

Validation of an Inductive Sensor for Monitoring Marine Gearboxes

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Abstract

In this paper the validation of an inductive sensor for an energy self-sufficient sensor for condition monitoring of wet-running steel disc clutches in marine gearboxes is presented. For a reliable operation of these a permanent monitoring of their state is advisable. As part of condition-based maintenance, more and more sensors are being installed in machines. Reliability becomes even more important when people are endangered by possible failure of the machines. In shipping, it is essential that, for example, the powertrain and thus the transmission are in perfect condition. In case of long distance traveling, wear or even damage of important components has to be known so that maintenance can be carried out proactively.

To address this need an energy self-sufficient and wireless sensor network is developed. Miniaturized sensor nodes monitor torque, rotational speeds, temperatures as well as the wear condition of the torque transmitting components. The energy needed to operate these sensors is obtained from the surrounding environment. Thus, the system operates wirelessly and without an external energy supply, whereby the installation and maintenance costs decrease significantly.

In addition to the concept of sensor integration in the transmission, the energy harvesting concept is also described in more detail. Finally, measurements are taken in a gear-like environment and the behavior of a magneto-inductive sensor in a not constantly supplied situation has been examined.

1 INTRODUCTION

In [Sch18] different methods for the measurement of wear of marine coupling systems were described and discussed in detail. In particular, initial investigations on the appropriateness of inductive sensors for the addressed purpose have been carried out. Inductive distance sensors have been known for a long time and are continuously developed and miniaturized by industry to this day [Len89, Pop96]. For example, Giant Magneto Resistive (GMR) Sensors, which are based on the 2007 Nobel Prize-

winning measuring principle, are currently being used in industrial metrology.

In this paper, the influence of the clutch structure and various ambient media (air, water, oil) on the measuring behavior of the inductive sensor is investigated. As under real operating conditions, the sensor can get in contact with different ambient media within a clutch. For this reason, the influence of these environmental situations on the sensor behavior regarding the measurement signal needs to be investigated in a laboratory experiment. In addition, the behavior of the inductive sensor as an electrical load and the integrity of its measurements within an energy harvesting system has to be examined.

2 MOTIVATION

The used inductive distance sensor Micro Epsilon (MDS-45-M18-SA) provides a voltage output signal which is proportional to the distance between the sensor and a manufacturer-specific magnet (i.e. to a magnetic field). Since the sensor is used within a metallic structure, it can be assumed that the field caused by this magnet can be influenced to varying degrees by the material properties of the clutch. This change in the magnetic field structure could potentially lead to an unwanted change or influence on the sensors output signal and a resulting malfunction of the overall system. In this paper the investigation of some typical scenarios that could occur while operating the sensor within a wet-running clutch is described. This includes the use of the sensor in combination with machined parts made of aluminum as well as the direct contact of the sensor with air, water and oil. It is also important to consider the possible impact of an energy harvesting system on the sensors behave with respect to its operation, its signal integrity and its overall appropriateness for the described task.

For the estimation of the operating behaviour of the considered sensor, two variables have to be worked out. On the one hand the properties of the measurement signal under the influence of the mentioned environmental conditions to estimate their influence on the distance measurement (experiment 1). On the other hand, the electrical properties of the sensor as a load within an energy harvesting system under different conditions (experiment 2).

3 EXPERIMENT 1: DISTANCE MEASUREMENT IN ALUMINUM WITH THREE DIFFERENT AMBIENT MEDIA

Setup

In order to examine the above-mentioned sensor in a controlled environment under the influence of aluminum, a cylindrical two-piece aluminum test body is manufactured. The test body consists of two parts, a bottom and a top part, each with an outer diameter of 100 mm. For the experiment, the magnet is concentrically mounted onto the bottom part and surrounded by the axially pierced upper part, see Fig. 1. The through hole in the top part has an inner diameter of 22 mm. The intersection between the upper and the lower part is constructed as a flange gasket sealed by an O-ring that prevents media such as water or oil from leaving the test body. In addition to an easy assembly and disassembly, the separable structure enables easy cleaning of the test specimens. By choosing the medium to be introduced, there are three material pairings to be examined (aluminum-air, aluminum-water and aluminum-oil).

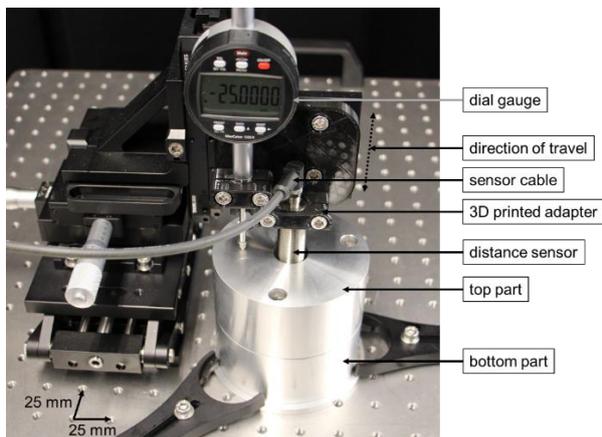


Fig. 1: Setup of the experiment

After installing the magnet in the bottom part, the top part is mounted and the central bore filled with the desired medium air, water or oil. Subsequently, the sensor is axially aligned to the bore in the top half of the test body a subsequently moved along the vertical central axis supported by a 50 mm linear axis. Afterwards the voltage output signal is measured with respect to the distance between the sensor and the magnet. Therefore, the position of the sensor can be adjusted using a micrometer gauge mounted to the vertical axis. The determination of the distance is carried out using the micrometer MarCator 1086R from the company Mahr, which is adjusted to the upper surface of the top part.

Results and discussion

Fig. 2 shows the averaged values of the measurements taken for different supply voltages and different surrounding media. The sensor signal voltage is measured as a function of the

distance between the sensor and the magnet (gap width). It can be seen a continuous linear increase of the sensor signal voltage from 2 V to 6.48 V for a traveling distance of the sensor by 25 mm. This corresponds to a slope of $0.179 \pm 0.002 \text{ V/mm}$. According to the data sheet, a slope of about 0.177 V/mm is to be expected, so that the specification is reached when considering the start and end values.

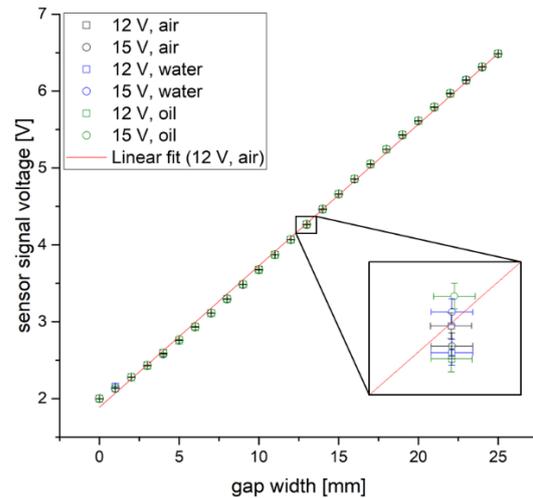


Fig. 2: Sensor signal voltage of the inductive sensor with respect to the magnet to sensor distance at different supply voltages (12 V, 15 V) and in different media (air, water, oil)

Looking at the equation of the linear fit of the data of 12 V in air with a Pearson correlation of $\rho \approx 0.993$ lies – as expected – within the sensor specifications taking into account the linearity error:

$$U(z) = (1.88 \pm 0.02) + (0.184 \pm 0.002) \cdot z.$$

In the functional equation, $U(z)$ describes the distance-dependent sensor signal voltage in Volts. The distance z between sensor and magnet is given in millimeters. This equation is identical with the specified limits for all given measurement points and therefore representative, so that both the influence of the different supply voltages of 12 V and 15 V as well as the different ambient media are to be regarded as not significantly influencing. Thus, the sensor can be used both in aqueous or oily environment and within a supply voltage between 12V and 15V without a significant impact of the signal integrity.

The slight oscillation (i. e., small amplitude) of the sensor signal voltage around the fitted line cannot be explained by measurement errors indicated by the error bars. However, it should be noted that the measured values all fits inside a range of $\pm 0,3 \text{ V}$ with respect to an ideal voltage to distance function and comply to products specifications. Furthermore, this oscillation has

a period of (> 5 mm) and thus is negligible in the later relevant measuring range of less than 1 mm. In addition, the oscillation is visible in all repeated measurements, so this could be considered as a systematic and not as a statistical error. In further investigations, the systematic error can be minimized or at least examined more closely, so that its influence can be minimized if necessary by calibration procedure. In addition, a simulation of the magnetic field propagation as well as a variation of the magnetic carrier material seems sensible in order to gain a better understanding of the present processes. For example, the test body could be manufactured from a ferromagnetic material. It and thus causes a change in the magnetic field. An investigation in this direction makes sense, since the use of steel pistons in multi-plate clutches is possible.

4 EXPERIMENT 2: DISTANCE-DEPENDENT AND MATERIAL-DEPENDENT SIGNAL BEHAVIOR AND POWER CONSUMPTION WITH TEMPORARY POWER SUPPLY

For the investigation of the sensors signal properties under different environment conditions, time-independent measurements were carried out in experiment 1. However, since the sensor considered here is to be used in a rotating multi-plate clutch and supplied by an energy harvesting system, the behavior of the sensor is also to be regarded as a discontinuous energy supply. This is due to the fact that the energy management supervising the energy harvesting system connects all consumers of the system to a voltage source only for defined time intervals and disconnects them again after the interval has elapsed. During this interval, the sensor is provided with a specific electrical power which has to be sufficient for an entire measurement cycle. Within this cycle, the sensor has to reach its operational state, gain a stable measurement status and generate an equivalent output signal, that has been transferred to a downstream processing unit.

For this purpose, it is necessary in a second experiment to analyze the time-dependent behavior of the sensor as an electrical load under various conditions and with regard to the quality of the expected measurement signal.

In order to simulate the electrical environment for the sensor and to be able to record and display the desired information with the aid of an oscilloscope, an electronic circuit is set up. This circuit provides different interfaces, so that all relevant electrical values like voltages and currents of the sensor and information about the supply interval can be measured, displayed and stored by an oscilloscope in an appropriate way.

In this setup, the electronic circuit connects the sensor for a definable time interval (e. g. 1 s) with an adjustable voltage source (e. g. 12 V). The supply voltage, the signal voltage, the sensor current and the start and the end of the supply period are therefore bypassed, generated or converted into equivalent voltage signals. While the signal conversion and load switching are realized by the means of analog circuitry, the timing of the procedure is controlled by a microcontroller. For the presented results, the circuitry has been configured in a way, so that the sensor has been connected to a discrete high-side switch, which can provide in its activated state a low impedance path to a voltage source. Otherwise, it shows a high impedance. For the pre-defined period of time, the microcontroller activates the high-side-switch and generates a TTL-compliant trigger signal that can be used to start a data acquisition process.

For the calculation of the consumed power, the supply voltage and the sensor current have to be measured. While the sensor supply voltage and the sensor signal are bypassed to the oscilloscope, the sensor current has to be measured on board and converted to an equivalent signal voltage that can be calibrated using appropriate measurement equipment.

Therefore, the circuit offers terminals for the connection of the sensor under test as well as the measuring devices for the above-mentioned voltages. For manual or a master slave configuration, the circuitry offers a manual push button for manual usage or an opto-isolated interface for external triggering.

Figure 3 shows the circuit realized for the experiments.

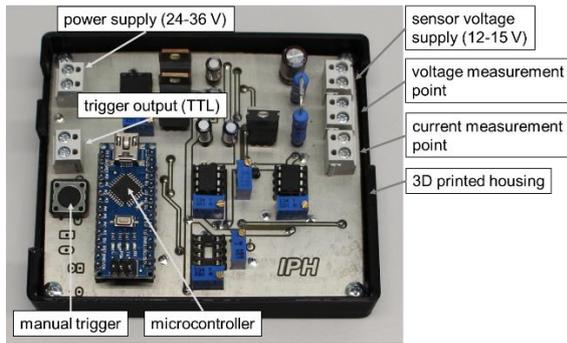


Fig. 3: Developed circuit for imitating a variable timed power source (similar to the energy harvesting system)

Results and discussion

In Fig. 4, the power consumption at a constant supply voltage of 12 V and in air is shown. As can be seen in the figure, after the activation of the high-side switch, the power consumption over the time period of 1 s became basically constant around 160mW, starting with a peak consumption of around 600mW.

After this period, the power drops back to zero, which is not shown in the figure. The short peak at the beginning of the measurement may indicate the existence of a capacitive load inside the sensor, causing an increased inrush current in the order of 50 mA.

This behavior has to be taken into account for the calculation of a minimal measurement time and the dimension of the power supply.

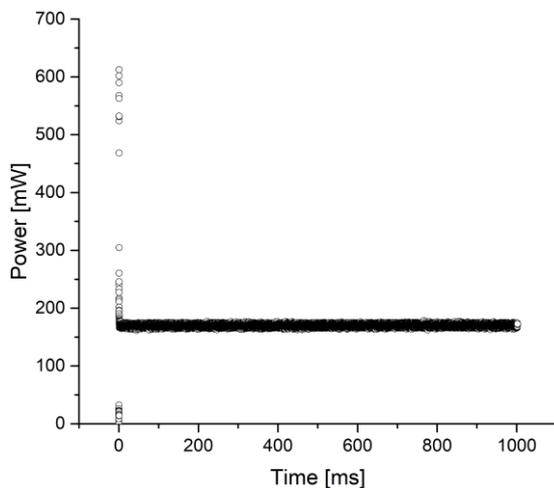


Fig. 4: Representation of the power required to measure the distance in air over a period of one second at a supply voltage of 12 V

Results and discussion

Using the above procedure, the current consumption and the power provided are measured and integrated over one second, thereby estimating the absorbed energy, see Fig. 5. It can be seen that with increasing distance in 5 mm steps from 0 to 25 mm between sensor and magnet, due to a decreasing sensor current, the necessary energy drops from about 170 mJ to about 157 mJ.

Knowing the consumption characteristics of the sensor, it is thus possible to estimate which situation-dependent power consumption is performed by the sensor, which supply interval is necessary for safe data acquisition and which amount of energy the energy harvesting system has to be able to provide for safe operation of the sensor.

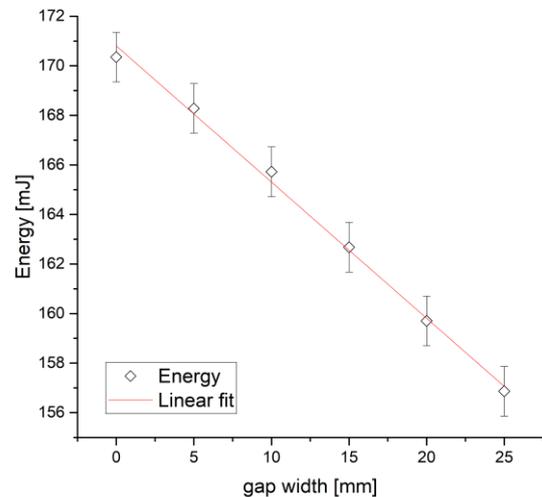


Fig. 5: Estimation of the energy required for the measurement over one second at different distances between sensor and magnet

The regression fit for calculating the necessary energy is given by a Pearson correlation of $\rho \approx -0.998$:

$$E(z) = (0.170 \pm 0.003) - (5.5 \pm 0.2) \cdot 10^{-4} \cdot z$$

Further investigations such as voltage measurements in the installed state of the sensor in a real and thus rotating multi-plate clutch are still pending. Above all, the integration into the sensor network will be carried out during the year, so that both the power supply via the energy harvesting and the signal evaluation will be implemented.

5 REFERENCES

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