Tuning the Magnetic Orientation of Ferrite Segments for Cogging Torque Optimization in Small PM DC Motors.

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In the automotive applications, the cogging torque is often regarded as a source of vibrations that must be decreased because it can generate an unwanted acoustic noise.
Several cogging torque minimization methods have been investigated since a long time and UGIMAG uses most of them to answer its customers' requests [1]. These methods often focus on the geometry of the armature [2] [3] [4] [5]. Sometime, magnets assembling parameters are also analyzed [4] [6]. However, the magnetic orientation of the magnets is rarely investigated because of the difficulties to measure and to design it. It can yet lead to significantly different cogging torque performances at constant magnet geometries!

This paper introduces the origins of the cogging torque and the main generic methods to decrease it, It then focuses on the effect of the magnetic orientation of the magnets by describing, the measurement and the design methods developed by UGIMAG to solve a real example.

1- The cogging torque and its usual minimization methods.

Basically, the cogging torque is generated by the variations of the magnetic energy stored in the motor air-gap when the slotted armature turns. These variations occur each time a slot pass a magnet end. Considering a teaching simple bipolar structure with 2 slots (Figure 1) a torque pulse is generated when a slot moves under the first magnet end (a). A second one is generated when the slot moves away from the other magnet end (b).
In a real multi-polar motor with a multi-slotted armature (Figure 2), the cogging torque results from the combination of the torque pulses generated by all the slots moving under all the magnets ends (b). When adding progressively the effect of each slot, for instance with 6 slots (a), compensations clearly appear between nearly opposite pulses that cause a cogging torque peak-to-peak decrease.

The usual cogging torque minimization methods are based either on the minimization of the magnetic energy variations or on the torque pulses compensation effect:

- The magnetic energy variations are related to the derivative of the flux density distribution in the motor's air-gap (Figure 3). With sharp transitions at the magnets' ends, the pulses are high and narrow. On the contrary, smoothing the transitions makes the pulses smaller and wider. The height of the pulses directly impacts the cogging torque magnitude. Their width makes the pulses compensation effect more or less easy and more or less dependant on the magnet's dimensions variations. Finally, with wider pulses the solution is more robust in regard of the magnet geometrical tolerances. The minimization of the magnetic energy variations is generally achieved by mean of the magnet geometry (inner profile) and/or the armature geometry (teeth shape, skewing). But the magnet's magnetic orientation also impacts the magnetic energy variations;
- The compensation effect is achieved by adjusting the angular location of the torque pulses. Theoretically, a full compensation (zero cogging torque) is obtained when the pole angle matches exactly one or an integer number of armature tooth pitch. The perfect compensation is generally impossible because it would require very high precisions and zero tolerances for all the physical parameters, which describe the magnetic structure of the motor. Partial pulses compensation is also achieved with an angular shifting of the north poles comparatively to the south ones.

Finally the optimization for a low cogging torque, high flux and robust solution is complex because any flux density distribution change impacts the pole angle and, at least, the pulses compensation efficiency. Consequently, the different minimization methods must be involved in a long iterative solving process.

2 - Using magnetic orientation for cogging torque tuning.

2.1 Practical example.

Figure 4 shows the design of a 160W max output power, 1.8 Nm max torque, 60 mm diameter and 80mm long (without gear) 2 poles front wiper. The magnet inner profile with non-concentric outer and inner radii and tapered tips is already optimized to achieve a low cogging torque and a good robustness. The magnetic orientation is requested to be radial and the magnets fixed with soft magnetic steel springs (not represented).
In spite of this optimized configuration, the cogging torque is still too high. However, the customer doesn't want to change anything in the geometry of the magnet and of the motor in order to avoid any change in the assembly line. So the only free optimizing parameter is the magnetic orientation.

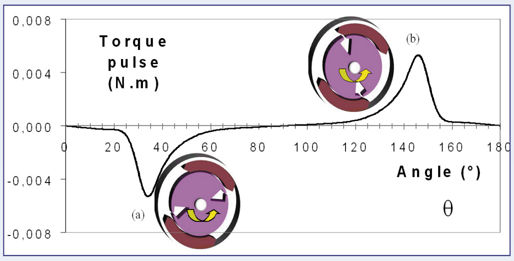

Figure 1: Torque pulses due to the magnetic energy variations.

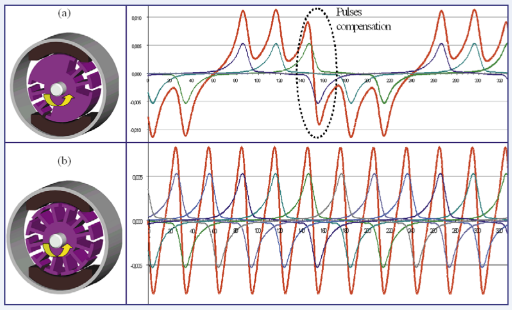

Figure 2: Torque pulses compensation (a) and combination (b) in a real motor.

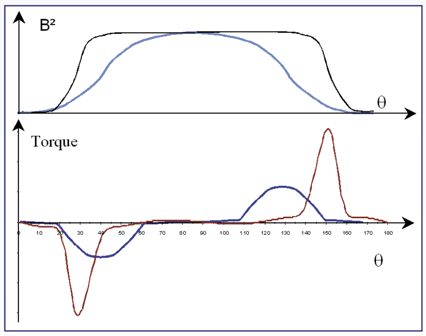

Figure 3: Torque pulse versus magnetic induction distribution.

(continued on page 13)

Tuning the Magnetic Orientation of Ferrite Segments for Cogging Torque Optimization... (continued)

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2.2 Measurement of the magnetic orientation.

We must be able to measure the magnetic orientation of our ferrite magnets prior to use it for cogging torque minimization purpose.
Basically, the "magnetic paper" can be used as a simple and fast visualization mean. This paper reacts with a white pattern where the flux lines are parallel to the paper surface. Figure 5 shows the different patterns provided by different orientation configurations. However, as the result is strongly dependent on the geometry, the method is only convenient to compare magnets that have exactly the same shape and a wrong conclusion remains always highly probable. Because the previous method is unable to provide quantitative data we developed another method based on the visualization of the ferrite grains. After a simple surface preparation, the magnet is over fired in order to exaggerate the grain growth. Then, using a simple optical microscope and thanks to the particular flat shape of the ferrite grains, the orientation of the magnetic axis (i.e. the C axis) can be estimated. Scanning the entire magnet's surface, we can finally plot the orientation angle ψ versus the angular location α (figure 6).

2.3 Finite elements model and calculation

FLUX 2D, the finite elements program from CEDRAT is particularly well dedicated to investigate the cogging torque performances of a motor. The intensive use of parameterized geometry allows a complete new geometry to be set up in less than 2 hours (including meshing) and the transient state parametric resolution module speed up the investigation of successive configurations.
Figure 7 shows a typical model with 26 000 nodes where the geometry and the location (including secondary gaps) of the magnet in the case are faithfully described. The attaching springs are also modeled because they generally impact the result.
The magnet's properties are described in an Usrmag routine that computes the X and Y components of the coercitive field. The model is linear but the orientation angle is computed at each point with a polynomial function issued from either the experimental data or a press tooling design parameter.
In spite of a non linear solving process (saturation in the case and the armature teeth) and of a step by step resolution repeated along a tooth pitch (with a 1° resolution), for a 12 slots motor the complete computation time is about 10 minutes using a Pentium IV, 2.4 GHz 512 Mo computer.

2.4. Results.

Three configurations are tested and figure 8 shows the corresponding measurements of the orientation angle ψ versus the location angle α. The radial configuration is the initial state. Solution 1 and solution 2 correspond to different press tooling structures that have been specially designed.
In table 1, it is interesting to observe that, when progressively disorienting the magnet, the cogging torque goes throw a minimum while the flux continuously decreases.

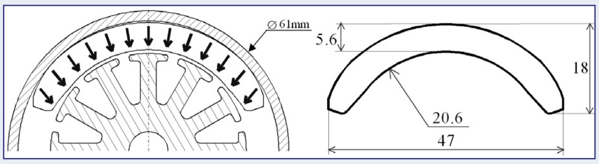

Figure 4 : Studied rear wiper configuration

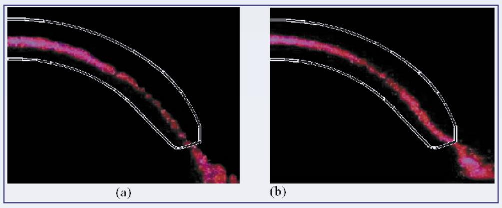

Figure 5: Visualisation of magnetic orientations with the «magnetic paper»

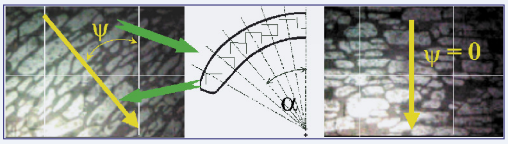

Figure 6: Visualisation of the magnetic orientation.

Solution		Radial	Solution. 1	Solution. 2
Cog. Torque (mN.m)	Calc.	21.7	13	15.6
	Meas.	21.6	10.2	17.4
Flux (mVs)	Meas.	0.650	0.638	0.622

Table1: Results.

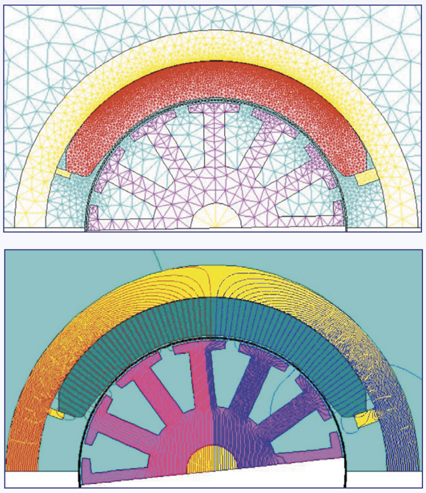

Figure 7: Finite elements model (meshing and flux plot).

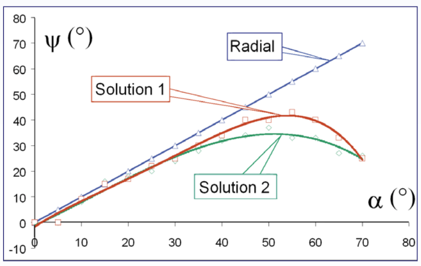

Figure 8: Orientation tested.

Consequently, the solution 1 corresponds to the optimal flux / cogging torque configuration that can be achieved with the given magnet's geometry. This solution was finally selected to achieve the customer's request.

3. Conclusion.

In addition to the usual geometric and structural factors, the magnetic orientation is another major parameter, which must be taken into account to design low cogging torque motors.
For more than 10 years, UGIMAG has developed specific methods and expertise to issue cogging torque optimized magnet and assembly products. FLUX 2D has been a key tool to decrease the number of prototypes and to issue specific magnetic orientations in the pressing tool design.

References

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