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Magnetoresistive sensors for the condition monitoring of high-frequency spindles

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Abstract

The magnetoresistive (MR) sensing principle was first applied industrially in the read-heads of hard disc drives. However, in the past decade the MR effect has also been used successfully for sensors to measure position, current and magnetic fields. MR sensors offer a number of benefits compared to other technologies used for condition monitoring of machine spindles. They are more compact and offer a higher bandwidth than inductive or capacitive sensors. They are more robust than optical encoders, being largely insusceptible to oil, water and other contaminants [1]. MR sensors can be applied over a wider temperature range and with less demanding assembly tolerances. This makes them particularly well suited to applications with limited available space and demanding operating conditions, as is often the case in machine tool sensing applications. This paper explains the basics of magnetoresistive sensor technology and outlines the advantages compared to other sensor principles. Furthermore the results of a joint R&D project between Sensitec GmbH and the PTW Institute of the Technical University Darmstadt, funded by the Arbeitsgemeinschaft industrieller Forschungsvereinigungen "Otto von Guericke e.V. (AiF), to investigate the application of MR sensors to the condition monitoring of high-frequency air spindles will be described [2]. Position sensors based on the giant magnetoresistive (GMR) effect have been specially adapted to measure directly the radial and axial displacement of the spindle shaft. Importantly only minor modifications have been made to the spindle shaft to enable this measurement and the sensors are completely integrated within the spindle housing. Tests demonstrate that this solution can resolve axial and radial displacements of less than 0.5 µm with high repeatability under typical operating conditions.

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1. Introduction

Excellent surface finish and high dimensional accuracy of the machined part are major requirements in the field of ultra-precision machining. Machine tool vibrations, particularly from the motor spindle as a machine component with inherently low damping and stiffness are crucial for the work piece quality [3]. As a result, spindles with conventional rolling bearings are often substituted by air bearing motor spindles, because these systems promise to provide a better overall accuracy. Air bearing spindles feature smaller synchronous and asynchronous error motions, allow higher rotational speeds (up to 100.000 rpm) and have fewer issues with shaft growth due to thermal effects [4]. Extensive research has been conducted for the condition monitoring of high-frequency spindles e.g. to detect shaft displacements, temperatures etc. [5] Damage or wear in angular contact bearings can be monitored for the purposes of condition-based maintenance. Typically, force, acceleration or displacement sensors are used for this task. The actual shaft displacements have a great influence on the performance and the overall accuracy of the machine tool and machined parts. It is possible to increase the accuracy by compensating these displacements. Despite considerable research efforts and the potential benefits, the practical applications of condition monitoring systems for standard applications with rolling bearing spindles are still sparse,

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primarily due to the significant cost of such systems. As a consequence condition monitoring systems are only used when cost intensive work pieces with high accuracy requirements are produced. Air or gas bearing spindles (Fig. 1) offer performance benefits compared to conventional spindles, as described above, however are more expensive and are typically used in more sophisticated applications e. g. machining of mirrors, lenslets or hardened dies. Therefore they provide a useful object for sensor integration [6]. In these non-contact bearing systems the air gap between shaft and housing is only a few μm to secure sufficient stiffness properties. Typical values are between 10 and 25 μm. [4], with the result that the air gap is sensitive to variations in temperature and shaft speed. Furthermore, small changes of the air gap thickness lead to significant changes in the spindle stiffness and damping properties. On this account a monitoring of the air gap is necessary to further improve the performance of this type of spindle.

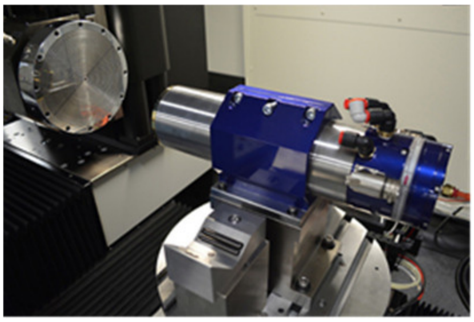

Fig. 1. High speed air bearing spindle (Source: Levicron GmbH)

Furthermore, time efficient cutting parameters adapted to the process and identified by condition monitoring lead to more reliable and safer spindle systems, better machine tool performance and lower total cost of ownership (TCO) for the machine [3],[5]. A good understanding of long-term behaviour is essential for forecasting the remaining life time of the spindle and the direct measurement of spindle shaft displacement provides an appropriate wear-sensitive approach [7]. Ideally, the sensors used must be low cost, non-invasive and not limit the machining envelope of the machine tool [8]. This is easier to achieve with displacement sensors than with sensors measuring force or torque.

This paper focuses on aerostatic bearing spindle systems where compressed air is passed into the bearing to generate a cushion of air. The shaft then floats in the bearing and a constant air gap is generated in the whole bearing (see Fig. 2). The air gap of the bearing changes depending on the rotational shaft speed and temperature as well as by acting forces of the machining process itself [5]. Centrifugal expansion of the shaft due to high rotational speeds leads to a decreased air gap. Additionally, increasing temperatures in the spindle system due to shear losses within the bearing gas and the influence of motor losses further intensify the situation. Imbalance of the spindle shaft or cutting tool, as well as process forces acting on the shaft, generate some eccentricity. This eccentricity especially has a great impact on the stiffness of the bearing. A negative superposition of shaft expansion and eccentricity of the shaft may lead to critical situations, such as contact between rotor and stator and in a worst case scenario a breakdown of the spindle system. Accordingly, the dimensioning of the air gap is a very important challenge of designing air bearing spindles. In [4] Dupont provides guidance for designing air bearing spindle systems and more detail on these dimensioning issues.

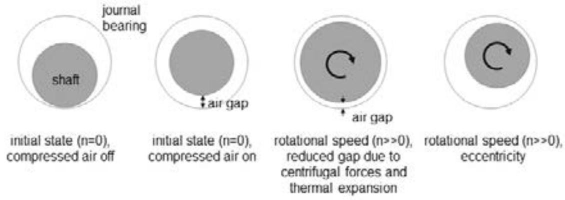

Fig. 2. Conditions in the air bearing system (Source: PTW Darmstadt)

This paper will show an approach of sensor integration of GMR (Giant Magnetoresistive) sensors in an air bearing spindle to detect shaft displacements. After identifying appropriate measuring points sensor holders were constructed, machined and integrated into the spindle system. The challenges being solved during the design process are described and the results of initial performance tests are given.

2. GMR sensor technology basics

GMR-Sensors are based upon the magnetoresistive effect (MR-effect) [9]. MR sensors are used in a wide range of applications, for example, position, angle, magnetic field or electrical current measurement. In general, the MR-effect describes the change of the electrical resistance in an external magnetic field. In most practical applications the MR sensor uses an active measurement scale, that is, a moving magnetic target, in order to provide rotational or linear measurement. However, there are many applications where the use of a magnetic scale is disadvantageous or not possible.

In some cases, where the operating temperature range is very wide, the thermal expansion of the plastic or rubber-based magnetic scale causes an unacceptable loss in accuracy. In other cases the mechanical loading of the scale due to centripetal forces is too high for magnetic materials to survive. Last, but not least, the machine designer often wishes to use an existing machine element as part of a direct measurement system. This approach can help to reduce assembly effort as well as increase system accuracy, by directly measuring the position of the moving machine element. In order to help machine designers realise compact and accurate contactless encoder solutions for this type of application, Sensitec has developed a new range of tooth sensor modules incorporating GMR sensor chips and an integrated bias magnet.

The basic structure of the tooth sensor module is shown in Fig. 3(a). The sensor chip is mounted directly on a bias magnet and enclosed within a housing. The arrangement of the chip and magnet is such, that the strength and homogeneity of the field is ideal. The magnet and sensor chip are subsequently encapsulated to protect them from difficult environmental conditions [9]. The completed module has dimensions of just 3.5 x 5.5 x 13 mm^3. The user simply has to mount the module at the right distance from the machine element that is used as measurement scale.