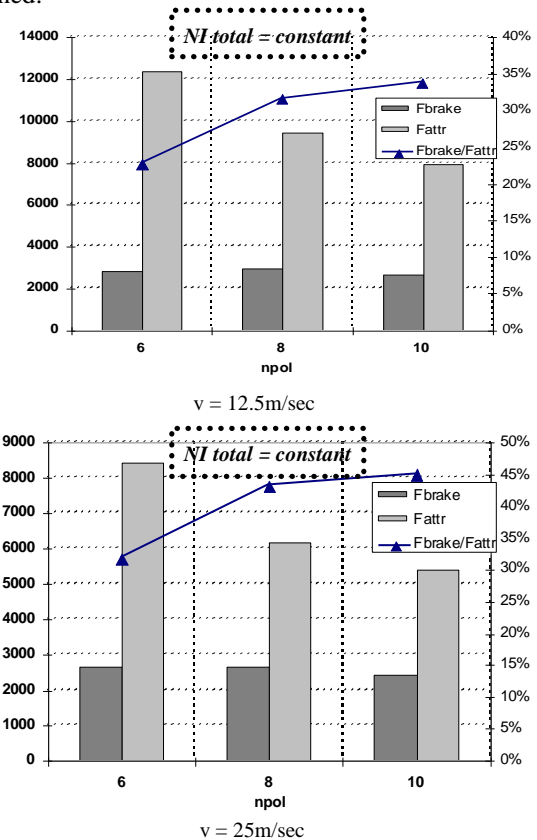


Fig.6: Attractive and braking forces versus number of poles for two speeds.

These results show that the maximum of the braking force is obtained for Npol = 8, but the ratio Fbrake / Fattr requires to increase the number of poles. Effectively, the braking force is maximum with the '8-pole' model and for 15m/sec, and remains equal to constant. But, the attractive force is minimum for '10-pole' model and decrease very quickly with the speed. A good compromise between a maximum of braking force and a minimum of attractive force is obtained with the '8-pole' model.

B. Response Surface Methodology (RSM):

In order to study the response variations, RSM designs have been computed. For example, the inputs are the factors j and v for the '8-pole' model. The second order model is directly deduced for the attractive force and the braking force.

Thanks to these models, the sensitivity of the responses can be easily computed and analyzed. Figure 7 shows response surfaces obtained for the attractive force and the braking force versus j and v.

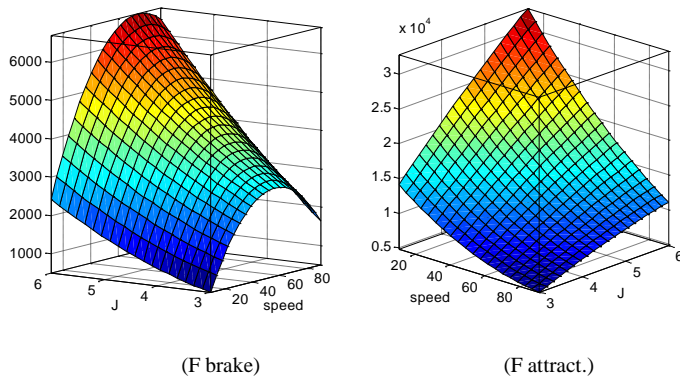


Fig.7: Attractive and braking forces versus speed v and j

Then, it's possible to deduce the desirability function [12] versus speed v and Npol in order to verify the good compromise between a maximum of braking force and a minimum of attractive force, figure 8.

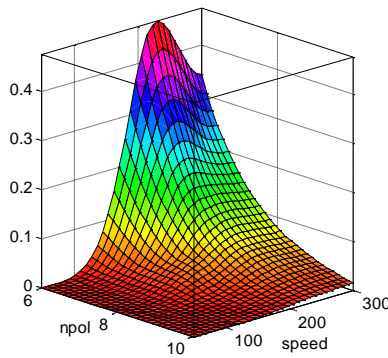


Fig.8: Desirability function versus speed v and number of poles Npol

C. Optimised model :

The Fbrak and Fattr characteristics (figure 8) are presented for the optimised model. This model has 8 poles, NI(j) and Hy are imposed, and e=9mm.

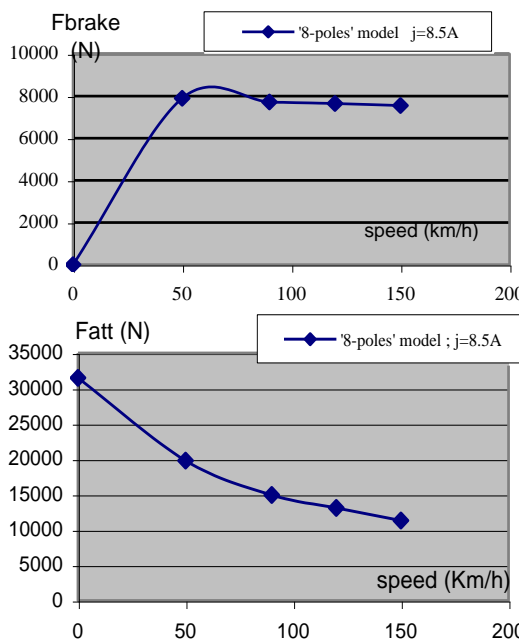


Fig.8: Attractive and braking forces versus speed v.

The configuration characteristics are :

- Fbrake \cong 7.5 kN (that is 25% of the total braking force needed)

- Fattr \leq 15 kN and Fbrake/Fattr = 55 %.

With this study, we have demonstrated that the eddy current brake can be used when the speed of the train is greater than 100 km/h. Effectively, if the speed is lower 100km/h, the attractive force is more important and this brake can be destroyed the fixations or the rail.

V. CONCLUSION

The experimental design method combined with numerical simulation is an appropriate tool to design such an electrical device where no theoretical knowledge is available. It gives to the designer the ability to understand the tendency of each factor. With factorial fractional design, sophisticated shapes can be investigated, even requiring a lot of parameters or qualitative ones. It should be an appreciable part of any electromagnetic optimization package.

The attractive and braking forces characteristic versus the velocity and the ampere-turns has been obtained. A maximum value has been found for an 8-poles model.

The Response Surface Method is straightforward to localize an optimum taking into account its sensitivity.

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