SENSOR-INTEGRATED MACHINE ELEMENTS - A BRIEF OVERVIEW OF PRODUCTS AND CURRENT TECHNICAL DEVELOPMENTS

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Abstract

Digitalisation offers enormous potential for significant innovations. In order to utilise this potential, comprehensive and reliable data on the operating status of machines is required. Almost every machine contains standardised machine elements (screws, bearings, gears, seals, etc.) in the immediate vicinity of the process and thus offer the possibility of obtaining and evaluating process-related measurement data by integrating sensor systems into these machine elements. A brief overview of commercially available sensor-integrated machine elements and a presentation of some current developments will be given. In addition, solutions for the power supply and data transmission of sensor-integrating machine elements are also briefly presented.

Keywords: Machine elements, energy harvesting, bearings, seals, screws, couplings, splined shafts, idlers

I. Introduction

A machine element is defined as the smallest component in technical applications that can no longer be meaningfully dismantled. These are components or construction principles that fulfil the same or similar functions in different machines and devices and therefore always occur in the same or similar form. They fulfil certain functions and may be moving or stationary parts. They are made of different materials such as metal, plastic or composite materials, depending on the load-bearing capacity and durability requirements. Machine elements include, for example, screws, nuts, seals, couplings, shafts or bearings. [1]

Modern technologies make it possible to integrate sensors and other electronic components into machine elements without restricting their handling or function. This turns the machine element into a *sensor-integrating machine element*, or *SiME* for short [2].

Electronic components require electrical energy and the use of a SiME only makes sense if the data obtained can be transmitted for further use. Cable connections for energy and data transmission are technically simple, but more complex to install. Wireless data transmission and the generation of the required power by the SiME itself is technically possible and greatly simplifies the installation, but is technically more complex.

II. Measured variables and sensors

Suitable and usually highly miniaturised sensors are available for most of the measured variables relevant to machine elements, e.g. speeds, forces, pressures, strains, accelerations and temperatures. Further information, e.g. frequencies, spectra etc., can be easily derived from the measured variables. For this reason, the acquisition and processing of measured variables will not be discussed further here. The measurement principles and the algorithms for processing and deriving other measurements differ little or not at all from those used in conventional measurement systems.

III. Data transmission

As wired data transmission is often associated with installation work in the machine, only wireless data transmission options are discussed here.

Machines usually consist to a large extent of metallic structures, covers, etc. which makes the transmission of data by radio difficult. Ensuring reliable communication may require complex modifications, e.g. to the machine housing.

Suitable radio transmission protocols include WiFi [3], LoRaWAN (Long Range Wide Area Network) [4], Bluetooth Low Energy (BLE) [5], Zigbee [6], Mioty [7], Sigfox [8] or NB-IOT [9].

Which protocol is the most suitable for a specific application depends on various criteria, which may have different priorities depending on the application.

- Possible criteria can be, for example
- the required range
- the amount of data to be transmitted
- Transmission frequency
- the type of technical infrastructure into which the SiME must be integrated

Ultrasonic waves can penetrate metal with low attenuation. This approach is used successfully in some applications. [10]

Optical data transmission is unsuitable in the vast majority of cases due to the required line of sight and sensitivity to contamination.

IV. Energy supply

The SiME should fulfil its function in the machine reliably and maintenance-free, at least over the service life of the integrating machine element. A secure power supply is essential for this. A cable connection requires increased installation effort and the power supply via battery or accumulator requires regular battery changes or recharging and is therefore not maintenance-free.

An elegant option for maintenance-free energy supply is energy harvesting, the 'harvesting' of small amounts of energy and the operation of the SiME when sufficient energy has been 'harvested'. [11]

The possible energy sources are

- thermal energy, to be collected via thermocouples, so-called thermogenerators
- mechanical energy, to be collected via piezo elements, unbalance generators or similar inductive systems
- Optical radiant energy, to be collected via photoelectric systems (solar cells)

V. Selection of commercial SiME

PiezoBolt load cells (Consenses GmbH). The data of the sensor bolts from Consenses GmbH correspond to the usual bolt standards, but are fully-fledged force sensors and are available in sizes M12, M16 and M20. The screws are supplied with energy and the measured values are transmitted via the plug connection in the screw head. The force is measured in real time as long as the plug connection is in place, which also enables dynamic force curves to be recorded. However, the need for a cable connection restricts the field of application. [12]

Figure 1: *Force measuring screw PiezoBolt PB12 from Consenses GmbH with plug [12]*

Elastomer components with integrated DELTA-C® sensors. DELTA-C® technology works according to the capacitive principle and enables force measurement in conventional elastomer components such as elastomer bearings, couplings or seals. The sensors can be integrated into components that are already required and loads can be measured directly in the force path. The data and energy transmission is cable-bound and therefore restricts the field of application. These are prototypes that are further developed on behalf of customers. [13]

Figure 2: *Elastomeric bearings with integrated force sensors [13]*

Intelligent coupling from R+W Antriebselemente. The company R+W Antriebselemente has further developed its couplings into intelligent couplings in which the complete measuring, processing and transmission electronics for measuring torques, speeds or temperatures are integrated. Power can be supplied by rechargeable batteries or externally by inductive coupling. Data is transmitted wirelessly and can be sent simultaneously to a mobile device or via a gateway to the machine control system. [14]

Figure 3: *Schematic of the intelligent coupling of R+W Antriebselemente [14]*

VI. The DFG-Focus programme 2305 "Sensor-integrating machine elements"

As part of the focus programme 2305 of the Deutsche Forschungsgesellschaft (DFG), the scientific basis for sensor-integrating machine elements and their methodically supported conceptual design and system integration are to be researched. The focus is on 'ordinary' machine elements as standardised basic elements of mechanical engineering with a defined shape and design, which generally cannot be dismantled non-destructively without losing their primary function. [15]

Some of the projects in the priority programme are briefly presented below. The projects were selected and ranked without prioritising them.

I²G - Integral instrumentation of gas foil bearings. A gas foil bearing is being researched and developed as a sensor-integrated machine element that determines the physical measured variables of temperature, acceleration, structure-borne noise and airborne noise in-situ without restricting the primary functionality. In addition to these directly measured variables, the speed is estimated via a Kalman filter and the lift-off and friction conditions are determined. This makes it possible to monitor the condition of the bearing and to record data for monitoring the operation of the bearing-mounted rotor system. The wireless sensor network consists of a base station and a sensor node that is as energy self-sufficient as possible and is integrated into the gas foil bearing. For energy self-sufficient operation, the different energy harvesting approaches - solar cell, thermoelectric generator, piezoelectric foil and piezoelectric vibration generator - are being analysed and, if necessary, combined. For some selected sensor concepts, a first concrete implementation in a prototype with an experimental proof of function in the bearing test bench will be carried out. [16, 17]

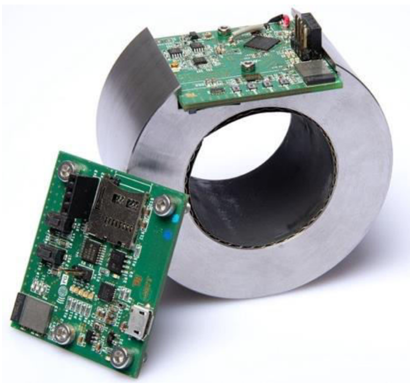

Figure 4: *Gas foil bearing with the first version of the sensor system [16]*

Load-sensitive splined shaft with sensory material. The principle of the sensory material is based on a structural transformation from metastable austenite to martensite when stressed above a limit stress which can be detected by eddy current testing. The sensory material stores the load information, does not require an electrical power supply and can be read out at any interval. As a measuring point, the sensory material can be individually adjusted locally by means of laser heat treatment. The research focuses on the methodical investigation of the constructive integration, the analysis of the effects of sensor integration on the machine element and the qualification of the sensory material. An energy-efficient eddy current readout unit that can be operated autonomously by means of energy harvesting is used to provide proof of function on splined shaft connections in the test rig. [18, 19]

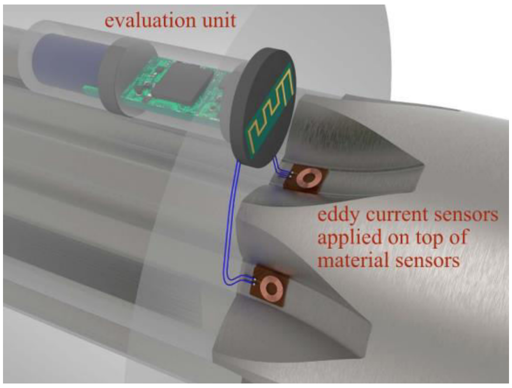

Figure 5: *Concept of the load-sensitive splined shaft with sensory material [19]*

SiSmaK - Sensor-integrating screws for multi-axial force measurement and derivation of a design methodology for sensor integration in closed cylindrical machine elements. Fasteners such as screw connections are particularly suitable for measurement at process-relevant points in and on the machine, as these are located directly in the force flow. Multi-axial force measurement is indispensable for recording loads from different directions and utilising them for process monitoring with early fault detection. In this project, a design methodology for cylindrical machine elements is being researched that addresses the aspects of sensor integration, energy management and signal transmission. The aim of this project is to design and solve the interdisciplinary research questions of a sensor-integrating screw with multi-axial force measurement that fulfils the requirements of installation space neutrality and a self-sufficient energy supply with hermetic sealing. At the same time, the primary function of load-bearing capacity should be affected as little as possible. The procedure for realising this goal should also be used to expand existing design methods for mechatronic systems, especially for the development of sensor-integrating machine elements. [20, 21]

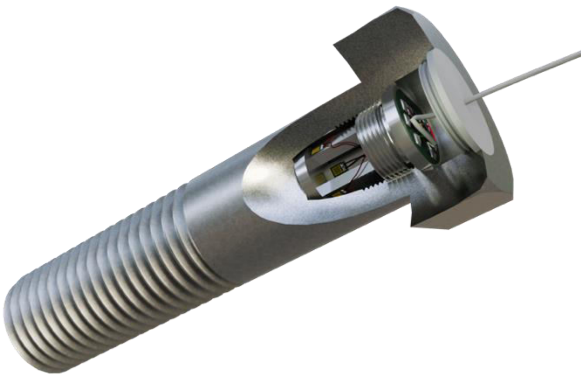

Figure 6: *Sensor-integrating screw of the project SiSmaK [21]*

The sensor-integrating labyrinth seal. As passive support and guide elements of the conveyor belt, idlers are an essential component of belt conveyor systems. An idler consists of an axle, an idler shell, which is rotatably mounted on the axle by two bearings, and two labyrinth seals that protect and seal the inside of the idler and the bearings against dirt and moisture from the outside. Regular visual and acoustic checks with and without measuring devices are standard. Direct monitoring of one or more parameters of each individual idler roller is technically possible, but very time-consuming.

The authors at the BTU Cottbus - Senftenberg are developing a system that records measured values inside an idler roller on the labyrinth seal and transmits them wirelessly to an external receiver module. The required energy is obtained from an inductive system by means of energy harvesting. [22, 23]

The system was used for initial testing in an idler roller in the idler roller test rig (Fig. 9) to measure the heating of a labyrinth seal in the idler roller. The measuring module installed inside the idler roller is shown in Fig. 7.

It is able to measure 4 temperatures on the inner labyrinth sealing ring using PT100 sensors (Fig. 8). At the same time, a further 4 temperatures are measured on the outer, stationary labyrinth sealing ring. All measured values are recorded and analysed on a PC using MATLAB/Simulink. (Fig. 10)

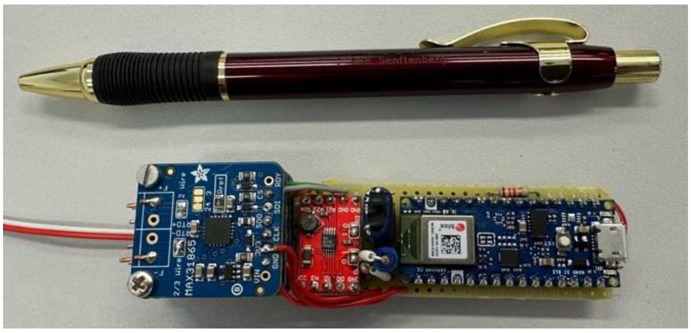

Figure 7: *Measuring module for measuring inside the roller in size comparison with a pencil [24]*

Figure 8: *PT100 temperature sensors idler in size comparison with a match [24]*

Figure 9: *Test rig for the Investigations*

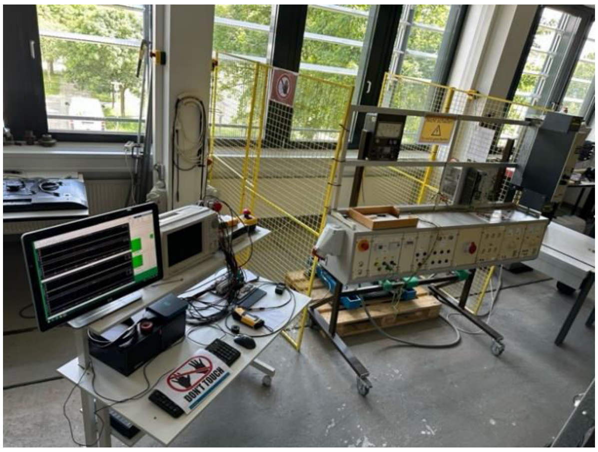

Figure 10: *Complete test stand [24]*

The results of two measurements are shown below. Fig. 11 shows the temperature curve when the labyrinth seal is operated without grease. The temperature increase is only slight but the sealing effect is not fulfilled. Fig. 12 shows the temperature curve when the labyrinth seal is filled with grease. With grease, the labyrinth seal can fulfill its task of protecting the bearing from contamination. The heating is greater due to the friction in the moving grease, but is far below the dropping point of the grease.

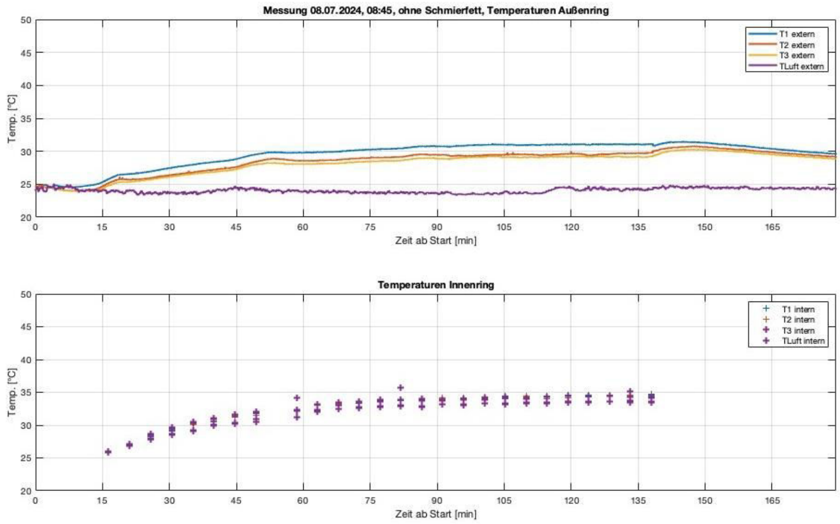

Figure 11: *Temperature curve when operating the labyrinth seal without grease [24]*

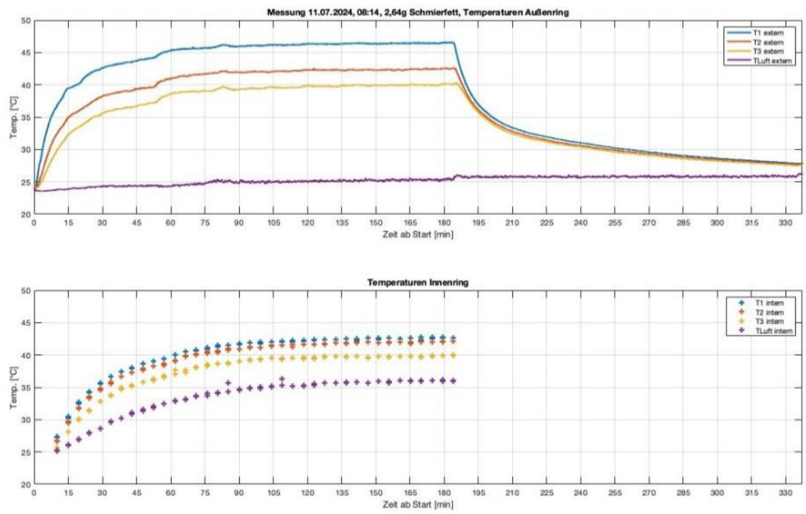

Figure 12: *Temperature curve during operation of the labyrinth seal with grease [24]*

VI. Summary and outlook

The article provides a brief overview of the current market offering of sensor-integrating machine elements without claiming to be exhaustive, and some examples of current research results for SiME are presented.

It can be assumed that with the strong developments in the field of electronics, the field of application of SiME will also grow. New mechanical production methods (coating technologies, additive manufacturing, new joining processes) and modern materials (composite materials, material production) will also accelerate development in the field of SiME.

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