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Improving motor noise and vibration by sensor-bearing optimization

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Abstract

Electric and hybrid vehicles are a growing alternative to standard powered passenger cars with an internal combustion engine. The need for efficient electric machines is significantly increasing; development efforts are being made along the complete industry value chain to decrease the emission of CO2 of a vehicle. For electric vehicles, an encountered problem concerns the disturbances in output torque that provoke undesired sound effects and unwanted vibrations in the drive train. This noise, vibration and harshness (NVH) finds its origin in the entire electric drive system.
The aim of this research is to investigate the possible improvements in audible noise and vibrations in electric motor systems. Since the core business of SKF is bearings, motor bearings are under continuous improvement to fit to the trend of electrification; optimization of cage, raceways and balls as well as grease and materials are regarded for this specific goal. Also, the angular sensor is an important component for the electric motor control and it is in this field that SKF proposes added value solutions in the form of sensor-bearings. The output signals of these sensors integrated in motor bearings can be tuned to the motor parameters in order to reduce the ripple on the output torque, limiting the NVH effects of the entire system.

electric drive, modeling, optimization, permanent magnet motor, simulation

1 Introduction

Electric and hybrid vehicles are a growing alternative to standard internal combustion engine powered passenger cars. The most important driver for this development is the necessary decrease of CO2 emissions of vehicle fleets to meet legislation standards. With the arrival of electric vehicles on the streets, several practical problems have to be solved in order for such vehicles to be a success. One of the issues that have come forward is the radical change of sound of a car. Although inside the passenger compartment the noise level is lowered in the case of an electric vehicle, the electric powertrain does generate different audible noise frequencies which can be in some cases unpleasant for people to hear.
Depending on the speed of the vehicle tire noise and motor orders, transmission noise and higher order electromagnetic frequencies from the electric motor define the audio spectrum for an electric vehicle[1]. This new audible spectrum of a vehicle can be analyzed and optimized through its components by regarding an important source of the audible noise: the electric motor system (see Fig.1). In Fig.1 the

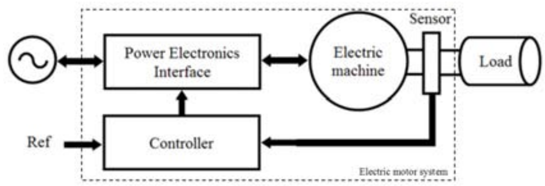

Figure 1: Electric motor system

four main components of the electric motor system are displayed: the power electronics interface, the controller, the electric machine and

the sensor. Imperfections and disturbances might occur in these components which eventually cause noise and vibrations. There are design strategies to limit noise on the torque output of the system but also each component in the chain can be optimized to limit the effect on the noise radiation of the electric motor system. In this paper the focus is on the noise related to permanent-magnet synchronous machines.
For permanent magnet machines, the audible noise basically comes from three sources [2],[3]:

- Electromagnetic field;
- Mechanical phenomena;
- Aerodynamic phenomena.

Mechanical phenomena are for instance bearing rolling friction resulting to noise and vibrations and aerodynamic phenomena are for instance the noise of the fan blades of an air-cooling system. The audible noise related to electromagnetics contains the frequencies most sensitive to the human ear due to the periodicity of the fields and electromagnetic forces. The contribution of the electromagnetics is thus visible when the variation of nominal output torque of the electric machine is regarded. Also depending on the speed of the vehicle the audible noise is different, due to frequencies in the audible torque output spectrum that are dependant of the motor speed.

Several motor system parameters have an influence on these three main noise sources, but an important one is the rotor position sensor angular error. The rotor position angle is used inside the control strategy to define the currents that should be fed to the stator windings (see Fig.2). In typical control for permanent magnet synchronous machines (sinusoidal or vector control) the Park and Clark transformations are used where angle information is necessary. In

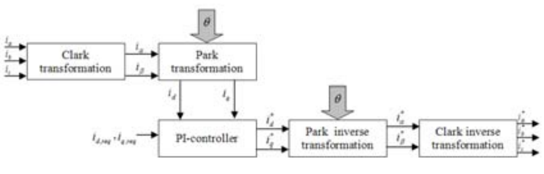

Figure 2: Basic control strategy for PMSM

this paper, the effect of certain electric motor parameters on the sensor output is regarded. The application might have an influence on the performance of the sensor, and in order to be able to quantify this influence and improve the sensor in areas where the impact will be the biggest, this passive analysis has to be done.
Furthermore a strategy will be proposed to actively analyze the influence of the sensor on the motor, and to tune the sensor parameters such, that better motor performance will be obtained.

2 Method

This part is built up as follows. First of all, the sensor is described and some examples are given regarding the harmonics present in the output for different input parameters of the sensor using a simulation tool. Then the system is described on which the measurements have been performed. Last, the method is described for the investigation of the passive influence of the motor on the sensor performance.

2.1 Sensor

The sensor that gives the rotor position is the SKF Rotor Positioning Sensor-Bearing Unit. It is a magnetic sensor that can be integrated in bearings of different sizes. It consist of a magnetic target wheel attached to the rotating inner ring of the bearing which can have either one north and south pole for absolute sensing, or multiple north and south poles (multipolar) for permanent motor rotor magnet matching. The analogue output

Figure 3: RPSBU

signals, a sine signal and a cosine signal phase shifted 90 with the sine signal give information about the angular position of the rotor. This position can either be expressed in electrical degrees or mechanical degrees depending on the number of pole pairs on the magnetic ring. It is calculated using the arctangent function after normalizing the output signals.
The output that is interesting for this investigation is the error in the rotor position information. This is indirect information that can be calculated from the measured output of the sensor in several ways. One common way of expressing the angle error is the peak-to-peak accuracy which is the difference between the largest and smallest error over one mechanical revolution. Another way of expressing the angle error is the angle accuracy quadratic mean value, calculated as:

$$\Delta\Theta_{RMS} = \sqrt{\frac{1}{T_2 - T_1}\int_{T_1}^{T_2} \Delta\Theta(t)^2 dt} \qquad (1)$$

with its corresponding mean value. A last common way of expressing the angle error is to look at the harmonic spectrum of the error, by calculating its FFT. It is logical that the first two methods of expressing the angle error are not of much help when audible noise and frequency spectra are important, so here the last method of angle error representation is used.

The angle error is calculated over one mechanical revolution, such that the fast Fourier transform (FFT) is related to the mechanical angle. Harmonic 1 then means that over one mechanical turn, there is a sinusoidal term with frequency 1 over one turn.

2.2 Simulation tool sensor

Depending on sensor parameters, there are many different harmonic output spectra possible. This can be investigated with a Design for Six Sigma simulation tool of the sensor that has been developed. With this tool, the inputs can be varied such that the output (here, the angle error harmonics) variation is known.

An example is given in Fig.4 where for different numbers of active elements in the sensor, the harmonic spectrum of the output error is given. It is taking the largest simulated value of the concerned angle error harmonic over 300 simulations of the same bipolar sensor. It is seen

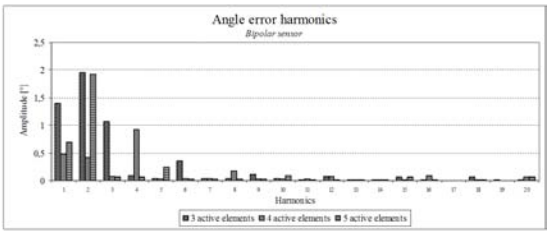

Figure 4: Output spectrum sensor error for different numbers of active elements

in Fig.4 that the harmonics in the error are highly dependant on the number of active elements. Different harmonics are preponderant and also their magnitudes vary. Another investigation is done for the number of pole pairs keeping the same number of active elements in each sensor (see Fig.5). The simulations whose results are

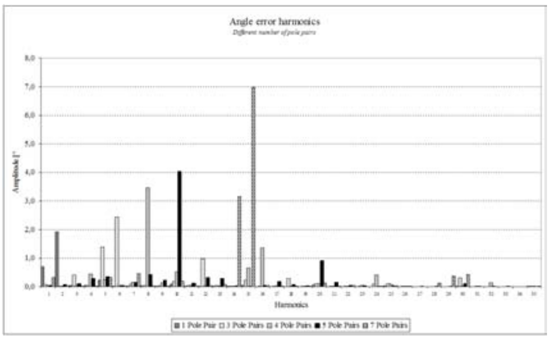

Figure 5: Output spectrum sensor error for different numbers of pole pairs

shown in Fig.4 and 5 are all performed using measurements of real magnetic rings to obtain the best image possible of reality. But the sensor has not been simulated in its application, which can increase certain harmonic levels.

2.3 Motor set-up

To investigate how the different configurations of the electric motor influence the sensor output, measurements have been conducted on a motor test bench. This bench contains a PMSM prototype having six permanent magnets glued to its rotor. It is thus a three-pole pair motor. Some other characteristics of this motor can be found in Table1. In Fig.6 a photo of the test-up

Table 1: PSMSM characteristics

Nominal power:	10 kW
Maximum power:	15 kW
Nominal speed:	2600 rpm
Maximum speed:	3500 rpm
Stall torque:	210 Nm
Nominal torque:	45 Nm
Number of pole pairs:	3
Number of stator phases:	3
Torque constant:	0.45 Nm/A
Electrical constant:	0.38 V/(rad/s)
Weight:	23.8 kg
Outer diameter housing:	236 mm

is shown; on the left the electric motor is not shown for confidentiality reasons. The motor is controlled with the information from an internal rotor position sensor using digital signals. On the location where normally the fixed motor bearing is mounted, the sensor-bearing is press-fitted on the inner ring and press-fitted also on the outer ring to prevent rotation of the sensor body during operation. The sensor-bearing consists of

Figure 6: Motor test set-up

a magnetic ring attached to the inner ring of the bearing and a sensor part attached to the outer ring. There are several active elements present in the sensor body that are recombined externally of the sensor-bearing to a sine and cosine signal, which are recorded during the tests. The torque output measured by a torque sensor (using a torsion bar placed between the two motors on the shaft) and the index signal of the internal rotor position sensor are recorded as well. The index signal will give a pulse every time a full revolution of the shaft is performed.

To calculate the angle and control the motor vector control is used. There are two loops: one speed loop and one current loop inside this control loop to control the output torque. To process the calculated currents a power stage using MOSFET technology is used. It has a supply voltage of 160V and is liquid cooled. For the load an induction motor is placed at the other end of the shaft where the torque sensor is placed on (see Fig.6). This induction motor is torque and speed controlled with resistance dissipation and it is using a standard industrial controller. Its rated power is 15 kW and its air-forced cooled to avoid excessive heating. It has three phases and has a supply voltage of 380V.

2.4 Method

First simulations are done using the simulation tool described earlier. Then the measured sine signals are compared to the simulated ones, and their performance is investigated. The same is done for the angle error calculated from the signals. Then a conclusion can be drawn on the influence of the motor on the sensor. Measurements will be done varying three different motor parameters. Since the motor is not controlled using the sensor information, the influence can be seen independently from the control. The three different measurement cycles that have been done, are:

- Varying speed for constant load torque and supply voltage
- Varying load torque for constant speed and supply voltage
- Varying supply voltage for constant speed and load torque

Each time the induced current is measured as well, since high currents will probably be the most disturbing for the sensor since it will measure the magnetic field induced by these currents as an addition to its own rotating magnetic field. Also the magnetic field at the sensor-bearing location will be measured and compared to the sine/cosine output to investigate the robustness of the sensor-bearing.

3 Results

The simulation tool for sensor-bearings described earlier is used to first of all simulate a population of 300 bipolar sensor-bearings having the same configuration as the sensor-bearing mounted in the test bench. In Fig.7 the harmonics present in the sine are shown; the minimum and maximum individual values of all harmonics. For the cosine the results are similar. Also, the harmonic profile of the best and worst sensor are shown; e.g., the sensor that has respectively the best or the worst peak-to-peak angle error. Using Fig.7 the preponderant harmonics of the

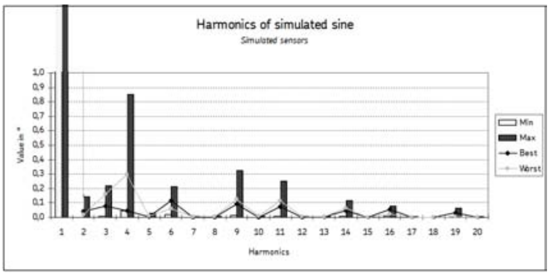

Figure 7: Sine harmonics of simulated sensors

error can be identified: harmonic 2, 1 and 5. The harmonics are plotted as function of the preponderant harmonic 1; this is the case for a bipolar sensor. In Fig.8 the minimum and maximum individual values of all angle error harmonics are shown. Also, the harmonic profile of the best and worst sensor are shown. Using

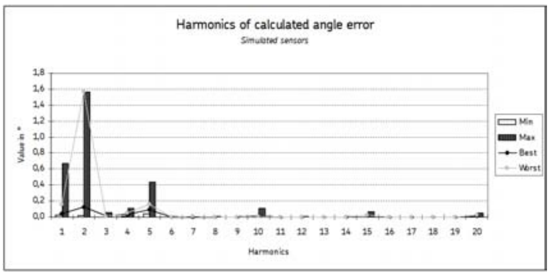

Figure 8: Angle error harmonics of simulated sensors

Fig.8 the preponderant harmonics of the error can be identified: harmonic 2, 1 and 5. Now the different measurements are done and the results are discussed.

For the variation of the speed, the relative harmonics of the sine are shown in Fig.9 below. The cosines spectrum is similar thus it is not shown. These harmonics are calculated over one turn of the sensor and are averaged over multiple turns. The load torque in this case is 10% of the

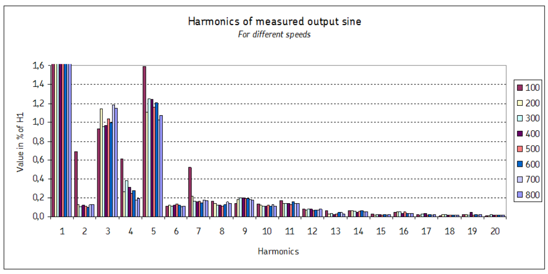

Figure 9: Relative harmonics of sine over speed

maximum torque and the supply voltage is at its nominal value of 140V. The legend is showing the different speeds in RPM.

In Fig.9 it is seen that harmonic 3 and 5 are present in the spectrum and at low speed some more harmonics are seen, notably harmonic 2 and 4 and also the harmonic 7. But the harmonics do not change significantly over speed, except maybe the harmonic 2 and 4 where a very slight decrease can be noticed which might be related to the auto-centering effect of the shaft that occurs from a certain speed. Comparing Fig.9 to Fig.7 the differences

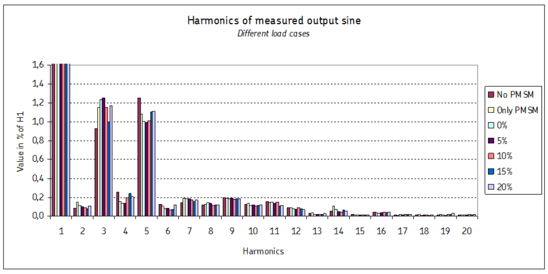

Figure 10: Relative harmonics of sine over load torque

between simulation and real measurements can be analyzed with disturbances present of the electric motor. The most significant changes are the harmonic 3 which is five times higher than in simulation and the harmonic 5 which is 20 times higher.

Then the varying load torque. The different load cases that are considered are rotating the system by rotating the induction motor without the PMSM working. This way of rotating the PMSM shaft will induce currents in the wires of the stator and has to be limited in order to not damage the motor. Then the induction motor is not turning and only the PMSM is turning without any load. Subsequently both motors are being used; where the load torque goes from 0 to 20% of the nominal torque by steps of 5%. The results of the sine can be seen in Fig.10. The cosines results are similar. The speed is 500 rpm and the supply voltage is still at its nominal value of 140V. In Fig.10 is seen that the harmonic 3 and 5 are still the two harmonics the most disturbing, but they do not seem to change significantly for the different load cases.

Then for the last varying parameter: the supply voltage. The idea is to create the highest currents here since if the voltage is lowered, the amplitude of the current will have to increase to respond to the demand. The currents are measured and shown in Fig.11 below. The speed is kept constant at 500 rpm and the load torque is at 10% of its nominal torque. The results of the varying supply voltage on the sine output are shown in Fig.12. Again there is not a lot of variation except for the harmonic 2 in the sine and cosine. This is due to the analogue compensation algorithm present in the reconstruction of the sine and cosine. When the results for the speed are shown for the output of one active element only, it is clear that the reconstruction helps to decrease the unwanted

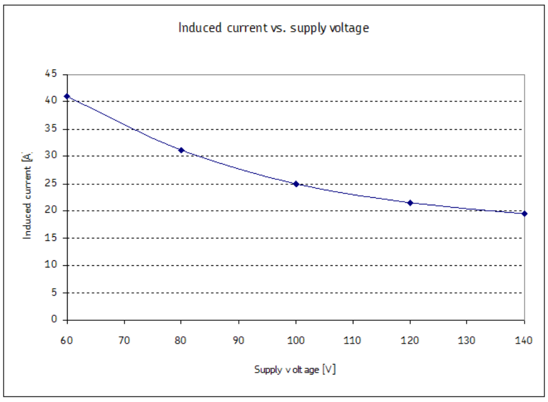

Figure 11: Supply current versus induced current

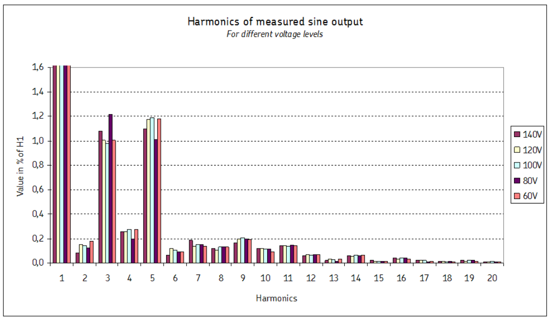

Figure 12: Relative harmonics of sine over supply voltage

harmonic content of the sine and cosine caused by its magnetic environment. The level of harmonic 3 in the active element output is 3% or 2% for speeds which are multiples of 3 (see Fig.13) and in the sine, only 1% of harmonic 3 is found which stays stable over the variation of the three parameters load torque, speed and voltage (current level). Now, to get a better

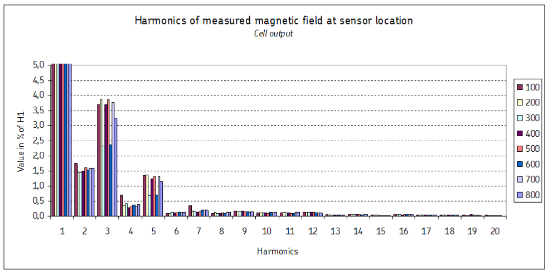

Figure 13: Relative harmonics of magnetic field measured at sensor location for different supply voltage levels

idea of what these measured sine and cosine mean the results for the calculated angle error are presented. This angle error is calculated using the sine and cosine measured of which the offset is deleted. Subsequently the signals are normalized and the angle is computed using the atan2 function. The angle error shows different behavior in some cases as can be seen in Fig.14:

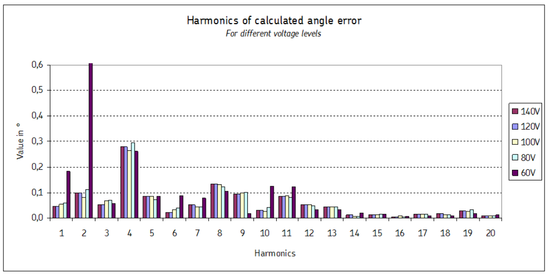

Figure 14: Harmonics of angle error for different voltage levels

the harmonic 2 increases for 60V supply voltage and also for 20% of load torque (not shown), all cases where quite high current is induced (about 45 A). This can be due to the fact that for both linearly increasing load torque and linearly decreasing supply voltage the induced current is increasing exponentially and thus more quickly reaching its maximum value.

Comparing Fig.14 to Fig.8 gives the comparison between simulated angle errors and measured angle errors; here for voltage variation only. Where in the simulation results the preponderant harmonics in the error are harmonic 2, 1 and 5, in measurement harmonic 4 is the largest. This is due to the higher harmonic 3 and 5 in the sine and cosine that are measured. These harmonics must be coming from the motor. It seems that on the motor a sensor with low harmonic 2 and 5 is mounted.

Something else to consider is the fact that at the considered speed for the voltage drop test, there is a low resonance frequency due to the torsion bar that is not realistic for the motor itself. To really prove the sensor performance stays constant over speed, load torque and supply voltage the test should be done at a different speed than the resonance speed which is around 500 rpm as can be seen in Fig.15 since there the variation in peak-to-peak amplitude of the torque output is high from one revolution to the next one.

4 Conclusions

The influence of the motor parameters on the sensor output is significant. It is shown that when comparing simulated sensors to measurements, the levels of harmonic 3 and 5 in the sine and cosine output are respectively about five and twenty times higher.
This must be related to the motor: since the motor has three stator phases it might explain the observed increase in harmonic 3.

The influence of the variation of motor parameters on the sensor output is minor. In three different cases, namely variation of load torque, speed and supply voltage, no significant changes in harmonic content of the output signals of

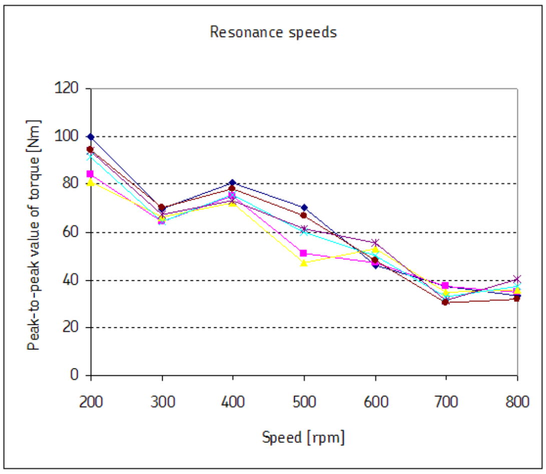

Figure 15: Resonance speeds

the sensor-bearing are observed. This might be due to the reconstruction method applied to the sensor-bearing where for a certain number of outputs of active elements in the sensor, two outputs (sine and cosine) are created. With measurements is shown that the preponderant magnetic field harmonics (magnetic target plus external disturbances coming from motor) measured at sensor-bearing location are sensitive to speed. These harmonics are diminished in the sensor output signals; from a value of 3% in worst case to a value of 1% and their values are stable over the three different cases.

Thus, it can be said that if the sensor would be less sensitive to the motor parameter that is visible in the sensor output through harmonic 3 and 5, then the sensor is tuned to the motor in order to get the best possible performance over the speed, load torque and supply voltage range.

5 Recommendations

To further investigate the noise levels in the electric motor system and the role that the sensor-bearing plays in this, further research is necessary. The strategy to quantify the influence of the sensor on the motor is the following:

- Close the control loop with the sensor-bearing on the test bench;
- Regard the torque output of the PMSM in different load cases, for different speeds and for different supply voltages;
- Link the sensor output to the torque output;
- Define which sensor parameters can be improved to improve overall motor performance.

References

[1] Dipl.-Ing. Dipl.-Wirt.-Ing. Gregor Schrmann, Institute for Combustion Engines, RWTH Aachen University, *Acoustics of Electric Vehicles with and without Range Extender*, CTI Automotive Transmissions and Hybrid & Electric Vehicles conference proceedings, , 2011, 649-658.

[2] R. Lateb, N. Takorabet, and F. Meibody-Tabar, *Effect of magnet segmentation on the Cogging torque in surface-mounted permanent magnet motors*, IEEE Trans. Magnetics, vol. 42, no. 3, 2006, 442-445.

[3] M. van der Giet and others, *Fast-and-easy acoustic optimization of PMSM by means of hybrid modeling and FEM-to-measurement transfer functions*, 2010 XIX International Conference on Electrical Machines (ICEM), vol., no., 2010, 1-6.

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