EXPERIMENTAL DESIGN METHOD APPLIED TO THE OPTIMISATION OF A LINEAR EDDY CURRENT BRAKE.

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Abstract :

This paper illustrates the use of experiment design technique applied to the optimisation of an electromagnetic brake. This device is used in rolling stock equipment. Previous studies showed the influence of particular characteristic dimensions on the braking and attractive forces created by this device. Our aim is to determine accurately the variations of these forces especially around the optimal point using the 3D finite element method associated to the experimental designs. The advantage of the Response Surface Methodology is to determined a polynomial model for the braking and attractive forces versus studied parameters. In addition, a comparison with the experimental measurements is realised in order to validate our model.

1. 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. Its complete geometry is obtained by the repetition of a simple pattern, the pole-pitch. 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. The braking force must be maximal and 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. So the only practical method of computation seems to be the Finite Element Method (F.E.M.), in a cutting plane 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 studied different parameters. Few simulation results are compared to the experimental measurements in order to validate our model.

Then, the experimental design method is used to optimize this structure with a good compromise between the maximum of braking force and the minimum of attractive force.

At last, the polynomial expressions for these response functions, braking and attractive forces, are calculated over the validity domain of the design.

2. Linear eddy current brake

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 plan view of one pole is presented, with geometrical parameters defining its shape.
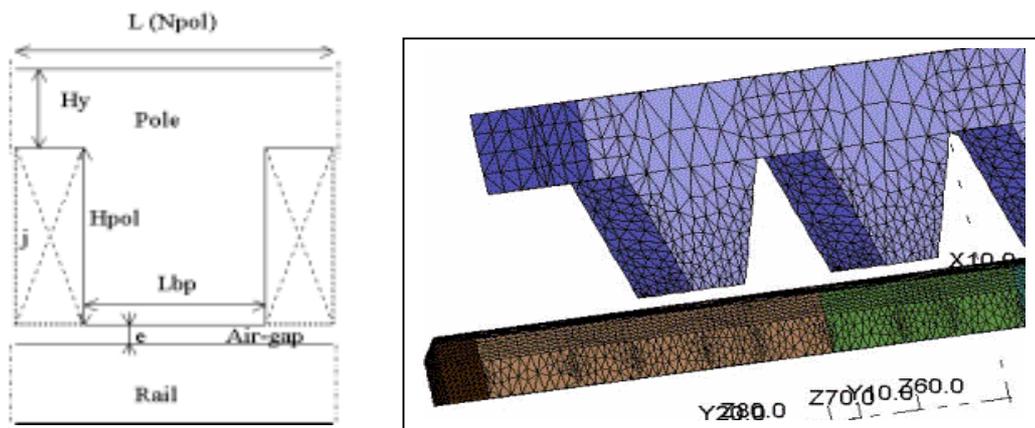

Fig. 1: Plan view of one pole and parameters, and 3D mesh example

The pole pitch L is linked to the number of poles (Npol), the total length of this braking system being constant. The coils, supply by a direct current (j), are placed around the poles. The other parameters are : Hy the yoke height, Hpol the pole height, e the air-gap thickness and Lbp the width of the pole bottom.

3. Experimental design method

In this study, classical optimisation methods like Steepest Descent or BFGS are not used. The application of the experimental design method has been preferred [7, 8, 9, 10].

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 an objective function can be constructed. 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).

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 optimisation manager [11]. 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 disposal 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 available, which gathers them afterwards and uses them.

Electromagnetic computations of the linear braking system have been performed by Finite Element analysis. This analysis takes account of relative velocities that is those of inductor and the rail in this case.
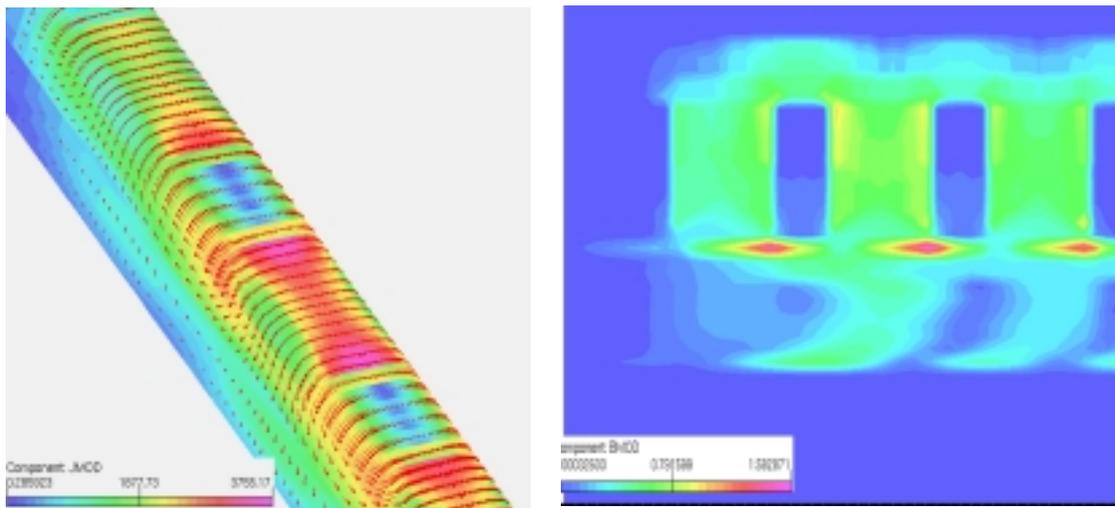
4. Experimental and simulation results

4.1. Model validation

An experimental bench is realized with six poles. It's possible to measure the flux through the bottom and the top of a pole, but 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-gap.

For the simulation, the 3D mesh is defined with six poles, as shown in figure 1, and hence, the end effects are taking account. The braking force is obtained by the Lorentz forces ($F = J.B$) and the attractive force by the Maxwell' stress tensor.

In first time, the 3D simulation results are presented, for example, the distribution of eddy currents in the rail for v (speed) equal 12.5m/sec, figure 2.a. Hence, the distribution of the induction is modified by these currents, as shown figure 2.b.

a) Eddy current distribution   b) Induction

Fig.2: 3D simulation results for v=12.5m/sec

In the second time, a comparison between simulation and experimental measurements is realized in order to validate our model. The flux at the top and the bottom pole and the braking and total attractive forces are compared in figure 3 (NI=10000AT).
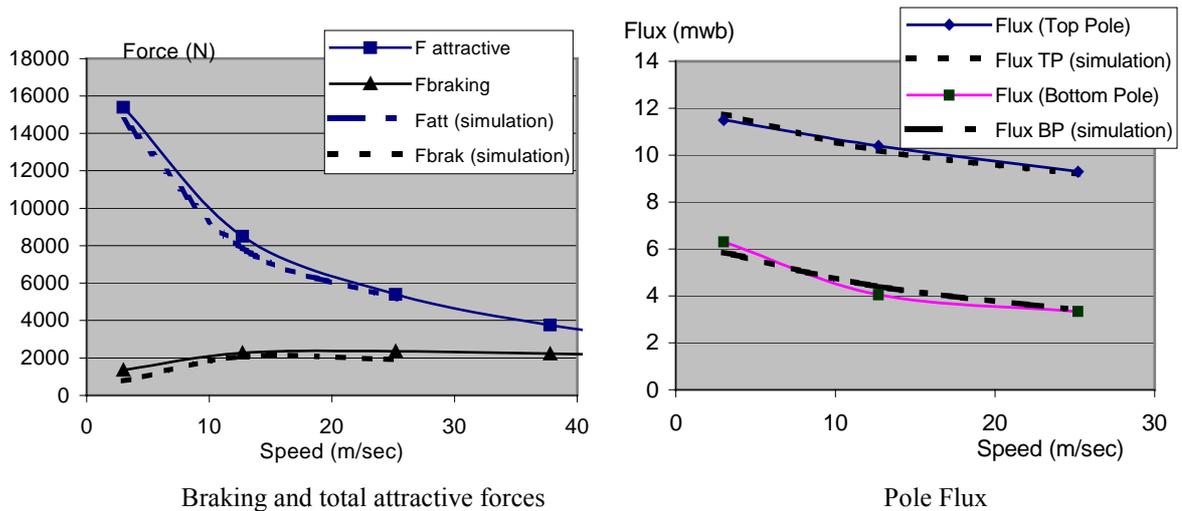
Braking and total attractive forces   Pole Flux

Fig. 3: Experimental and simulation results (NI=10000AT)

These simulation results are very close to the experimental measurements for different ampere-turns values, and it's possible to simulate a complete 3D model with a reasonable computing time (10 to 15 hours). Hence, the optimisation of a 3D linear eddy current brake is possible.

4.2. Experimental design method

Different parameters are considered, as shown in figure 1. In references [4], [5], a screening design is realised in order to determine significant parameters.

4.2.1. Screening design :

Two values or levels for each parameter are chosen in order to establish the effects of these parameters and their interactions on the braking force. The levels for the different parameters are :

  e : ± 2 mm; Hpol : ± 20mm;   Hy : ± 30mm;
  Lbp : 0 to 30%; Npol : 6 to 10;   j : 6 to 8 A/mm²;

Starting from the number of factors, the number of experiments allowed, the resolution and from well chosen alias, factorial 2 level fractional designs are easily built [7]. A 2^{6-2} design is defined and hence, only 16 simulations are calculated.

Then, ANOVA, the variance analysis [7], determines which factors have an effect on the studied response. If too many alias forbid any clear interpretation, supplementary simulations can then be added until satisfactory result.

For example, the variance analysis shows, in figure 4, that only 4 parameters are really significant Npol, j, Hy and e for the braking force at the low speed (v=50km/h).

ANOVA : variance analysis

brf : braking force (response)

Significant factors

a : Npol
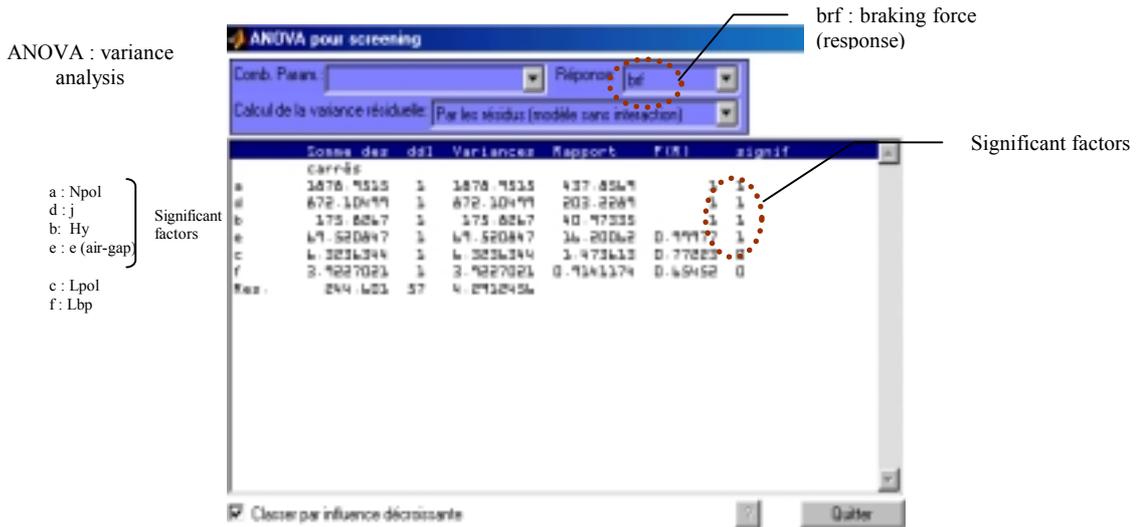d : j
b: Hy
e : e (air-gap)

Significant factors

c : Lpol
f : Lbp

Fig. 4. : Variance analysis and the significant factors.
(*v= 50 km/h*).

This analysis is directly obtained by our optimisation manager [11].

Then, the experimental design method is used to optimize this structure with a good compromise between the maximum of braking force and the minimum of attractive force. So, an optimisation process can be started using only 4 parameters : Npol, j, Hy and e. The Response Surface Methodology is used to build a polynomial model of the attractive and braking forces versus the chosen geometric parameter and then to use this model as an objective function within an optimisation problem.

4.2.2. Response Surface Methodology

In this part, a full 3 level factorial design is performed as non-linear effects can be expected. For this study, two significant factors Npol and j (the more significants) have been considered for different speeds. For the third parameter Hy, the yoke induction is verified and must be lower than 1.5-1.6T. And the last parameter e is equal constant to 9mm.

In first time, simulation results present the influence of the pole number (Npol) linked to the pole pitch (L), as shown figure 1, and the speed versus the attractive and braking force (figure 5). In addition, the braking force (Fbrak) on the attractive force (Fatt) is determined.
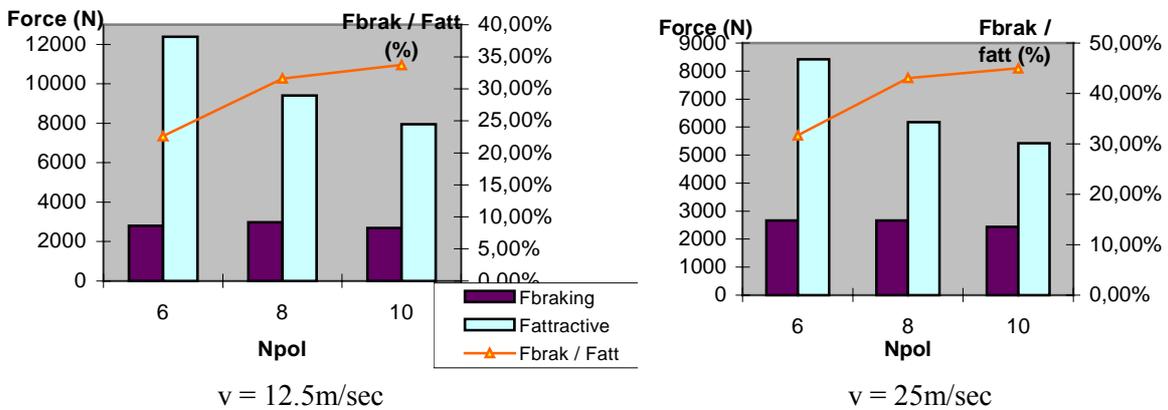

v = 12.5m/sec   v = 25m/sec
Fig. 5: Attractive and braking forces versus number of poles for two speeds.

With this results, the maximum of the braking force is obtained for Npol = 8, but for the F_{brak} / F_{att} result, it's necessary to increase the number of poles. The best result (F_{brak} / F_{att}) is obtained for 10 poles and for v = 25m/sec.

Effectively, the braking force is maximum for 12.5m/sec, as shown figure 6, and remains equal to constant. But, the attractive force decrease very quickly with the speed v (figure 6).
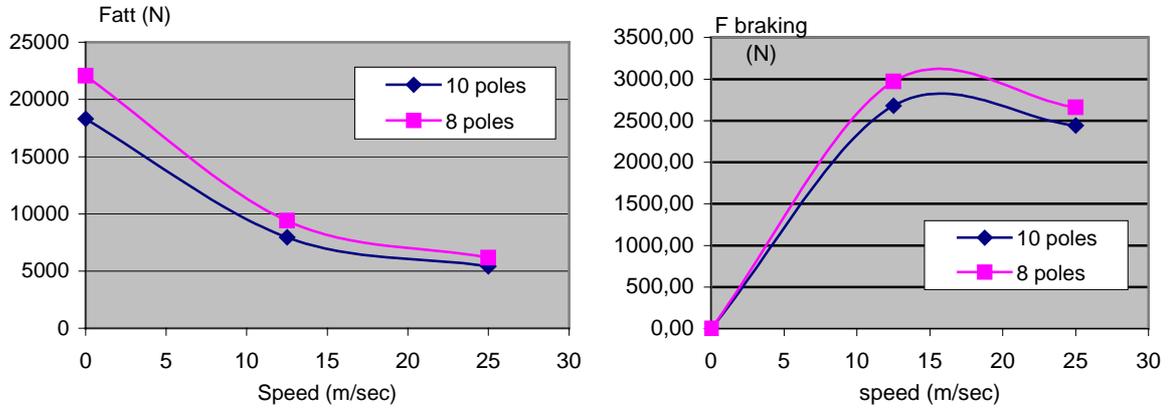

Fig. 6: Attractive and braking forces versus speed and number of poles.

With this results, we have chosen Npol = 8 in order to realize a good compromise between attractive force and braking force. In order to study the response variations, RSM designs have been computed. The inputs are the factors: the current density (j) and the speed (v).

Figure 7 shows a response surface obtained Fatt versus NI, equal to j.S (S the coil section) and the speed *v* for Npol=8.
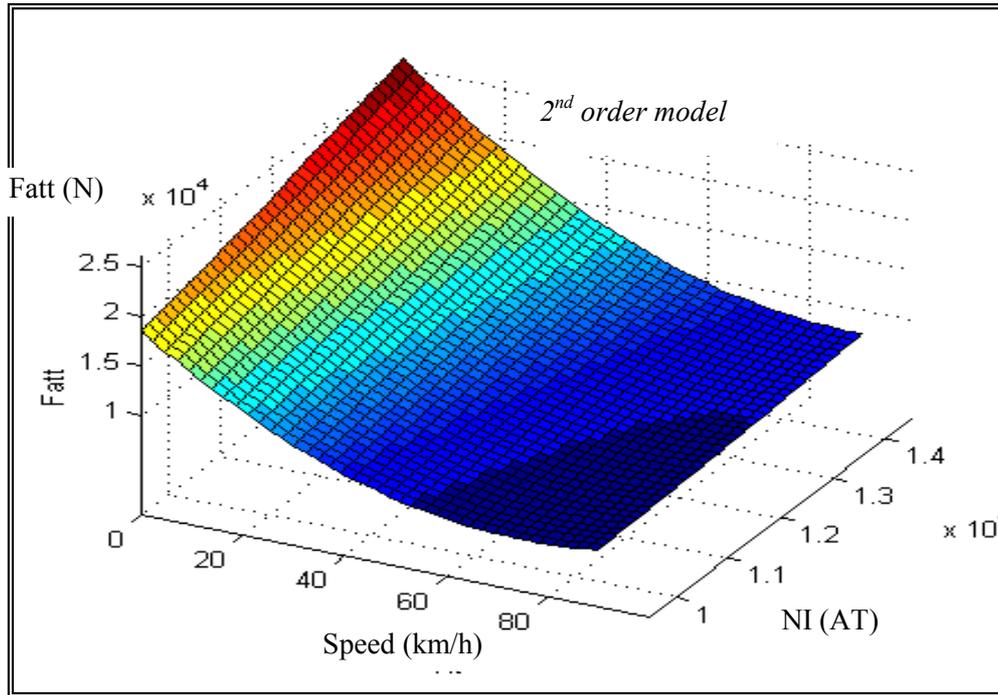

Fig. 7: Response surface for the attractive force versus speed and NI.

For example, the second order model used for the attractive force is:

$$F \text{ att} = 8953 - 233{,}2*(v) + 0.689*(NI) + 2.34*(v)^2 + 3.36E\text{-}5*(NI)^2 + 0.0126*(v*NI)$$

The same model is obtained for the braking force. Thanks to these models, the sensitivity of the responses can be easily computed and analyzed. Hence, the optimized results is given in figure 8 :
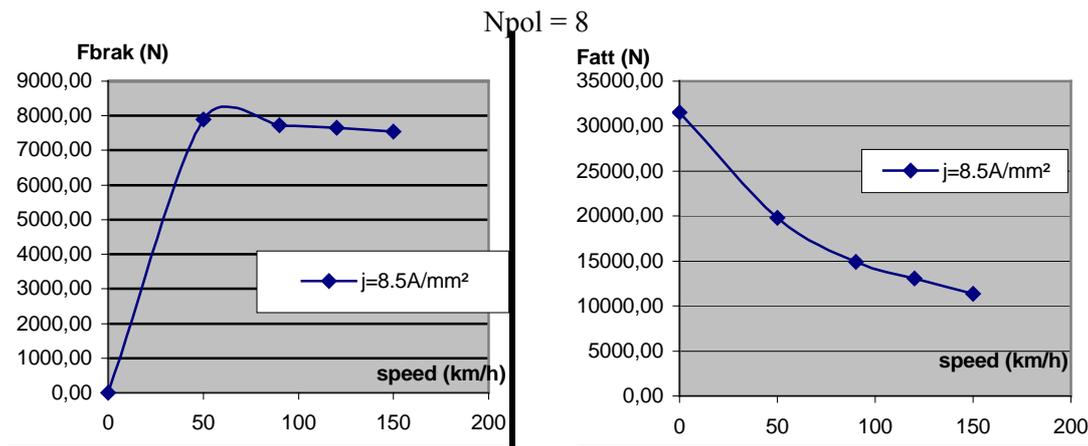
Fig. 8 : Optimized results of braking and attractive forces versus speed.

In this case, the $F_{braking} / F_{attractive}$ is equal to 55% at v=90km/h (or 12.5m/sec) and these results give a good compromise between the maximum of braking force and the minimum of attractive force.

5. 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.

6. References

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