Abstract - For automotive application, the main challenge is to deliver the best performances for the best cost. To do so, MMT has developed a new family of magnetic position sensors based on the measurement of the magnetic field angle variation recorded from a permanent magnet magnetized with sinusoidal magnetization. In the article, we explain the basic principle of the detection and report its application to rotary and linear sensors. The technology potential is illustrated through examples of sensors developed for transmission and for electric power steering. We also emphasize that “sinus” magnets are well-adapted to the development of high speed brushless motors.

1. INTRODUCTION
Because of new mobility challenges, new regulations, the automotive industry is implementing various auxiliary systems (like EGR valves, turbochargers, auxiliary pumps, etc.) to improve the engine combustion, reduce its consumption and clean the exhaust line.

Stop & Start system, for example, is managing internal combustion engine (ICE) stop and automatic restart in order to save on the consumption when the vehicle is not moving (or when the speed is less than 3-7 km/h). Gains are typically reaching 3% to 15%, depending on the driving conditions. To have this system operational, the presence of an additional sensor on the gear-box is required to detect the neutral range of the gear selector. To improve the robustness of this detection, transmission suppliers are now asking for a differentiation of odd, neutral and even gear positions, using a linear position sensor (Fig.1) able to detect these 3 stages in one displacement direction (translation or rotation according to the gearbox architecture) while staying unchanged on a 2nd axis of displacement (respectively rotation or translation).

Electric power steering (EPS) is also a fast growing application, for which cost reduction is also becoming a major issue. MMT has developed a new Hall-type angular sensor, which is already seen as a real competitive alternative to conventional expensive resolver used to drive the assistance brushless DC motor.

2. SINUSOIDAL MAGNETIC POSITION SENSOR
Recently, a new magnetic sensor based on the determination of the magnetic field angle has been developed by MMT. We describe hereafter the basic principle used for this detection and the extension of this principle to make linear sensor and also high precision angular sensor.

1.1 The basic detection principle
1.1.1 Diametrical magnetization for rotary sensor
Magnetic field angle measurement is usually based on same intensity SINE and COSINE signals generated by a one pole-pair disk magnet rotating in front of dedicated Hall IC (Tri-axis reference from Melexis) or MR elements. This system is well-know and widely used for so-called end-of-shaft detections (like chassis or pedal sensor) [1].

However, a large number of applications require through-shaft sensor detection, like transmission or steering column. For this reason MMT has first developed and patented a through shaft magnetic position sensor with a probe put next to a magnet ring magnetized diametrically,
as seen on Fig. 2a [2]. For a magnet ring with a finite length, the induction field components can be expressed as:

\[ B_{\text{rad}} = B_{\text{rad-max}} \cos \varphi \quad \text{and} \quad B_{\text{tan}} = B_{\text{tan-max}} \sin \varphi \]  

(1)

with \( B_{\text{rad}} \) = radial induction component 
and \( B_{\text{tan}} \) = tangential induction component

In the general case, \( B_{\text{rad}} \) and \( B_{\text{tan}} \) do not have the same amplitude. So, to compute the magnetic field angle of rotation, we need to compensate (with a gain \( G \)) the \( B_{\text{tan}} \) signal to come back to same intensity sine and cosine signals. It is then possible to get the rotational angle value by computing the arctangent function:

\[ \varphi = \arctan \left( G \times \frac{B_{\text{tan}}}{B_{\text{rad}}} \right) \]  

(2)

We report on Fig. 2b the results obtained at room temperature for a single turn steering angle sensor. The non-linearity of the sensor output is less than +/-0.35% (+/-1.3°) as compared with a best fit-line. So we verify here that this MMT solution is able to deliver a very good performance enough for most of the automotive applications.

1.1.2 Sinusoidal magnetization for linear sensor

It was however not obvious to apply the same principle to develop a linear sensor. The “smart” idea was to unroll the ring magnet of the rotary sensor in order to get a flat magnet with a continuous rotating field following the magnet displacement axis (Fig. 3). Using once again the formula (2), the linear displacement of this sine-type magnetization magnet in front of a specific Hall IC delivers a field “angle” variation directly proportional to the displacement of this magnet [3].

From this concept, MMT has developed mass production magnetization fixtures able to “print” a customized sinusoidal magnetization profile on standard “rigid” magnets available on the market, including bonded rare-earth magnets, or even ferrites (mostly isotropic grades).

As reported Fig. 4, the sinusoidal magnetization magnet developed for the Stop & Start transmission system exhibits a very good accuracy with a +/-0.40% non-linearity on the 1D (dimension) sensor (here a +/-20° non-linearity).
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rotation; for other gear box a 20mm translation is preferred) integrated on a 2 dimensions displacement gear selector (translation + rotation). Further developments now also include 2D sensors for “all gear” detection.

2.1.1 Sinusoidal magnetization for high precision angular sensor
The accuracy required for an angular sensor used for brushless motor control or steering position sensor is typically below +/-1°, which means +/-0.27 % non linearity on a complete mechanical turn. This is 1.3 times less than the non-linearity record for our through shaft design presented in paragraph.

To enter this market, MMT has developed a high precision sensor using signal combination from two probes shifted by 90° (electric) and measuring each two components of the magnetic field, as follows [4]:

\[ B_{rad} = B_{rad1} + B_{tan2} \quad \text{and} \quad B_{tan} = B_{tan1} - B_{rad2} \] (3)

it is then possible to get a “clean” SINE and COSINE signals having the same amplitude that enable to deduce (after processing) the angular value with a non-linearity below +/- 0.2% of the full stroke. As you can see on Figs. 5a, 5b and 5c, the signal combination is acting like a filter since parasitic contributions on the magnetization are subtracted. Moreover, this solution is also drastically reducing the effects of homogeneous external magnetic fields, and simplifies the sensor integration on the brushless motor (not reported here).

For brushless motor control, engineers usually require a sensor with at least the same electric period as used for the motor. But for application shafts over 40mm, a “simple” multipolar radial magnetization exhibit field components with high harmonic contents that would badly impact on the sensor accuracy. Therefore MMT has proposed to apply the continuously variable magnetization also to n pole-pairs magnet configuration.

Then, taking advantage of both multipolar sinusoidal magnetization and signal combination, MMT can propose a simple and accurate (non-linearity < +/-0.5°) angular sensor with n period(s) per mechanical turn, able to compete with nX-type resolver based on variable reluctance [5].

3. SINUSOIDAL MAGNETIZATION APPLIED TO BLDC MOTORS
Recently, the automotive industry is showing a strong interest for high-speed motor (over 50 000 rpm) for applications like e-booster or e-turbo to improve the response time of the turbocharger or in order to recover some energy lost in the exhaust line.

The main challenge for these applications is to deal with high speed phenomena like Eddy current, hysteresis, vibration and friction that would inevitably impact on the motor performance at high speed. MMT has then used its expertise in electromagnetism to design a simple motor structure, efficient in a range of speed in between 20 000 and 200 000 rpm and suitable for mass production.

3.1 The MMT high-speed motor design
Because of higher efficiency and power density versus variable reluctance and asynchronous technologies, the brushless motor (BLDC) structure (slotted type) was preferred. As compared with our “conventional” BLDC motor designs, we proposed a structure:

- With a reduced number of poles on the magnet
- With a minimized residual torque
- Keeping our industrial values, i.e. using coils wound off-line mounted on straight stator poles

Finally, the MMT opted for a BLDC motor with 6 poles on the stator, 4 poles on the rotor and a sinusoidal flux in the air-gap obtained either via sinusoidal magnetization of a ring magnet or via shaped magnets (see Fig. 6b).
The motor can receive 3 or 6 coils, depending on the performance required, especially concerning the efficiency or the continuous output power [6].

The stator pole profile (shape and width of the stator poles) are dimensioned to minimize the saturation and to keep the detent torque as low as possible thanks to sinusoidal flux profile in the air-gap. As mentioned, using a magnet with a sinusoidal magnetization is a favorable solution allowing us to reduce the number of “parasitic” harmonics contained in the detent torque and consequently, minimize the iron losses which are usually increasing rapidly with the rotation speed.

3.2 Application example: the e-booster

MMT developed a motor prototype using a SINE-type magnet that was able to deliver 2 kW at 75 000 rpm with a water cooled stator in size Ø62 mm * 15 mm (Fig. 7). This is almost 1.5 times more compact than the equivalent slotless motor.

Nevertheless, the magnet volume required to achieve this performance remains more important than the volume that would be required with a radial magnetization. A stable sinusoidal magnetization was successfully “printed” on an isotropic magnet (here a bonded NdFeB with Br < 0.65T) using the MMT magnetization tools (see Fig. 6.b1). For higher grades, we are still obliged to use magnet segments diametrically magnetized to implement a sinusoidal flux variation in the motor air-gap (Fig. 6b2).

Further improvements would be to use anisotropic magnets compatible with sinusoidal magnetization. This will allow us to develop compact and highly responsive high-speed motor with better temperature resistance and reasonable cost.

Fig. 6 Comparison between 2 MMT motor structures and the corresponding magnet magnetization required.

Fig. 7 MMT high-speed motor performance (stator alone = Ø62mm * 15 mm) and corresponding performance on the compressor.

4. CONCLUSIONS AND PERSPECTIVES

In this paper, we have illustrated, through different examples, the great potential of sinusoidal magnetizations in the advent of innovative sensor and motor technologies for automotive applications.

REFERENCES

[1] MLX 90136 or MLX 90204 datasheet from Melexis.