Thick-Film Radial Position Sensor for High Temperature Active Magnetic Bearings*

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***Abstract* – This paper presents the development of radial eddy-current position sensors for high temperature active magnetic bearing (AMB) applications. Thick-film technology was used to realize silver coils printed on ceramic substrates. Long term measurements showed a good stability of this technology at high temperature. However, silver migration was observed between the wire connections and countered with the use of dielectric pastes. An AC current source at 900 kHz and high impedance amplifiers enabled the sensor temperature compensation. The sensor response was measured from room temperature up to 600°C. Finally a solution is given to mount radial sensor ceramic disk into a metallic housing.**

***Index Terms* – Position sensor, thick-film, high temperature.**

I. INTRODUCTION

The European community is supporting research in the field of high temperature AMBs [1][2]. That work has lead to the development of sensors for systems working at 550°C.

Inductive and eddy current sensors are widely used in AMBs as position sensors [3]. They are typically installed as several coils mounted symmetrically around the rotor. An interesting solution for high temperature eddy current position sensors based on standard technologies is shown in [4], where the coils are wound on a non-magnetic and non-conducting (ceramic) holder. Such a solution leads to relatively high production costs and to low reproducibility and reliability.

Recent developments lead to a new concept for radial position sensors, TFS^{TM} (Transverse Flux Sensor) [5][6], where conventional coils are replaced by inductors printed on a PCB (Printed Circuit Board) substrate.

On the other hand, thick film technology proved its capabilities to work at high temperature, for example in applications such as heating elements [7] and high temperature electronics packaging [8].

This paper focuses on the design and realization of a low cost eddy-current printed position sensor, applied on ceramic substrate with thick-film technology and suitable for applications up to 550 °C.

II. BASICS OF THICK-FILM TECHNOLOGY

Thick-film technology [9] involves building up layer by layer an electrical circuit on a substrate by successively screen-printing, drying and firing operations. The term thick-film is derived from the fact that the fired film is fairly thick (5 to 50 µm) compared to thin- film (0.02 to 1 µm). Thick-film and PCB technology are similar, and both allow the fabrication of multilayer circuits. The interlayer electrical connections are somewhat different. PCB technology essentially uses metallized holes in the substrate, and this is also possible in thick-film technology. In thick-film technology, multilayer circuits may additionally be built up on one side of the substrate by successively depositing conductive and insulating dielectric layers; in this case, the connections are directly established by the screen printing process..

The substrate is the support, on which the thick-films are deposed. It fills the function of mechanical support, electrical insulator and heat dissipator. The common substrate is a ceramic composed of 96 % pure alumina (Al_2O_3) ceramic, where the remaining 4 % consist of a glassy phase at the Al_2O_3 grain boundaries.

The present device uses two types of pastes (or inks): conductor and dielectric. Theses pastes consist of functional ingredients suspended in a temporary organic printing vehicle, which is removed during the drying and firing steps. The main functional ingredient of conductor pastes is metal powder, with additives to promote adhesion to the substrate (metal oxide powder and/or glass frit). Glass frit may also be added to promote sintering. Dielectric compositions have mainly insulating ceramic powder and glass frit as functional ingredients and densify essentially by liquid phase sintering through the glass phase.

III. SENSOR DESIGN

A. Sensing Principle

The presented high temperature sensor is based on the principle shown in [5]. Basically, the sensor is working on

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* This work is supported by the EC GROWTH Program, Research project “MagFly, Magnetic Bearings for Smart Aero Engines”, GRD1-2001-40 191.

the following way. An excitation coil, which is printed on a ceramic substrate, surrounds a non-magnetic metallic rotor and creates eddy currents on the rotor surface. For precisions about the functioning principle, please refer to the cited publication.

Four measurement coils are placed pair-wise symmetrically and differentially, on each cardinal directions of the substrate, allowing measurement of the rotor position in two orthogonal directions.

The measurement coils are connected together pair-wise in the manner to measure a zero signal when the rotor is centred. When the rotor is not centred, a voltage appears on the measuring coils. This signal is synchronous with the excitation signal and can be thus demodulated in order to obtain a suitable position signal.

B. Thick-Film Technology Prototypes

Thick-film technology enables the use of material suitable for high temperature applications, as the “standard” firing environment, used for most thick-film compositions, is 850 °C in air.

The sensor development was done in two steps. First, simple prototypes were realized in order to find suitable pastes for high temperature applications, and secondly the radial sensor was designed.

Printing a coil on a substrate means that at least two conducting layers are needed in order to have the connectors outside the inductor. The coil prototypes (Fig. 1) consist of a coil realized with two conductor layers and pads for wire connections.

Three standard pastes were used: Au (DuPont 5744), Ag (ESL 9912A) and Ag-Pd (ESL 9635B). For each of these variants, sensors with two winding densities were realized; first with 0.15 mm for both conductive track width and track distance and secondly with 0.2 mm for both sizes. The conductor thickness was 10 µm for Au and 13 µm for Ag-Pd and Ag.

The dielectric paste ESL 4913 (based on calcium aluminium borosilicate) was used as insulation between the two conductor layers by applying three separately fired layers, for a total thickness of 50 µm. A protective layer against diffusion and migration on the sensor top surface was realized with two separately fired layer of ESL 4913 (total thickness: ~35 µm). All these thick-film layers were fired using a standard thick-film air firing profile, with a 10 min plateau at 850 °C and ca. 50 K/min heating and cooling rates.

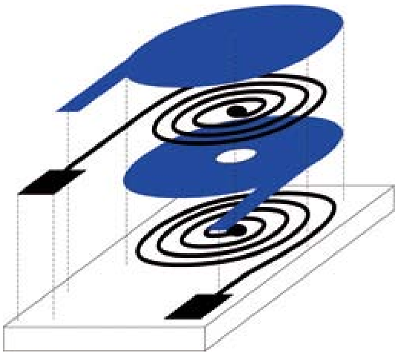

Fig. 1 Layout of the prototype printed coil realized with thick-film technology. Coils are realized with two conductive layers with connection pads separated and protected with a dielectric.

These prototypes were first tested at 600 °C without applied current. Ag-Pd and Au-clad Ag prototypes started to exhibit broken electrical connections after a short time (~200 hours), whereas samples with same conductor and pad material (Au and Ag) showed unchanged resistance or inductance throughout the 2000 hours test. We attribute the problems observed with dissimilar metals to Kirkendall diffusion effects.

Since position sensors in high temperature AMBs require long connecting cables, and using dissimilar metals creates reliability problems, the solution using silver was preferred over gold. The cable connection principle is described in the next section.

100 mA DC current was applied on the silver prototypes at 600 °C ambient temperature. Coils with the 0.15 mm geometry exhibited changes of colour and electrical characteristics after a short exposure time (~24 hours), whereas silver sensors with 0.2mm tracks did not significantly age throughout the same test, as shown in the plot of the inductance and electrical resistance (Fig. 2). The inductance variation is less than 0.1% and that of the electrical resistance less than 2%.

C. Cable Connections

In the present system, cables connect the sensors, in the high temperature system, to the drive electronics located outside a furnace at room temperature. In order to get the best properties at high temperature, 0.4mm silver wires with alumina braid insulation were chosen. In principle, the sensor and the wires do not require any protection against air, as metallic Ag is thermodynamically stable with air at high temperatures.

The bonding of the wires to the device contact pads was carried out by mechanically holding each wire on its pad. Then a thick layer of heavily glass fritted silver paste (ESL 590G, a composition formulated to achieve easy densification) was manually pasting over.

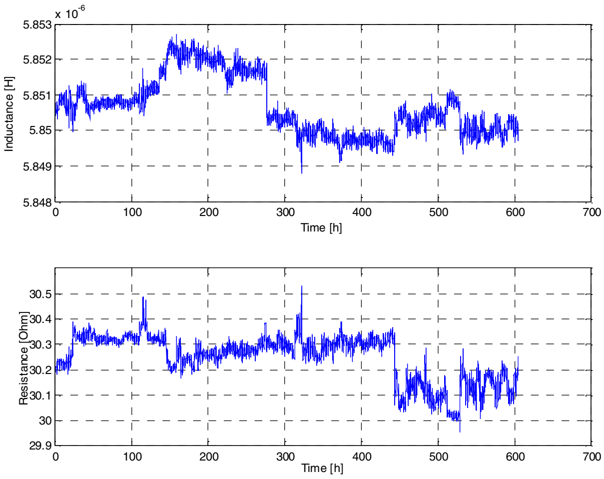

Fig. 2 Sensor resistance and inductance of a thick-film sensor prototype with 100mA DC current at 600°C.

The paste was fired at 850 °C in a laboratory furnace with relatively low heating and cooling rates, 20 °C/min and -10 °C/min respectively.

D. Final Sensor Layout

The final sensor was made of the same silver coils and dielectric printed on a 96% alumina substrate. Fig. shows a picture of a sensor, here without the top dielectric layer in order to reveal the second layer of the printed coils.

The substrate was laser-cut in a round shape from a standard 4”x4” substrate with 0.635 mm thickness. The inner hole allows passage of the rotor. The sensor nominal air gap is 0.75 mm. Four notches were cut on the external part in order to receive maintaining parts.

Fig. shows the excitation coil, which surrounds the rotor and the position sensing coils. On the sensor external part, a temperature sensor was realized with a long track. The sensor temperature is measurable with the resistance of this track.

The sensor shown here is not complete, in order to keep the coils visible. In the complete version, the coils are covered with dielectric, leaving only the connecting pads exposed.

E. Production Cost

Production cost of thick-film device is quite low for large series. Only standard equipment for thick-film production is used for the manufacturing of high temperature sensors. The production cost of a laser-cut substrate with seven separately fired films remains under 50 $.

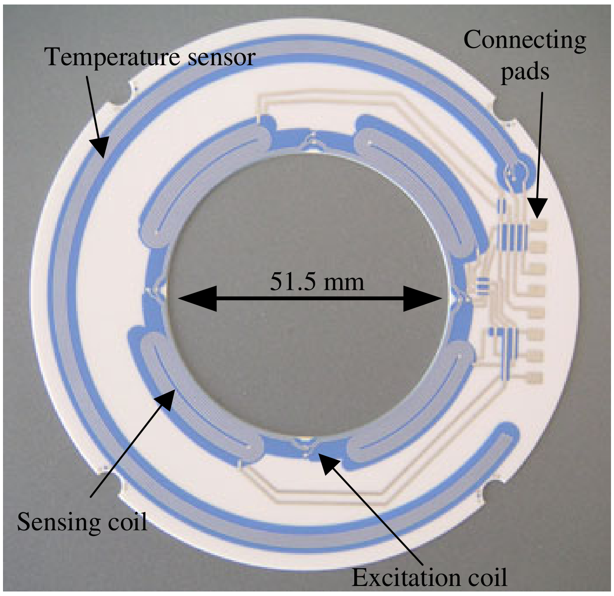

Fig. 3 Sensor layout without top dielectric layer. Coils are printed on a ceramic substrate. An excitation magnetic field is produced with a coil embracing the rotor. The position is measured with four symmetrical coils connected differentially and pair-wise. A thermo-resistance temperature sensor is implemented on the outer substrate part.

IV. SILVER MIGRATION

Silver migration was observed between silver pads. Conductive bridges were thus created, producing noise in the measuring signals (Fig.). This phenomenon occurred after several tens of hours at 550 °C in an atmospheric air environment.

In order to counter this phenomenon, dielectric was deposed over the wire connections. The aim here is to have a protection dense enough to stop the silver atoms from moving. Several pastes were tested in order to find a reliable solution.

ESL 4913 was applied on the connections and fired with the laboratory furnace. The sensor was supplied with 80 mA AC current (900 kHz) at 500 °C. Cracks were observed in the dielectric due to the relatively large wire diameter and due to high thermal expansion of the wires. Moreover, due to a too low furnace heating rate during the firing process, no dense dielectric layer was obtained with ESL 4913. Silver diffused into the dielectric and sensor noise was observed.

The pastes ESL 4903 and ESL 4904 were tested with 100 mA DC current (~3 V) at 600 °C in atmospheric air environment. Conduction between the connecting pads was measured after the 220 hours test.

ESL 4924 was tested as well with 100 mA DC current at 600 °C in atmospheric air. With the use of this paste, no short-circuits were observed during a 760 hours test. This paste is a candidate for use in real working conditions; nevertheless no test has been done in the high temperature AMB so far.

All the previously mentioned tests were performed with dielectric pastes. Another way is to put low conductive paste over the pads, in order to create a screened room, and a zero electrical field on the silver region. Silver migration should in this case not occur anymore. For this purpose, the resistive pastes ESL 3915 and ESL R315 were tested. Unfortunately, these pastes did not show good stability at high temperature.

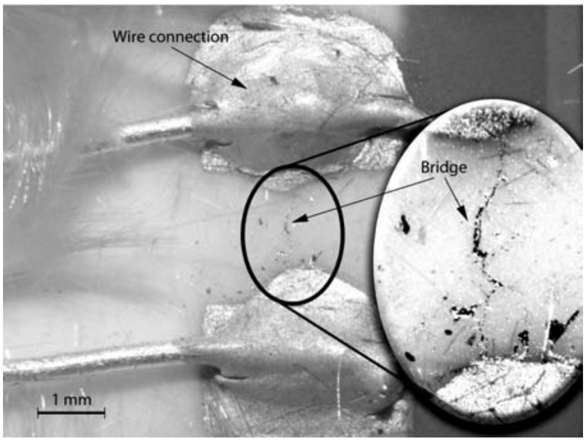

Fig. 4 Migration of silver particles on 96% Al2O3 sensor ceramic substrate. A conductive bridge is created between the sensors connecting areas creating a short-circuit.

V. MEASURING ELECTRONICS

A. *Temperature Compensation*

Basically the printed sensor device does not require different electronics than state-of-the-art eddy current circuits. Nevertheless, special care has to be taken concerning the electrical resistance, which increases about three and a half times across the whole temperature working range. Thus, to enable the sensor measuring independently from the temperature, the sensing circuitry has to give a response independent of the sensor electrical resistance. For this purpose a special device was developed.

The magnetic field depends on the current in the excitation coil. A current source able to deliver a constant current (independently of the sensor resistance) guarantees to produce a temperature independent excitation. A 900 kHz AC current source was realized with an operational amplifier driving a push-pull transistor pair.

The induced differential output voltage is amplified using high input impedance amplifiers having high common mode rejection ratio (CMRR) and low noise. Their high input impedance ensures that the load on the sensor is negligible. By this way the measured value, does not depend on the temperature.

In order to improve noise rejection, a band-pass filter – combine with a transformer to ensure galvanic insulation – was added on the output.

The temperature can be estimated by knowing the resistance of the sensing coils. A DC signal can be added to the sensing coil without changing the AC signal, thus it does not disturb the position measurement. A 0.75 mA DC current supplied the measurement coils. The resulting voltage is differentially amplified and gave the temperature information

VI. EXPERIMENTAL RESULTS

A. *Sensor Response Linearity*

In order to provide measurements of the sensor response at different high temperatures in function of a given displacement, a special setup device was built.

The sensor was put into a furnace. It was mounted on a bar, going through the furnace wall, enabling to move it from a room temperature region. The sensor was displaced with an X-Y table aligned with the two orthogonal sensor sensing axis. A piece of rotor (a non-magnetic metallic cylinder) was put into the furnace as well, playing the role of sensor target.

The sensor sensitivity was measured in this manner from 20 °C to 600 °C. Fig. 5 shows a measurement done at 600 °C where the rotor was moving along one axis and staying still along the other one. The measurement maximum error compared to the linear fit is 10 µm, which is actually the resolution of the measurement setup.

A sensitivity of 7.75 V/mm has been obtained room temperature and 7.46 V/mm at 600 °C.

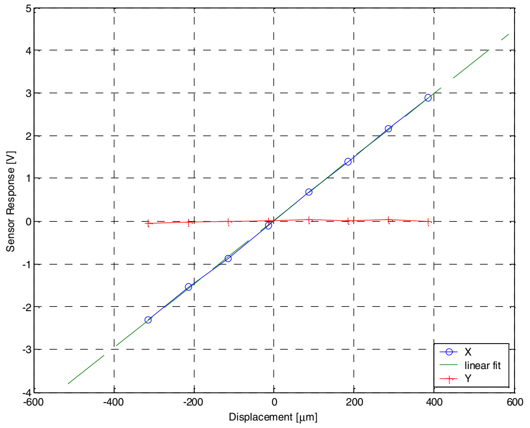

Fig. 5 Sensor orthogonal responses and linear fitting (dashed line) for a rotor displacement in one direction. This measurement has been done at 600°C furnace temperature.

B. *Sensor Sensitivity*

The sensitivity was studied in function of the temperature. The sensor response was measured from room temperature up to 600 °C. The sensitivity was estimated for each measurement with a first order fit. The estimated sensitivities are visible in Fig. 6 in function of the temperature.

A non-negligible sensitivity increase in function of the temperature was measured. Considering the temperature compensation electronics presented previously, the sensitivity change is not due to electrical modifications. This augmentation can be explained with the fact that sensor and rotor are made with different materials. They have different thermal expansion coefficients. This means that the air-gap "sensor-rotor" is reduced at high temperature. This is gives a higher sensitivity at high temperature.

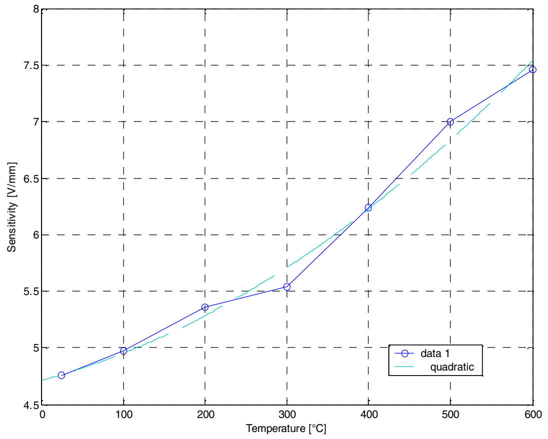

Fig. 6 Sensor sensitivity in function of the temperature. An increase of sensitivity is due to thermal expansion difference between the sensor ceramic substrate and the metallic rotor.

C. Integration in a High Temperature System

This sensor was integrated in a five degree-of-freedom high temperature AMB. The problem was to keep the sensor centered inside a metallic (Hastelloy X) housing. Thermal expansion at 550 °C of the sensor alumina substrate is $7{\cdot}10^{-6}\ \mathrm{K}^{-1}$, which is much lower than the AMB housing one ($15.2{\cdot}10^{-6}\ \mathrm{K}^{-1}$). This results in a thermal expansion difference of 0.45 mm between the sensor external diameter and the housing at 550 °C.

An elastic structure (Fig. 7), which compensates the thermal expansion and keeps the sensor centred in the housing, was realized. The system symmetry is the key point of this structure. This compliant support is composed of four fingers pulling on the sensor sides along four orthogonal directions. The pushing force has to be low in order to keep low stress on the sensor substrate and to avoid cracks in the ceramic. It is 6 N at room temperature and 2.7 N at 550 °C.

Long fingers were designed in order to reduce the difference of pushing force between room temperature and 550 °C. The sensor rotation due to finger movements is negligible and does not affect the whole system behaviour.

In order to protect the sensor signal against noise, the connection wires needed to be twisted. The sensors are relatively sensitive to the wires movements. That is why it is important to keep the wires as close as possible from one another, and avoid relative movements. Furthermore, excitation cables were shielded with a silver wire wound around the excitation twisted wire pair. On the sensor side, the wires were clamped to avoid mechanical stress on the wire connections.

VII. CONCLUSION

Thick-film technology was tested from room temperature up to 600 °C. Wires were connected with the use of thick-film silver paste. By high temperature applications, silver migration was observed between the wire connections creating conductive bridges. The consequence is sensor noise and potential unreliability. Tests were done in order to find a dielectric paste able to prevent the migration phenomenon. A possible solution was found and needs to be tested in real working conditions.

High temperature thick-film eddy current position sensors were built according to transverse flux measuring principle. Electronics was developed to make the sensor temperature independent.

Acquired data, from 20 °C up to 600 °C, show linear measuring characteristics. These sensors were successfully integrated into a high temperature AMB system.

Fig 7. Sensor holder for thermal expansion compensation, with and without position sensor.

This sensor shows extremely interesting characteristics in terms of production cost, reliability and measuring capabilities.

Finally, next sensor generations should take the phenomenon of silver migration into account. Connecting pads have to be for example further apart from each other to avoid this phenomenon.

ACKNOWLEDGMENTS

The authors are indebted to Mr. Giancarlo Corradini and Matthias Garcin for the fabrication of the sensors.

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