A captivating approach:

Speed sensor on phonic wheel.

Marc Vilcot - CEDRAT.

❖ Introduction

The speed sensor on a phonic wheel is a simple device, consisting of a cogged wheel, a magnetic pole over which there are a magnet and a coil connected to a measuring resistance. The model of this device has to be a 3D one. Indeed, the wheel has a plane structure, whereas the sensor has revolution symmetry. Moreover, the flux lines of the sensor run in the three dimensions.

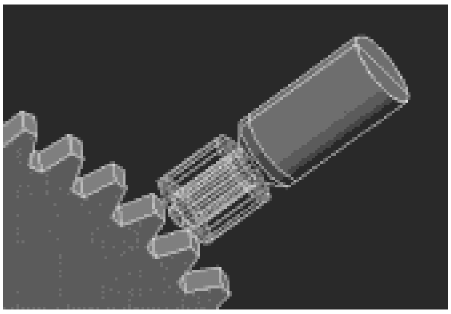

Figure 1 - Geometry of the sensor.

In many cases, a simple 3D multi-position computation allows the determination of the variation of the flux Φ as a function of the position θ and thus the voltage between the terminals of the measuring resistance can be obtained by computing the derivative of this curve:

$$e = -\frac{d\Phi}{d\theta}.\frac{d\theta}{dt}$$

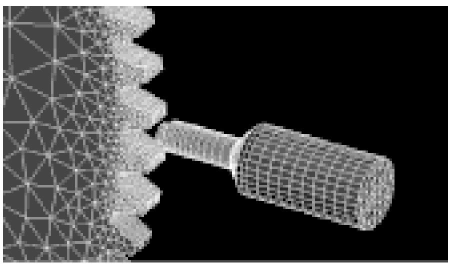

Figure 2 - Mesh of the geometry.

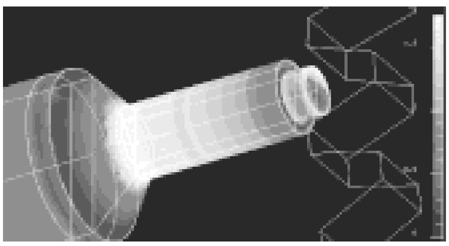

Figure 3 - Magnetic flux density in the sensor.

However, the Snecma Moteurs company has proposed us a very interesting case. The sensor is in fact adapted on a phonic wheel having a relatively low resistivity (25 E-8 Ω.m), the measuring resistance being 1kΩ.
With respect to the previously described ideal case, the effects of the flux variation in time require consideration, which implies:

- Eddy currents that are developing in the wheel;
- The effect of the current in the measuring circuit on the magnetic field, that is what will be called the measuring circuit reaction.

In order to highlight these phenomena, the figure 4 shows the voltages obtained across the measuring resistance for a wheel with right teeth in three cases:

- Voltage obtained by computing the derivative of the flux with respect to the wheel position ($e = -\frac{d\Phi}{d\theta}.\frac{d\theta}{dt}$) multi-static computation;
- Voltage obtained by taking into account the measuring circuit reaction (coupling between magnetic computation and electric circuits), but without eddy currents in the wheel (the wheel is considered as having an infinite resistivity);
- Voltage obtained by taking into account the measuring circuit reaction and the eddy currents in the wheel.

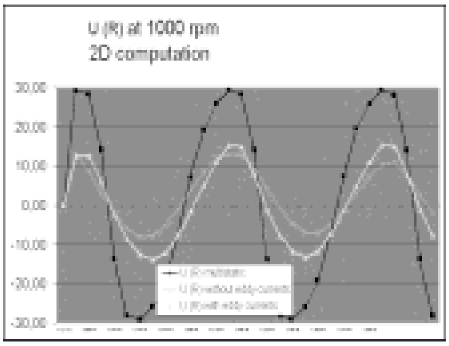

Figure 4 : Voltage obtained for different modelling hypothesis.

One can see that at 1,000 rpm, the flux variation with respect to time can no longer be neglected.

❖ Modelling approach

In order to model the device correctly, the dynamic behavior of the device should be taken into account, that is:

- The computation of the device should be carried out in a transient state;
- The movement of the wheel should be taken into account;
- Eddy currents that may appear in the wheel should be taken into account;
- The measuring circuit reaction should be taken into account.

The FLUX software packages offer the possibility of modeling the device by taking into account all these phenomena, in 2D, as well as in 3D.

However, the higher the speed of the wheel is, the longer the time needed for the transient computations will be:

- The transient state up to the permanent regime takes longer and longer (influence of the eddy currents and of the measuring circuit reaction).
- Skin depths in the wheel are lower and lower (0.05 mm at 10,000 rpm): therefore, finer and finer meshes are required for an appropriate consideration of these phenomena (two elements in the skin depth).

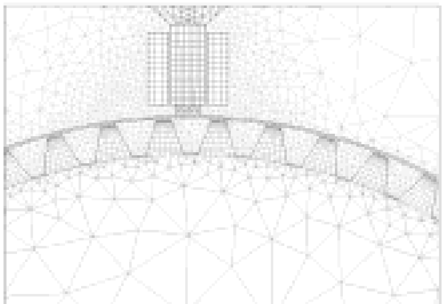

Figure 5 : 2D mesh of the device, taking into account the skin depths .

This leads to a non-negligible problem size.

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FLUX3D offers functions that allow the user to solve transient models coupled with movement and electric circuits (measuring circuit reaction). However, we thought to be interesting to propose a 2D model much quicker to optimise. Therefore, we propose the following original approach:

- Proposal of a 2D "equivalent" model by a comparison between the 2D and 3D multi-static solutions;
- 2D transient computations by using this equivalent model for the following speeds: 100 rpm, 1.000 rpm, 5.000 rpm and 10.000 rpm, taking into account the eddy currents and the measuring circuit reaction.

❖ The 2D equivalent model

The goal of this approach is to find an equivalent depth value that should be imposed to the 2D-plane model so that the fluxes through the coil be the same in 2D and in 3D. In this section, we show first the comparison between the 2D and 3D multi-static models and then the corrections to be made: the fluxes are computed in 2D and 3D at every 0.5 degrees.

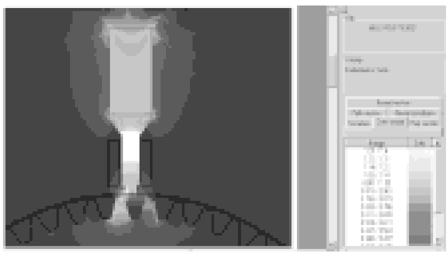

Figure 6 - Magnetic flux density in the 2D model.

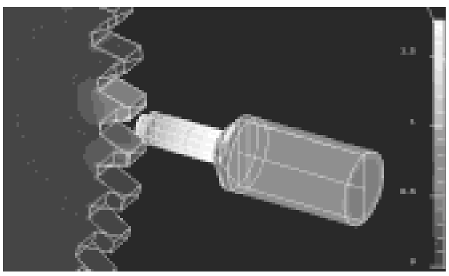

Figure 7 - Magnetic flux density in the 3D model.

The 2D computation is carried out for a device of 1 mm depth. The equivalent depth is the one used to multiply the flux computed for this unit length in order to make the correspondence between the middle points of the two FLUX curves (2D and 3D) as indicated below.

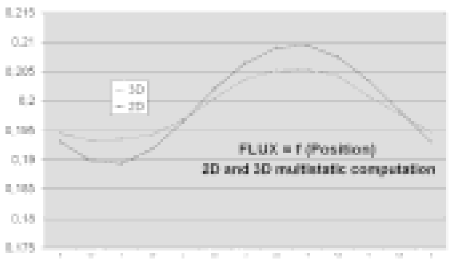

Figure 8 : Comparison of the flux curves obtained by multi-static computation.

❖ Corrections to be made to the 2D model

Even if this equivalent depth allows the correspondence of the middle points of the curves of flux function of position, it does not allow to stall the two curves. In fact, one can see that the peak-to-peak variation of the flux in the 3D model is only 60 % of the variation obtained in 2D. What is going on from the physical point of view? In 3D, so in reality, the flux sees the teeth of the wheel, but also the two plane faces of the wheel, which do not induce a flux variation. Therefore, it is normal to find that the flux variation is lower in 3D than in the 2D model, where the flux is restricted to seeing only the teeth of the wheel. Therefore, two corrections have to be made to the 2D model:

- **The voltage computed in the 2D model has to be multiplied by 0.6** in order to obtain a value close to the measurements (correction of the variable part of the flux). Another choice would be to the insert a compensation resistance in the electric circuit of the sensor to allow the direct adapting of the measuring voltage, but it would strongly distort the eddy current reaction as to the flux variation. The correction made a posteriori definitely improves the quality of the results.
- On the other hand, due to the fact that the eddy currents generated in the wheel are proportional to this flux variation (σ dA/dt), the conductivity of the material has to be multiplied (or the resistivity of the material has to be divided) by 0.6. **Therefore, we will use an equivalent resistivity of 41E-8 Ω.m for the wheel.** If this correction is not carried out, then the eddy currents generated in the wheel will be too important.

❖ Results

The table below gives the results of the peak/peak voltage across the measuring resistance computed in 2D, the corrected value, the measured value and the relative error with respect to the measurements for different values of the speed:

At low speed, everything is like in magnetostatics. Due to the corrections carried out, there is good agreement between the computation and the measurements. When the speed increases, the flux is strongly modified. It penetrates the teeth less easily but it reaches there because all the faces are accessible (5 sides). The skin depth value is close to half of the depth of the wheel. Thus, the real flux variation will be lower than in the 2D case, where only 3 sides are accessible. The flux is forced to be in the computational plane. In the 2D simulation the flux seen by the wheel is too high.

Finally, at high speeds, the flux does not penetrate the wheel any longer, either through the teeth or through

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Speed	Modelling results of the 2D model	Corrected modelling results	Results of measurement	Ratio
100 rpm	7.5 V	4.5 V	4.7 V	4,2 %
1000 rpm	29.5 V	17.7 V	14.5 V	18,1 %
5000 rpm	24.8 V	14.9 V	14.5 V	2,8 %
10 000 rpm	20.3 V	12.2 V	13 V	6,15 %

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the sides. The results no longer depend on the material of the wheel and therefore there is good agreement between the computation and measurement results.

The repartition of different quantities that can be visualized at each time step, such as:

- The flux density:

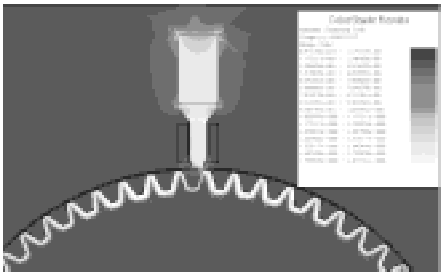

Figure 9 : Magnetic flux density.

- The power density in the wheel:

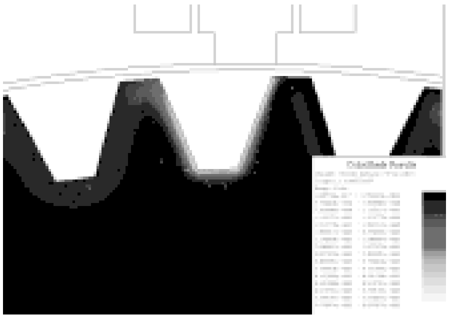

Figure 10 : Power density, image of the eddy currents.

- The flux lines that shows the influence of the speed:

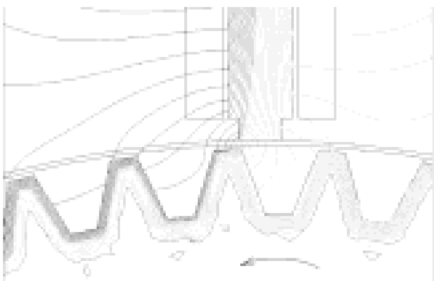

Figure 11 : Flux lines.

Quite obviously, magnetic and electric global quantities are available.

❖ *Conclusion*

The described method represents an approach to be used in a phase of the device design. This 2D approach has the shortcoming that it forces the whole flux to see the teeth, and thus to vary with the wheel position. In reality, a part of this flux, the one that passes through the sides, remains constant.

At low speed, the error due to the 2D approximation is corrected by choosing the device depth of the 2D problem. At higher speed, the magnetic flux has an important role. The correction of the resistivity allows the correction of the variable component of the magnetic flux, but not of the constant one.
It should be noted that this 2D model, allowing to solve the problem by taking into account all the phenomena (saturation, Eddy currents, eddy current reaction), is an interesting achievement as it proposes an interesting accuracy/ computation time ratio.
This method can be refined by working more on a direction to find equivalent properties of the materials, mainly of the magnet, in order to get the flux versus wheel position curves in 2D and 3D to be in correspondence.
We would like to acknowledge the Snecma Moteurs company for their participation in this article and the publishing authorization granted to us.

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