3D optimisation of a linear eddy current brake using the experimental design method

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Abstract—**This paper illustrates the use of the Experiment Design technique applied to the optimisation 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.**

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. 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.

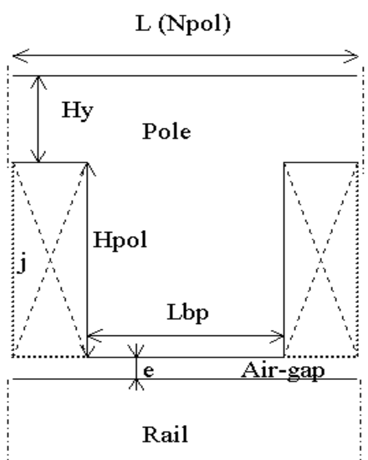
So the only practical method of computation seems to be the Finite Element Method (F.E.M.), in a cross section or in full 3D. As the induced eddy currents in the rail are stationary in the co-ordinate system of the brake, magnetodynamic solver taking into account the velocity [6] can be used to simulate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

2. 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.



e : air-gap width
Hp : pole height
Hy : yoke width
NI : Ampere-turns (or J: current density)
Lbp : bottom pole width
L (Npol) : pole pitch or pole's number

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.

3. Simulation and Experimental Comparisons for a curved-model.

An experimental bench : a curved-model is realized with six poles, as shown in figure 2.

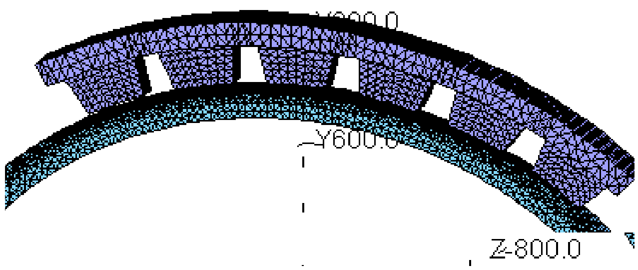
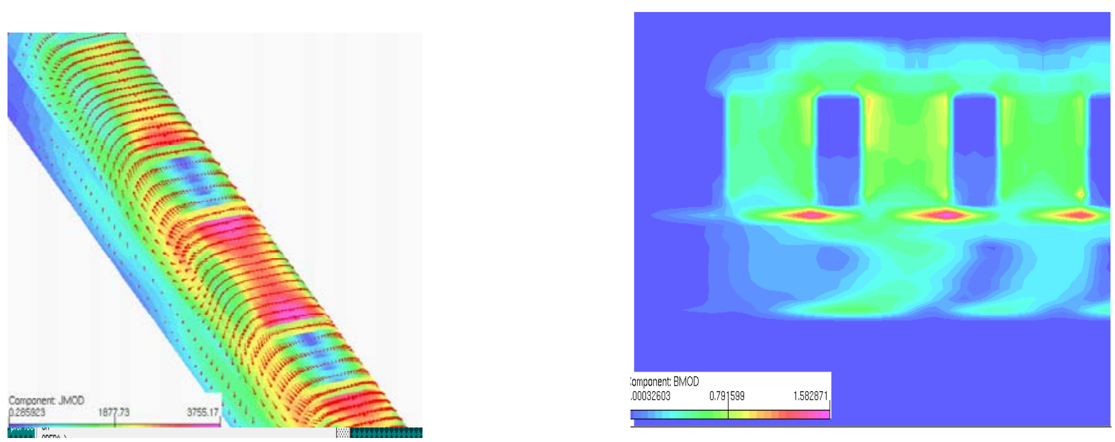


Fig.2. Experimental bench : curved-model

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 or the distribution of the induction modified by these currents, as shown in figure 3.

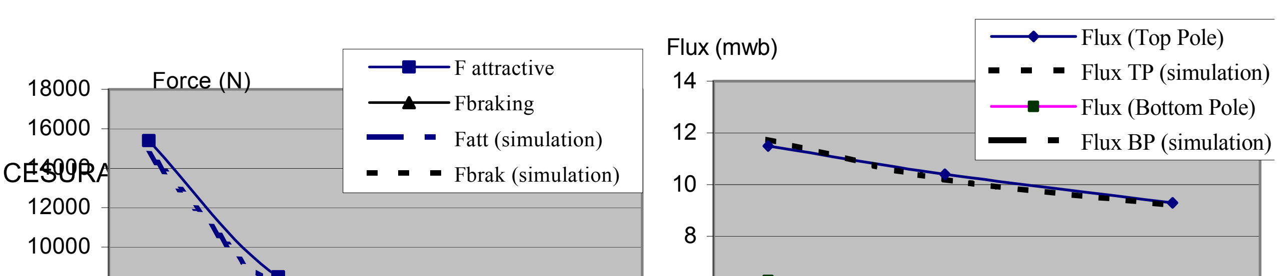


Eddy current in the rail

Induction

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

A comparison between simulation and experimental measurements for the curved-model is realized in order to validate our model 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 4 (NI=10000AT).



Braking and total attractive forces Pole Flux

Fig. 4. 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 optimisation of a 3D linear eddy current brake by this mean is possible.

4. Design of Experiments Method.

In this study, classical optimisation 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 optimisation 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 optimisation 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.

4.2. Linear model definition:

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 5, that only 4 parameters are really significant Npol, j, Hy and e for the braking force at the low speed (v=50km/h).

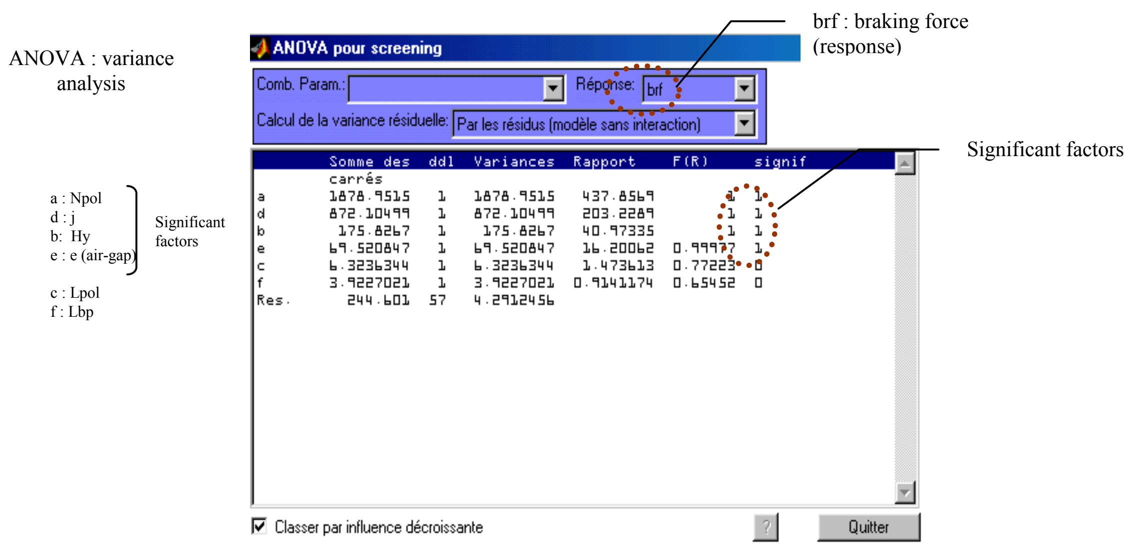


Fig. 5. Variance analysis and the significant factors. (*v= 50 km/h*).

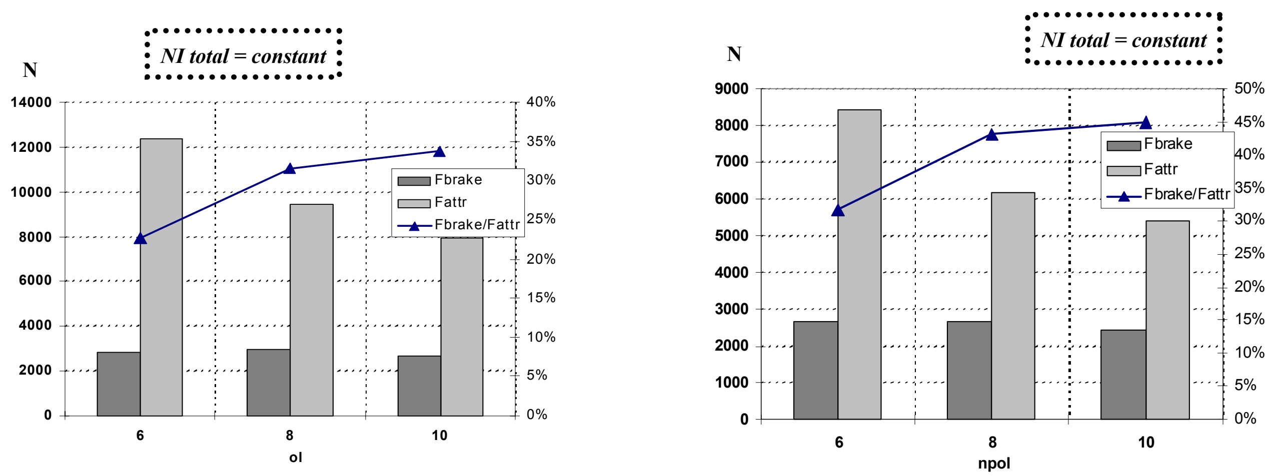
All the analysis are performed by the optimisation manager [11].

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 a reduced 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, only two more significant factors Npol and j have been considered for different speeds. The third parameter Hy is imposed so that the yoke induction is verified and must be lower than 1.5T. And the last parameter e is put at 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 6). In addition, the braking force (Fbrak) on the attractive force (Fatt) is determined.



V = 12.5M/SEC V = 25M/SEC

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.

In second time, 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. Second order models are 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.

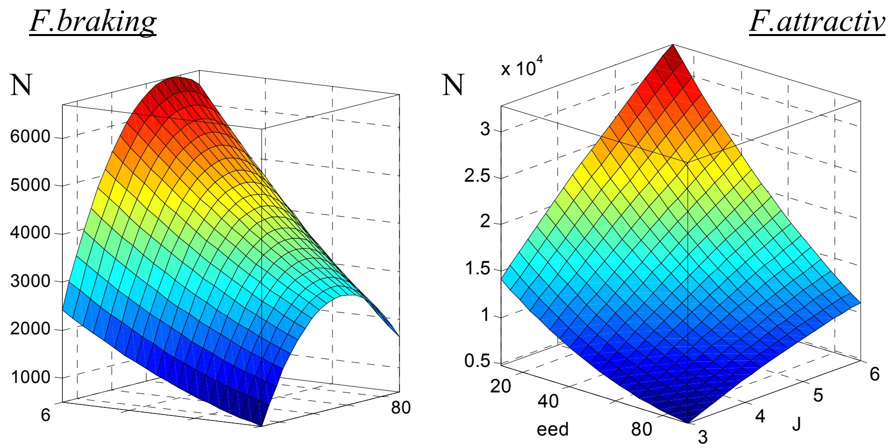


Fig.7. Attractive and braking forces versus speed v and j

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

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

With NI equal to j.S (S the coil section).

4.2.3. Optimized model :

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

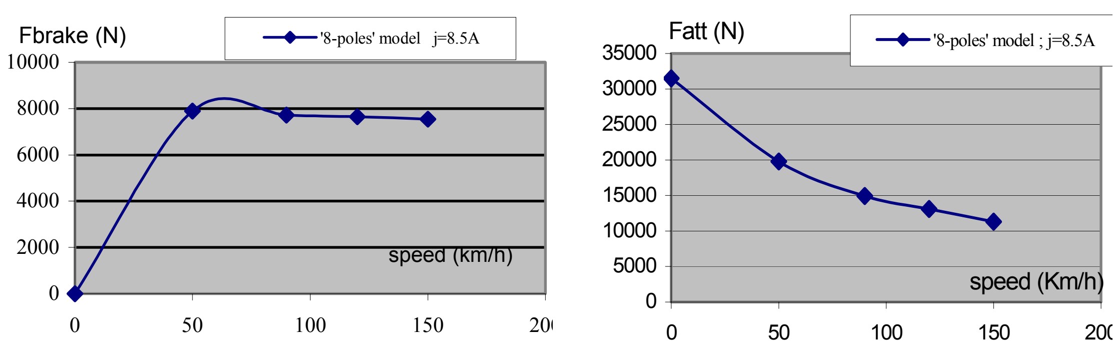


Fig.8: Attractive and braking forces versus speed v.

The configuration characteristics are :

- Fbrake ≅ 7.5 kN (that correspond to 25% of the total braking force needed)
- Fattr ≤ 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 the brake damaged the fixations or the rail, if the current density (j) is maintained.

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 optimisation 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 giving also its sensitivity.

6.References

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