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ROTATIONAL SPEED MEASUREMENT AND ANGULAR POSITION REFERENCE FOR A CRYOGENIC PROPELLANT ELECTRIC PUMP

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Hall sensors with an analog output were used as rotational speed sensors and provided an angular position reference for other diagnostics measurements during a cryogenic Propellant Electric Pump (PEP) test campaign. Frictionless foil bearing, which is a very important technology that needs to be well characterized during the tests, was tested in the PEP. Hall sensor outputs helped to process signals from eddy current radial and axial shaft displacement sensors and piezoelectric vibration sensors. The Hall sensor signal was also used as the main motor speed feedback signal for the test-bench control system.

Keywords: Hall sensor, electric motor, rotational speed measurement, angular reference

1 INTRODUCTION & MOTIVATION

Hall sensors with an analog output were used as rotational speed sensors and provided an angular position reference for other diagnostic measurements during a Propellant Electric Pump (PEP) test campaign. There is a strong scientific and commercial demand for a new generation of space propulsion systems. Several new technologies for re-ignitable medium thrust cryogenic in-space propulsion were evaluated and developed in a recent project [1]. The PEP designed for delivering liquid hydrogen or methane to the rocket motor was one of the core project topics [2]. The PEP development was led by Snecma (now Airbus Safran Launchers) together with Mikroma (who developed and delivered the electric motor). Czech Technical University in Prague provided a set of PEP sensors, signal conditioning, data acquisition and signal processing software. The measurement setup cooperated with a test-bench control system at the University of Liege, where the whole test campaign was conducted.

Frictionless foil bearing, which is a very important technology that needs to be well characterized during the tests, was tested in the PEP. There were multiple sensors on the PEP: three orthogonal shaft displacement sensors (based on eddy currents), temperature, pressure, vibration and shaft speed / angular position (SPD) sensors. Their layout is shown in Fig.1. Two linear output Hall sensors were used as the SPD sensors. The purpose of the SPD sensors was to provide reliable and redundant rotor speed information and improve the precision of shaft displacement measurement processing. This paper will present the effort to select an appropriate Hall sensor, its testing and qualifications for the application in the cryogenic conditions of the PEP, as well as the methodology for evaluating the rotor-permanent magnets' sensing and final measurement results.

Both digital and analog output Hall sensors are used for rotor position sensing while driving brushless DC electric motors. In conventional design, the position sensors are mounted at the end of the shaft outside the stator coils. In order to reduce the total rotor length and reduce the complexity of the mechanical design, we were forced to integrate the sensors between the stator coils so that they sensed the magnetic field of the rotor-permanent magnets. A similar approach was used in [3] for a compact pancake motor. An extensive effort was spent to prove that the Hall sensor will not be influenced by the motor currents; they will correctly sense the rotor-permanent magnets, and they will not pose any threat to other components or the whole system.

2 SENSOR SELECTION & TESTING

The space industry puts a lot of emphasis on using components that have already been successfully used in space projects and thus have the proper qualifications (Technology Readiness Level). If the component is new, it should be fully specified by its manufacturer for intended operating conditions, which usually increases the price and decreases the availability. In our case, the limiting parameters were the intended operating temperature range (-253–30°C; LH2 to ambient) and vibration resistance (20–2,000 Hz; 20 gr).

At first, we considered cryogenic Hall sensors supplied by Lakeshore or Arepoc, which fulfilled at least the operating temperature range. We ordered an HHP-NA from Arepoc and did preliminary testing in LN2. The sensor worked properly but we realized that its size (7 mm diameter, 8 mm length) and mechanical construction (not shock-vibration proof) was not optimal for our application. Additionally, there was a strong pressure to minimize the cost of the sensor since multiple pieces were needed (several prototypes of PEP motors built). The literature indicated that even a non-cryogenic Hall sensor can work in cryogenic conditions [4]. Finally, we ordered a CY-P3A sensor from Chenyang GmbH, which offered a very wide temperature range (−100°C to 180°C) and also

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a very acceptable price (<5 EUR/piece compared to 260 EUR for HHP-NA)—see Table 1 for the sensor's main parameters.

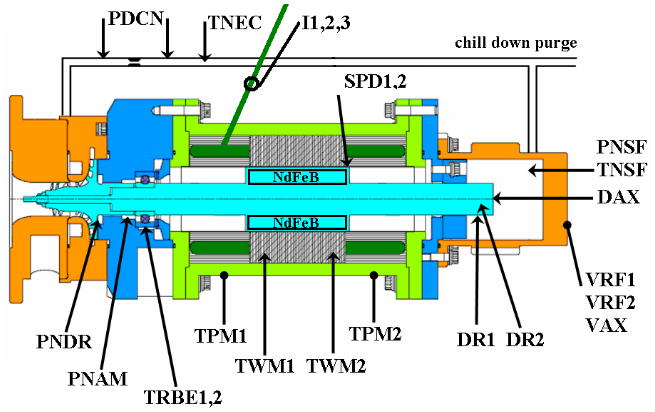

Fig. 1. Schematic model of the PEP, showing the location of various sensors: temperature (TRBE, TPM, TWM, TNSF, TNEC), pressure (PNDR, PNAM, PNSF, PDCN), shaft displacement (DR, DAX), vibrations (VR, VAX) and speed (SPD).

Table 1. CY-P3A Hall sensor main parameters

Sensitivity	380 V/A.T
Measurement range	0.1µT – 2 T
Input/output resistance	1.3 kΩ (typ.)
TempCo of Hall voltage	−0.08 %/°C
Linearity	1% (typ.)
Control current	1 mA (4.5 mA max.)
Package, Dimensions	SOT23, 3×2.5×1 mm

In order to qualify the sensor for our application, we successfully passed several tests: we tested sensitivity variation with respect to temperature (down to -196°C, using LN2), multiple ambient-cryogenic-ambient temperature cycling and vibration testing.

We used a permanent magnet placed outside of a little thermostatic chamber to provide a constant measured field and monitored the output of the probe with a DAQ card as well as the temperature using a PT100 sensor. The measurements were in line with the datasheet and no undesirable behavior was observed. The same applied for the temperature shock tests, however, the rate of change of the temperature was higher in this case (>100 °C/s). We looked for any discontinuity in the output signal during the procedure and cracks in the package after the test. Three randomly selected pieces of the CY-P3A sensors worked well. The vibration testing was done on a final assembly of the sensor; the SOT23 package was soldered directly to Vishay STC-32T-4, PTFE insulated, shielded cable and encapsulated with Stycast 2850FT epoxy (see Fig. 3). For testing, we used an improvised system consisting of a small vibration shaker, power amplifier, computer controlled arbitrary waveform generator, reference sensor with an amplifier and a DAQ system for monitoring the Hall sensor output. The sensor behaved correctly as we tried to copy the recommended Ariane 5 launcher vibration spectrum.

3 MEASUREMENT METHOD QUALIFICATION

As previously mentioned, it is essential in the space industry to prove that every component or system will work as expected and will not jeopardize any other system. The main concerns were related to the possibility of influencing the Hall sensor output signal with motor currents, which generate a magnetic field in the neighboring area. Another issue was connected to the proper installation of the sensor harness, as it could cause leakage problems if not treated properly.

The first prototype of the pump's electric motor, which was equipped with the Hall sensor, did not show acceptable results. It was proven by an X-ray inspection that the sensor was not installed correctly, its sensitivity axis was in the wrong direction and it was too far from its optimal position (see Fig. 2).

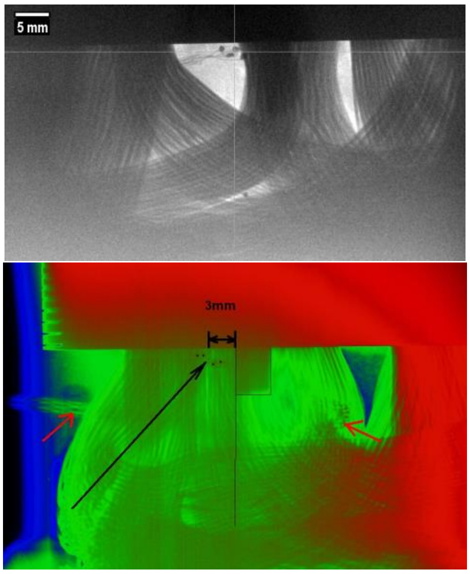

Fig. 2. X-ray inspection of the motor stator. The sensor position and orientation is visible thanks to a high-contrast Pb-Sn solder. Stator magnetic material sheets are on top and Cu winding is in the bottom part of the picture. The bottom picture shows the orientation with respect to a small permanent magnet placed to the nearest position in the rotor area.

This event triggered an even more detailed investigation of the sensor position's influence on the output signal. Additionally, we installed two Hall sensors into a prototype of the electric motor in such a way, that we could test the Hall sensor output signal with respect to its position to rotor-permanent magnets (see Fig. 4).

Fig. 3. Final construction: Hall sensor soldered to Vishay cable and protected by Stycast 2850FT epoxy

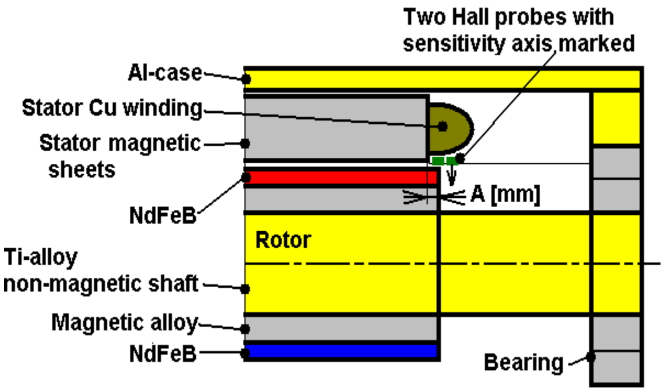

Fig. 4. Schematic drawing of the Hall sensor placement during its qualification tests. The "A" dimension is a distance between the end of the rotor permanent magnet section and the beginning of the stator magnetic sheets section. The Hall sensors were placed close to the stator sheets.

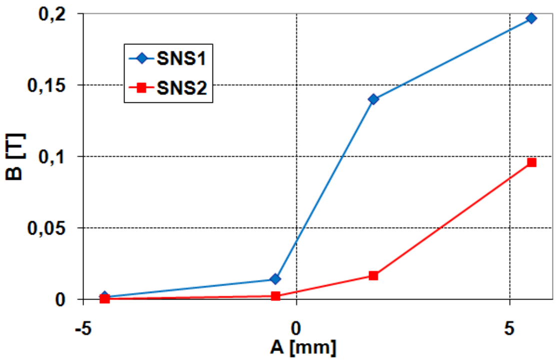

Fig. 5. Magnetic induction (max) measured by Hall probes with respect to "A" distance.

There were two rotors available, which differed very slightly in the linear position of the permanent magnet section. Because of these two rotors, and along with the fact that it was possible to mount the rotor "normally"—or, turned by 180 degrees to the stator - we were able to test four different distances, which are marked "A" in Fig. 4. Fig. 5 shows the maximal amplitude of a magnetic induction measured by the two Hall sensors. SNS1, which produced a higher amplitude, was always the one closer to the permanent magnet section. The expected normal operation position was at +2 mm, and the sensors were supposed to be mounted in SNS1 position, which gave a sufficient margin for reliable function. Finally, the Hall probes (shifted angularly by 90 degrees) were embedded into two stators, which differed slightly in nominal operation parameters (two Hall probes per each stator, see Fig. 6).

A specific setup of two mechanically coupled prototype motors was used to test the influence of the Hall sensor signal by stator winding currents. We monitored the Hall sensor output signal, which was placed in one of the motors (motor 1). At first, we used the other motor (motor 2) to spin motor 1. Therefore, there was no current in the stator windings of motor 1 (see Fig. 7: $I = 0$ A). Then, we connected motor 1 to the driver and used motor 2 as a brake (by connecting the load to its stator coils). In this way, we were able to see the influence of stator winding currents on the Hall sensor signal (see Fig. 7: $I = 2.2$ A and $I = 5.3$ A; nominal motor current). There is a visible influence; the shape of the signal is changed and there is a small increase in the amplitude of the signal. Finally, we concluded that the stator current's influence is acceptable and will not cause any trouble while processing the Hall sensor's signal for speed and raw angular position estimation (less than 10 degrees error thank to normalization of the signals prior to further processing).

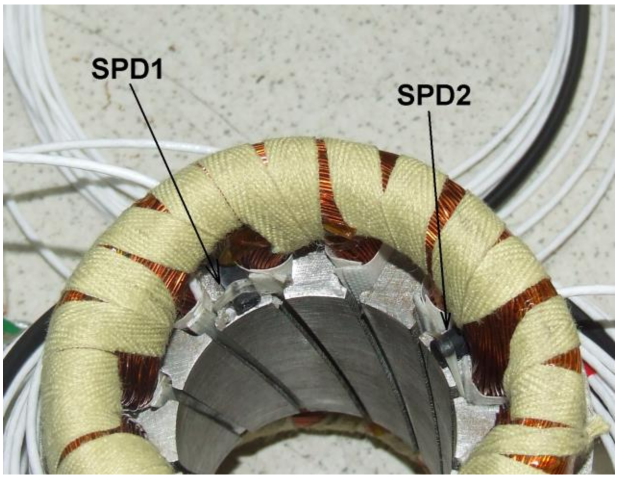

Fig. 6. Installation of the Hall sensors to the motor stator. Later, the assembly was placed into an aluminum alloy case and filled with epoxy.

4 TEST CAMPAIGN RESULTS

The SPD sensor proved to be reliable and useful during the PEP test campaign. Because of safety and cost issues, the PEP operated only with liquid nitrogen (LN2), although all components were tested and made as compatible to liquid methane and hydrogen as possible. The measured speed was in a range of 0-19000 rpm (LN2 operation), but the SPD sensors were tested to be usable up to 55000 rpm (LH2 operation, signal frequency of 917 Hz, two poles rotor). The measurement accuracy was excellent as the frequency measurements are usually very precise (< ±1 rpm, given by the measurement period). The Hall sensor signal was very useful during transient events; it clearly showed every irregularity in the pump function, which was caused, for example, by the tested foil bearing. The motor driver speed signal's bandwidth was too limited for this purpose. The angular position estimation precision was limited to approximately 10 degrees (due to the distortion of the signal and motor driver disturbances). Figure 8 shows a few of the start-up periods of the PEP rotation.

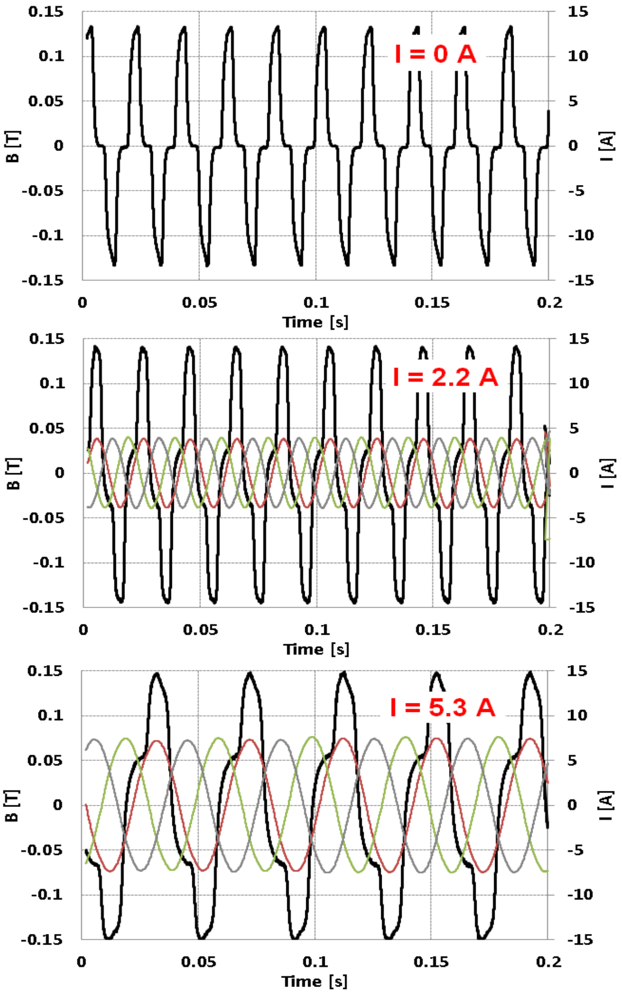

Fig. 7. Hall probe output waveforms for various motor currents (0 A, 2.2 A and 5.3 A)

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5 CONCLUSION

The PEP operated well during all scheduled tests and the test campaign was prolonged to test several additional configurations of the foil bearing. Altogether, far more than 20 000 liters of LN2 were pumped. The SPD sensor proved to be very useful and reliable except in one issue, which it shared with the TWM sensors. The SPD and TWM sensors used a Vishay STC-32T-4, PTFE insulated cable. Together, four cables went from the motor body through one bushing. Despite the fact that the free volume of the stator was filled with Stycast 2850KT epoxy, and the PTFE outer cable insulation had an "activated" surface, there was a considerable leakage through the bushing after a certain time. It was a lesson in what thermal expansion can do and that even a small detail can cause serious troubles in some applications.

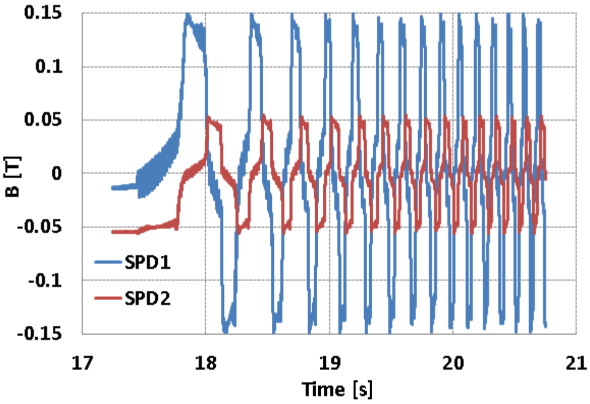

Fig.

Fig. 8. Hall sensors signal (non-filtered, with significant motor driver noise), recorded during the final test campaign. It shows the acceleration of the PEP from zero rpm. There is a ninety degree phase-shift clearly visible between the SPD1 and SPD2 sensors (given by their mechanical placement). The amplitude of SPD2 signal is lower, most probably because of a wrong gain setting in its signal conditioning circuit. It did not affect the results as both signals were normalized prior to further processing. The SPD signals were very useful during transient events; the motor driver speed signal bandwidth was too limited for this purpose.

Acknowledgement

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