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Development of a Contactless Hall effect torque sensor for Electric Power Steering

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ABSTRACT

In this paper, we will present an innovative torque sensor design which could be preferably used in Electric Power Assisted Steering (EPAS) application. This torque sensor is a non-contact Hall effect design. The specificity of this structure is its ability to measure the shift angle between two rotating shafts linked by a torsion bar. This measurement is done with stationary electronic components. This unique structure generates enough magnetic flux variation to measure angular shifts from +/-1° to +/-8° with low-cost standard Hall ASICs available from various suppliers. This torque sensor has convinced automotive industry due to its good performances, its compact dimension and a price compatible with the market expectation for this application.

This paper will explain the basic magnetic principle of this torque sensor, the improvements which have lead to a structure compatible with automotive industry requirements, some measurement results and possible sensor integration in the application.

INTRODUCTION

Nowadays, for cost and pollution reasons, the development of new vehicles is strongly driven by a research of fuel consumption reduction. One interesting way for such fuel economies is the replacement of current hydraulic power steering by EPAS using high power Brushless DC (BLDC) motors. The typical fuel economy realized by shifting from a hydraulic power steering to an EPAS is about 5 percent. With the improvement of the BLDC motor structures and the increase of the electric power available with batteries, the market shares of EPAS should grow quickly in the next few years [1].

In order to drive efficiently the BLDC motor, the ECU requires accurate information on the torque applied by the driver to the steering wheel. This torque signal usually comes from the shift measurement between two shafts linked by a linear torsion bar. The main concern in this measurement is due to the fact that these shafts are also rotating with the steering wheel and the integration of electronic on rotating parts is definitely a blocking point. An example of BLDC motor and torque sensor typical integration on the steering column is shown on the following drawing. The BLDC exerts its torque to the steering column through a worm gear mechanism.

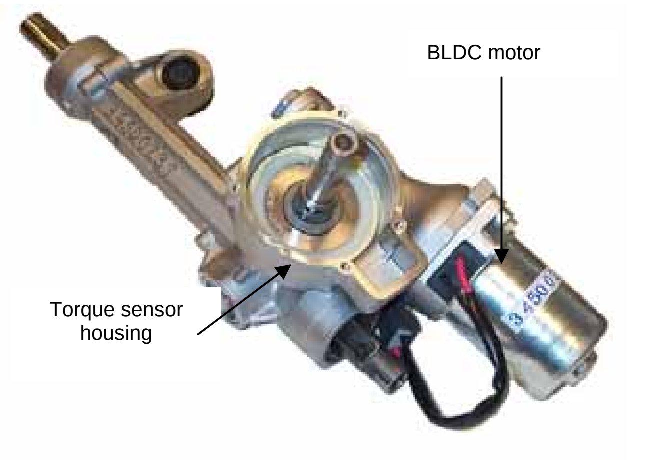

Figure 1: Electric Power Steering

Moving Magnet Technologies (MMT) has developed an innovative low cost structure answering all the requirements of torque sensing for EPAS. This torque sensor is based on a non-contact Hall effect principle and uses standard programmable Hall ASICs available on the market. MMT has applied for two patents regarding first a basic structure of this torque sensor and then an optimized design [2] [3]. These torque sensor designs are presented hereafter.

BASIC DESIGN AND SENSOR PRINCIPLE

The MMT torque sensor basic structure is shown hereafter.

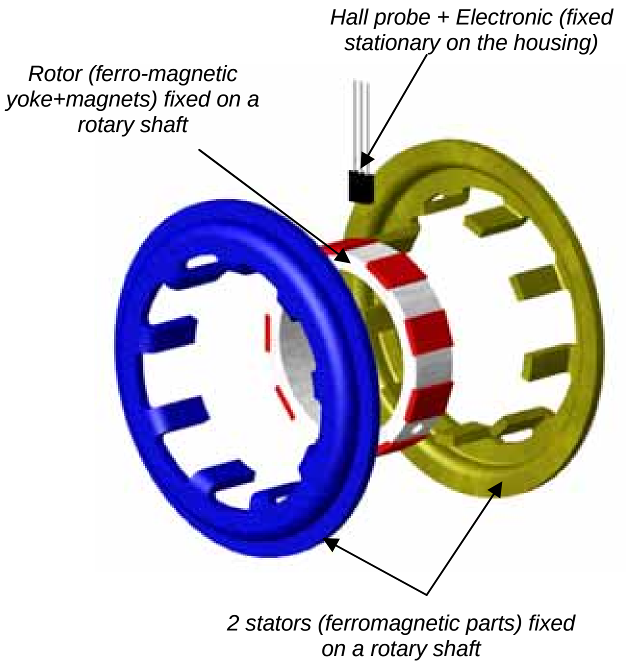

Figure 2: Exploded view of the MMT torque sensor

This sensor is made up of the following sub-assemblies:

- The rotor (grey and red parts), fixed on one rotary shaft of the steering column, is made by a plurality of permanent magnets fixed on a soft ferro-magnetic yoke.
- The stators (blue and yellow parts) are fixed on the second rotary shaft of the steering column, linked to the first one by a torsion bar. These stators are fixed one toward the other. They are made of soft ferro-magnetic material.
- One or two (for redundancy) Hall ASICs fixed stationary on the housing. The Hall probe is inserted in a measurement slot created between the two stators. With the MMT design, we generate enough flux variation to use the Hall ASICs available from Melexis (MLX 90251 or redundant MLX 90277) or Micronas (HAL 8XX).

The following figure shows the sensor in a working configuration.

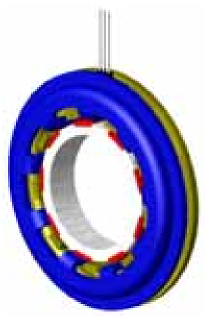

Figure 3: MMT torque sensor basic structure

On these two first views of the torque sensor, the rotor is realized with magnets of the same polarity (red parts) alternated with ferro-magnetic areas from the yoke. This magnet configuration could be replaced by a more industrial ring magnet with alternated north and south poles on its surface as shown below.

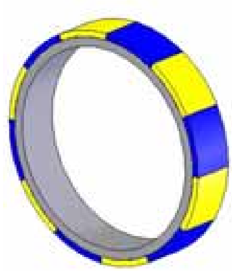

Figure 4: Rotor made with multipolar ring magnet

One couple of north and south poles of the magnet is associated to one tooth on each stator to create an elementary sensor as shown below.

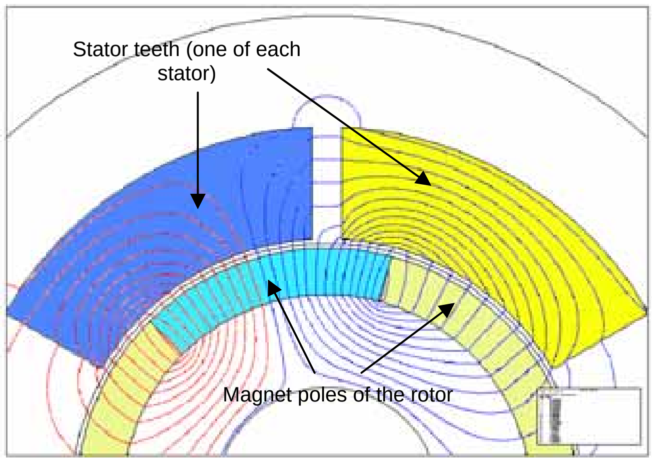

Figure 5: View of an elementary sensor in a beginning of the stroke position with flux lines

A magnetic flux variation is generated in the stator teeth when the magnet transitions are moving in front of them. This flux variation is a linear function of the magnet angular position and we have demonstrated the following analytical equation:

$$B_m = -\frac{4 B_r D_a L \Theta}{\alpha_1 . F . Da + 4 . \sigma . E . H}$$

Where:

- B_m is the flux measured in the slot between two stator teeth
- B_r is the magnet remanence
- D_a is the average diameter of the air gap
- L is the magnet thickness
- Θ is the angular position of the magnet transition
- α_1 is the angular length of one stator teeth
- F is the thickness of the slot between the two stator teeth
- σ is the flux leakage coefficient
- E is the radial air gap length
- H is the teeth radial length

As shown on the previous figures, in this sensor, we multiply the number of elementary sensors in order to increase the flux variation in the measurement slot. The flux variations generated in each elementary sensor are integrated in an external disc on each stator. These two discs create a radial measurement slot in between the stators. By design, the induction on a given radius in the measurement slot is constant as shown on the 3D simulation results hereafter:

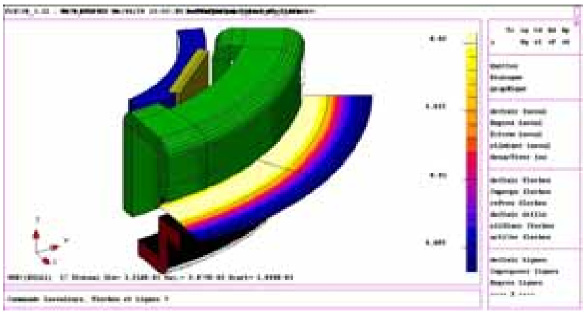

Figure 6: 3D simulation result showing the induction in the measurement slot

MMT has demonstrated that an analytical equation of the flux variation in the measurement slot is:

$$B_m = -\frac{4NZB_r D_a L\Theta}{ND_a ZF\alpha_1 + 4\sigma E S_m}$$

Where:

- N is the number of elementary sensors
- Z is the axial dimension of the permanent magnet
- S_m is the measurement surface.

MMT has also developed some rules in order to size the angular length of the stator teeth according to the stroke to measure and the diameter of the steering column on which we will mount the sensor.

This first structure has convinced some automotive partners of MMT with its performances and we have started a new development phase in order to improve the sensor performances and use some lower-cost parts.

DESIGN IMPROVEMENT TO AN OPTIMIZED AUTOMOTIVE SENSOR DESIGN

In order to increase the flux in the measurement slot, a good solution is to collect the flux from the stator with stationary ferro-magnetic parts, and then concentrate this flux on the Hall ASIC with a reduced surface measurement slot. These parts are shown in the figure below.

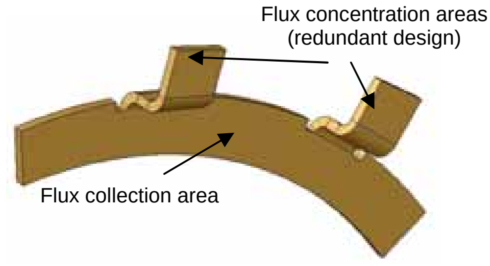

Figure 7: Flux collector/concentrator

The use of these flux collectors/concentrators allows a simplification of the stator design to L-shape stator. The axial collection of the magnetic flux on the stator could be done on the outside or the inside of the disc flux integrating area of the stator. Even if an outer collection of the flux leads to a little increase of the axial length of the sensor, MMT strongly advises this solution. Indeed, this outer collection of the flux decreases the flux leakage between the flux collector (18% increase on the flux variation) and the sensitivity to magnet transition rotating in front of the Hall ASIC is also decreased. These stator modifications lead to the design in the following figure.

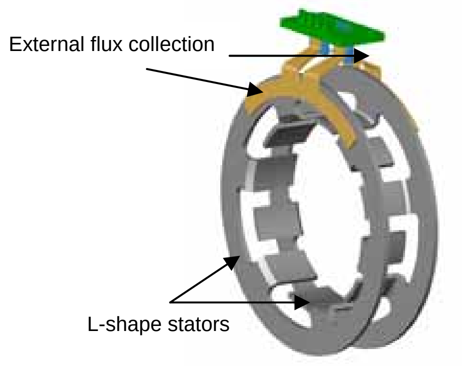

Figure 8: MMT design with simplified stators and external flux collector

The second modification on the stator shape has been done on the shape of the teeth. Indeed, in our first design, the stator teeth were overlapping the magnet on their axial direction. In order to optimize the axial dimension of the sensor, the collection area of one stator (disc area) was axially close to the end of the teeth of the other stator. In this proximity area between both stators, flux leakage was occurring. Some 3D simulations and prototype measurements have shown that shortening the teeth of the stator involves an increase of the flux variation in the measurement slot without any deterioration of other sensor performances.
3D simulation has also shown that the closer we are from the stator flux integration disc area, the higher is the induction and so the leakage from one tooth to the next one on the other stator. In order to increase the cross section of the teeth when the flux density increases (decrease of the induction in the teeth), we have designed some trapezoidal shape teeth. We have also validated this shape modification of the teeth with 3D magnetic simulations and prototype measurements.

The combination of these two modifications of the teeth shape leads to a 12% output signal increase in the measurement slot. Figure below shows the evolution of the stator shape.

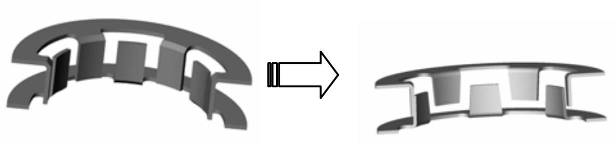

Figure 9: Teeth shape modification

These stator shape modifications lead to a part which could be stamped and formed easily and which allows a large saving in weight as compared with previous design (typically about 50%).

Today, MMT optimized torque sensor design for steering column application is shown on the figure below:

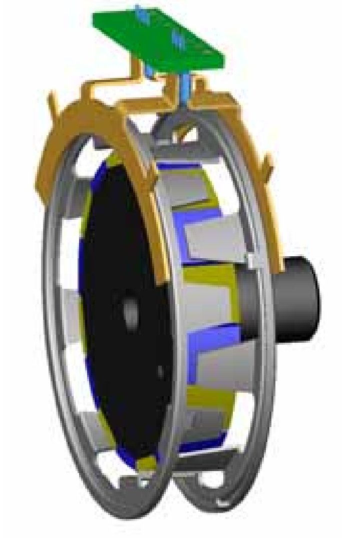

Figure 10: Optimized MMT torque sensor magnetic structure

PROTOTYPES MEASUREMENT RESULTS

Based on this optimized torque sensor, MMT has developed a family of designs with the same overall dimensions (magnet: OD=37.5 mm, ID=34.75mm, L=8mm) for strokes of +/-8°, +/-4°, +/-1°. In order to adapt the prototypes to the stroke, we have played on the stator teeth shape and number.

In this paper we will focus on the measurement results for the +/-8° stroke prototype. A table in appendix A gives a summary of these typical measurement results for the complete sensor family.

MEASUREMENT RESULTS ON +/-8°

The figures hereafter will show the output signal of this prototype, the non-linearity and hysteresis measurements, the output signal stability on one turn on mid-stroke position (no torque) and on end-stroke position (maximum torque).

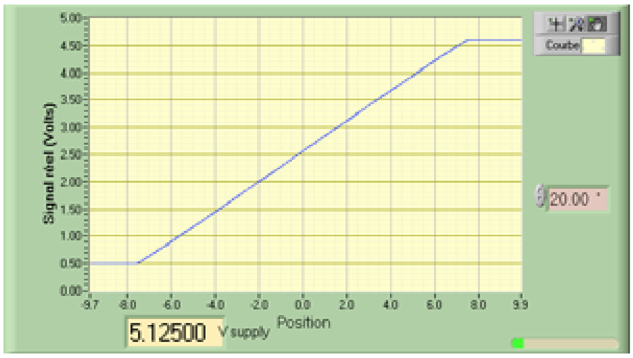

Figure 11: Output signal programmed on one probe (0.5 to 4.5 V)

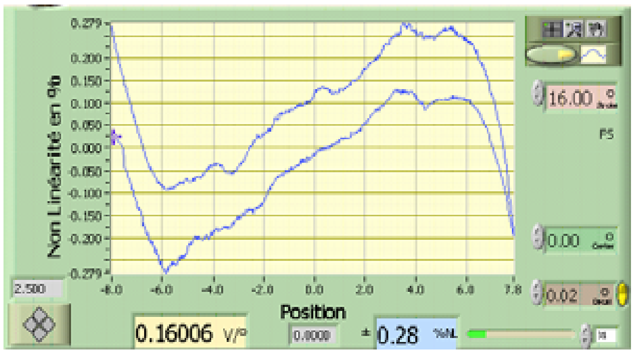

Figure 12: Non-linearity and hysteresis measurement over the stroke

With the available ASICs, we are also able to program the gain to optimize the non-linearity at the no torque position as shown hereafter.

Figure 13: Non-linearity optimized on the middle of the stroke

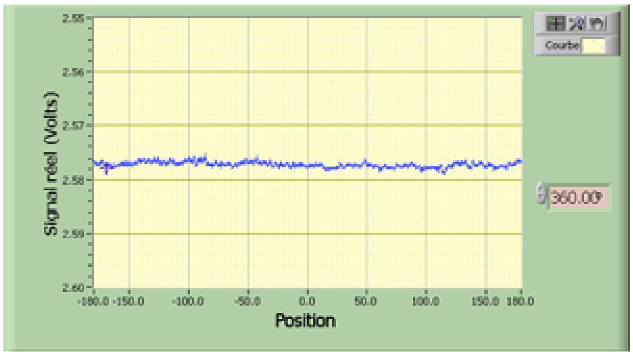

Figure 14: Stability on one turn at no torque position

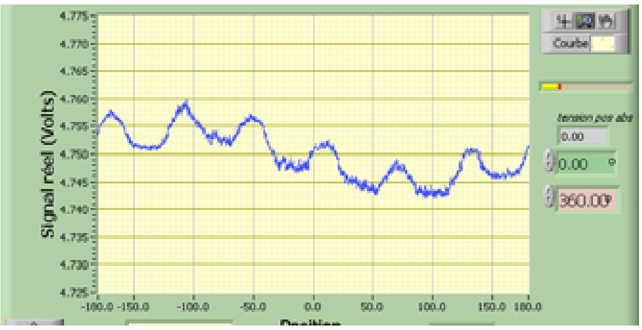

Figure 15: Stability on one turn at maximum torque position

INFLUENCE OF MECHANICAL AND THERMAL PARAMETERS

The results presented hereafter are similar for the whole torque sensor family. The view hereafter shows the direction for the off-centering on the sensor.

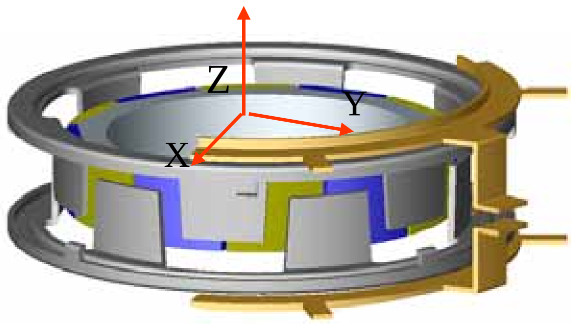

Figure 16: Directions for off-centering

With the standard Hall ASICs used in MMT, we are able to compensate the non-linearity of the output signal over an automotive temperature range (-40°C to 150°C) as shown on the figure below.

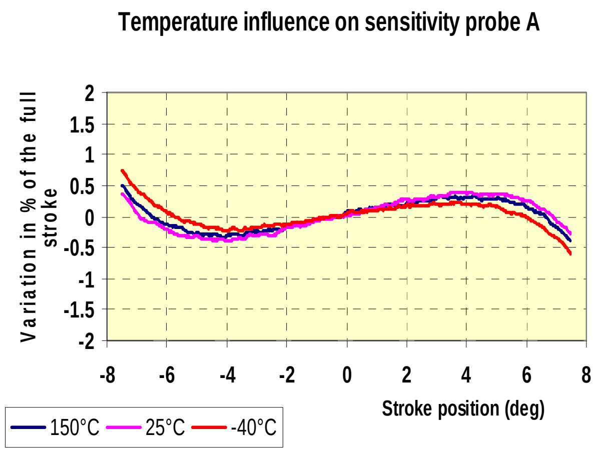

Figure 17: Thermal compensation of the output signal with standard Hall ASIC

We have also made a study on the variation of the hysteresis as a function of the stroke measured.

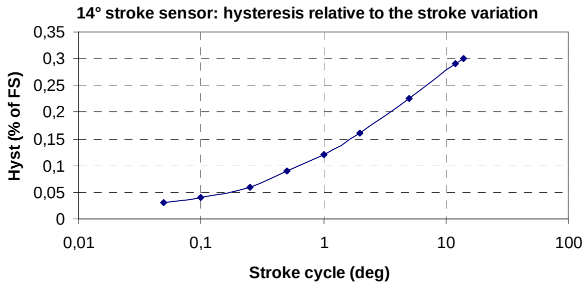

Figure 18: Peak to peak value of the hysteresis as a function of the stroke measured

We have also measured the influence of rotor displacement during the life of the sensor (in use) for a given programming of the Hall ASIC.

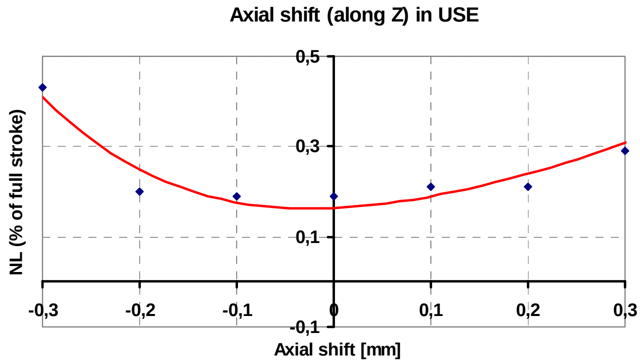

Figure 19: Rotor axial shift influence

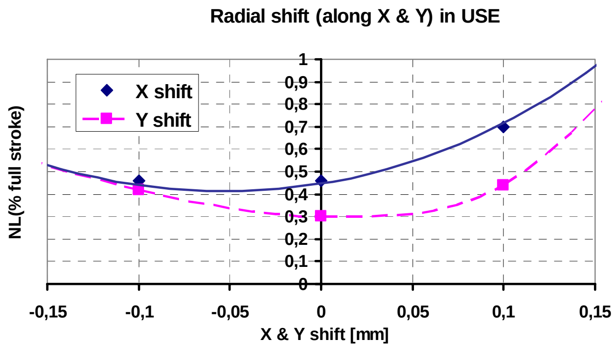

Figure 20: Rotor radial shift influence

On the measured prototype, the radial air gap between magnet and stator teeth is 0.5 mm. It is possible to increase this mechanical gap in order to decrease the influence of the radial shift if required.

The performances of these prototypes are suitable with the requirements of automotive industry for EPAS.

SENSOR INTEGRATION ON THE APPLICATION

A first solution for the integration of the sensor is an integration of the sensor parts directly on the steering column. This first integration will be preferred by automotive suppliers who deliver the complete steering column assembly.

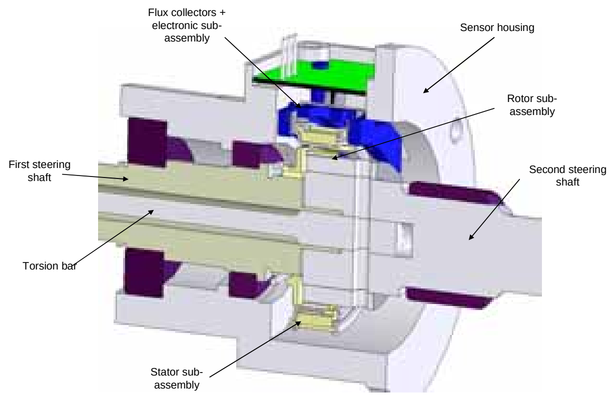

Figure 21: MMT torque sensor mounted directly on the steering column

Figure 22: Picture of a prototype torque sensor integration

The other possible integration of this sensor is the realization of a stand-alone sensor in a cassette design. This second integration will be preferred by automotive suppliers who supply the sensor to steering column manufacturer.

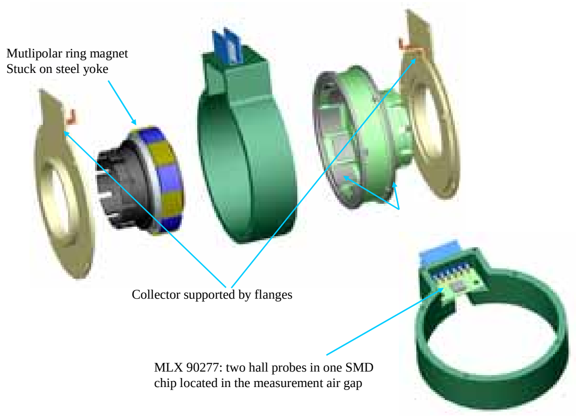

Figure 23: Exploded view of an MMT torque sensor in a cassette design

Figure 24: Picture of a cassette torque sensor

CONCLUSION

For the torque sensor technology presented in this paper, we have identified the following advantages and benefits:

- Hall effect patented non-contact design.
- Angular shift measurement between two rotary parts with a stationary electronic.
- Measurement of small angular displacement (down to +/-1°) with field density variation compatible with current ASICs
- Low parts number ⇒ Easy to industrialize
- Parts with design easy to manufacture ⇒ Low cost design.
- Possible redundant design
- Possibility to integrate the sensor parts directly in the column housing or to deliver it separatly as a stand-alone unit (cassette design).
- Parts adjustable to the stroke to measure.

These advantages have lead to successful collaboration with automotive suppliers involved in EPAS development.

MMT is still improving its design, for example with coupling this torque information with position information.

ACKNOWLEDGMENTS

Hereafter is a non exhaustive list of people who have been involved in this development: Claude OUDET, Pierre GANDEL, Daniel PRUDHAM, Jean Daniel ALZINGRE, Antoine FOUCAUT, Thierry DORGE, Yannick RONNAT…

REFERENCES

[1] Passenger Car Steering Systems – Preparation for the Technology of Tomorrow (26-27/04/2005 in Essen) Introduction presentation by Dr.-Ing. Alois SEEWALD

[2] “Position sensor, design in particular for detecting a steering column torsion”, US patent publication number #2004-0011138, Claude OUDET,

Daniel PRUDHAM, Pierre GANDEL, Didier FRACHON, Didier ANGLEVIEL

[3] “Capteur de position, notamment destine à la mesure de torsion d’une colonne de direction”, PCT application number #PCT/FR2005/050571, Daniel PRUDHAM, Gérald MASSON, Antoine FOUCAUT.

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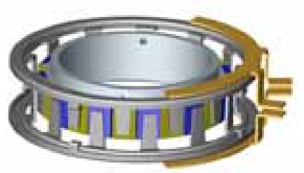
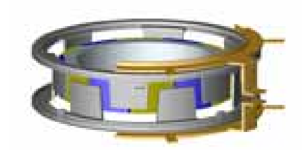
APPENDIX A

	STROKE +/-1°	**STROKE +/-4°**	**STROKE +/-8°**
PICTURE OF THE PROTOTYPE	 12 pole pairs	 8 pole pairs	 4 pole pairs
SENSITIVITY	300 Gauss/°	90 Gauss/°	72 Gauss/°
INDUCTION OVER THE STROKE	+/- 300 Gauss	+/- 360 Gauss	+/- 575 Gauss
NON-LINEARITY	+/-0.2% of Full Scale	+/-0.28% of Full Scale	+/- 0.25% of Full scale
HYSTERESIS FOR A FULL STROKE MEASUREMENT	+/- 0.3% of Full Scale	+/- 0.2% of Full scale	+/-0.05 % of Full Scale
STABILITY ON 360° @ NO TORQUE POSITION	+/- 0.03% of Full Scale	+/- 0.025% of Full scale	+/-0.05 % of Full Scale
STABILITY ON 360° @ MAXIMUM TORQUE POSITION	+/- 0.3% of Full Scale	+/- 0.38% of Full scale	+/-0.16 % of Full Scale