High Temperature Magnetic Sensors

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ABSTRACT

Magnetic sensors are widely used in health management systems for turbomachinery, but their applications in the hot zone are limited due to the loss of magnetic properties by permanent magnets with increasing temperature. The paper presents and verifies models and design solutions aimed at improving the performance of an inductive sensor for measuring the motion of rotating objects operating at elevated temperatures (200-1000°C), such as compressor and turbine blades. Physical, analog and mathematical models of the interaction of blades with the sensor were developed. A prototype of the sensor was made and its tests were carried out on the RK-4 rotor rig for the speed of 7000 rpm, in which the temperature of the sensor head was gradually increased to 1100°C. The sensor signal level was compared to that of an identical sensor operating at room temperature. The heated sensor works continuously producing the output signal whose level does not change significantly. What is more, a set of six probes passed an initial engine test in a SO-3 turbojet. It was confirmed that the proposed design of the inductive sensor is suitable for blade health monitoring of the last stages of compressors, steam turbines as well as previous generation gas turbines operating below 1000°C, even without a dedicated cooling system. In real-engine applications, sensor performance will depend on how the sensor is installed and the available heat dissipation capability.

1.0 INTRODUCTION

The need to monitor the health of the blades of jet engines and stationary turbines using the non-contact method results from the well-known problems with blade damage caused by ingested foreign objects or material fatigue. Blade Health Monitoring (BHM) systems have good commercial prospects, especially in power generation turbines which are increasingly operated in the off-design mode due to fluctuating market demand for energy. Magnetic sensors are better suited for monitoring systems than optical (Garcia et al. 2016) or capacitive sensors (Chivers 1989, Fabian et al. 2005) because they do not require cleaning, and their signals can be processed using commonly available electronic systems. However, only sensors with high durability and reliability are acceptable.

Blade tip timing (BTT) and tip clearance (TC) sensors have a lot in common and some types offer both measurements (Yu et al. 2020). However, sensors can be optimized either for clearance or vibration measurement. Due to the demand for higher turbine efficiency, the industry shows more interest in high-temperature TC sensors. Capacity probes are mainly used for this purpose, but several measurement solutions based on active eddy-current principle were proposed, e.g. (Sridhar and Chana 2017, Zhao et al. 2019, Borovik and Sekisov 2020). Some interesting sensor designs in low temperature co-fired ceramics (LTCC) technology were also presented (Lai 2005, Ihle et al. 2018, Ma et al. 2019).

Permanent magnet inductive sensors known as passive eddy current sensors (von Flotow and Drumm 2004, Przysowa and Rokicki 2015) do not have a high-frequency generator and detector. There is, thus, higher bandwidth and no problem with cross-talk and the carrier frequency related to the operation of the generator in active eddy-current sensors (Chana et al. 2016). The disadvantage of passive sensors is the dependence of the signal on the speed, but this is much less relevant in BTT, especially in constant-speed power generation machines. Tip clearance measurement is also possible but requires dynamic calibration. Another problem is the decrease in magnetization of permanent magnets with increasing temperature. At the Curie temperature, ferromagnetic materials become paramagnetic, i.e. they completely lose their magnetic properties and are no longer a source of a magnetic field. To avoid this, the permanent magnet can be replaced in the sensor with a DC powered electromagnet (Jamia et al. 2018).

Standard inductive sensors measure blade vibrations and rotational speed in machines such as compressors or steam turbines, where the sensor operating temperature does not exceed 125 °C. Their high temperature versions designed for turbochargers are specified at 230 °C (Honeywell 2000, TE Connectivity Sensors 2017). However, different sensor materials and manufacturing technologies are required for high pressure compressors and gas turbines. The main difficulty in the design of high-temperature sensors is developing low-temperature sensor production technologies, which at the same time guarantee the strength of the structure at an operating temperature of 1000 °C or higher. In particular, it is advisable to use materials and cements that do not need to fire the assembled sensor since this would deprive the magnets of their magnetic properties.

Most of the high temperature BTT sensors (optical and capacitive) are designed for short-term use and therefore cannot be used in BHM systems. Moreover, very few other sensors are constantly used in the engine hot section due to the high cost and the lack of materials and technologies to ensure durability. The exceptions include resistance thermometers (Pt100) and thermocouples, which are usually duplicated. Piezoelectric transducers such as pressure and vibration transducers (Stevenson et al. 2015) have a similar problem with the Curie temperature as in inductive sensors, but there is a group of materials that work above 600 ° C (Turner et al. 1994, Jiang et al. 2013).

Microwave sensors (Szczepanik et al. 2012, Zhang 2017, Abdul-Aziz et al. 2019) can be made of materials that can be used up to 1400 ° C. Unfortunately, changes in distances in the turbine caused by thermal expansion shift the sensor's operating point, which can be compensated for by using complex electronics. Despite recent advances, microwave TT/TC sensors have not reached full maturity yet.

The article presents selected design solutions and the results of rig testing of an inductive sensor with a permanent magnet, which can operate in gas turbines at a temperature up to 900 °C. A series of measurements was made to verify the suitability of the sensor for operation in a gas turbine. In order to check the sensor's performance at elevated temperature, the head of the sensor was heated with a blowtorch from 25 °C to 1100 °C, comparing its signal with the response of a cold sensor aimed at the same test wheel.

2.0 SENSOR

2.1 Principle of operation

The inductive tip-timing sensor is designed to measure the arrival time of blades. Like an electric generator, it uses electromagnetic induction to produce output signal as blades pass. The sensor consists of a probe and a specialized conditioning system, which can work near the turbine at a temperature as high as 150 °C if it is made from high temperature electronic components (Kotkowski 2021). The design of the probe and conditioning system must be adapted to the blade material, operating temperature and the length of the signal cable.

The field of the sensor is shaped in such a way that it reaches the blade tip. This make the blade an integral part of the electromagnetic circuit (Figure 1). The diagram illustrates the electrodynamic interaction between the induced currents in the passing blade i_1 and the sensor winding i_2. R_b and X_{rb} are the equivalent blade resistance and leakage reactance, and R_s and X_s are the sensor resistance and reactance. A current-voltage converter produces the voltage output signal which is proportional to the sensor current i_2.

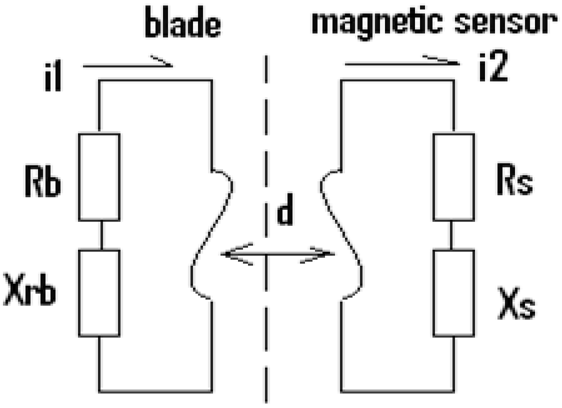


Figure 1. Inductive sensor circuit

The quality of the generated signal is related to the waveform parameters such as pulse amplitude, rise time and signal noise ratio (Hayes et al. 2016). The voltage reaches its maximum when the maximum energy of interaction between the blade and the sensor occurs (Jamia et al. 2018). Obtaining pulses of the appropriate quality requires the optimization of the magnetic circuit of the sensor so that the moment of force which it acts on the blade is the greatest. This is especially true if the blade is not ferromagnetic.

The range of the sensor should correspond to the variation of tip clearance during machine operation. It must not be too large especially in turbine where the blades are numerous and relatively densely spaced around the circumference. Then, the sensor interacts with two or three blades at the same time, which reduces the signal quality and resolution of the position measurement.

An earlier version of the sensor is presented in the article (Przysowa and Rokicki 2015). The probe design has recently been modified to improve durability, hot gas resistance and output characteristics. The solution is based on the patented high-temperature magnetic measurement technology based on the use of a pair of permanent magnets and a winding with a low number of turns (Rokicki et al. 2012). The use of two magnets prevents decrease in the magnetic properties of the sensor under the effect of exhaust gases. A low-turn winding reduces the impact of temperature on coil impedance and sensor performance.

The inductive sensor (Figure 1) can detect the rotating blades made of conductive ferromagnetic or non-magnetic materials due to the wide range of gains available in the conditioning system. It can be installed in a threaded hole and fixed with an M16x1 nut. Alternatively, a bracket with a 19 mm hole and two M16x1 nuts (Figure 2) can be used.

2.2 Sensor Design

The probe consists of a steel body, a magnetic circuit and a heat-resistant ceramic insulator. The two-piece body is the main structural element of the sensor, designed to operate in the turbine zone under thermal stress and high vibration levels. The steel body, in order to guarantee the sensor's durability, should have proper walls of appropriate thickness, and the threads used should ensure fastening. Inside, there is an isolator, and inside the insulator - fixed elements of the magnetic circuit, i.e. two magnets and a winding.

The insulator is made of ceramics (Al_2O_3 99.9% purity), fired in 1600 °C, which can operate in high pressure and temperature existing in gas turbine. Above 300 °C, ceramics becomes a semiconductor whose wave impedance is a function of the concentration of ions in the exhaust gas. Due to the high purity, the wave impedance of the ceramics is then about 120 Ω (not 1 Ω as for the contaminated one). The input impedance of the amplifier and the sensor winding is matched to the wave impedance of the hot insulator.

The ceramic insulator protrudes about 10 mm from the steel body. In this temperature range, there are no other materials than ceramics that could act as an insulator. Unfortunately, if it is hit when cold, it can break easily. Due to its fragility, it should be covered as much as possible by the steel body.

The assembled sensor cannot be repaired or disassembled without destroying it. The elements of the electromagnetic circuit inside the sensor cannot move. The correctness of the assembly or any damage can be checked using Computed Tomography (CT). You can also measure the winding resistance and the magnetic field of the magnets with a magnetometer.

The signal cables have glass-fiber insulation with an operating temperature of 800 °C. The cables can be extended with a standard twisted pair (Ethernet cable) if needed, but this reduces the signal-to-noise ratio. The maximum possible length (typically 12 m) depends on the application: the greater the gain, the shorter the cable should be. The operation of the sensor requires a microprocessor-controlled conditioning system (Kotkowski et al. 2021), which amplifies the signal and generates a digital TTL signal (Figure 3).

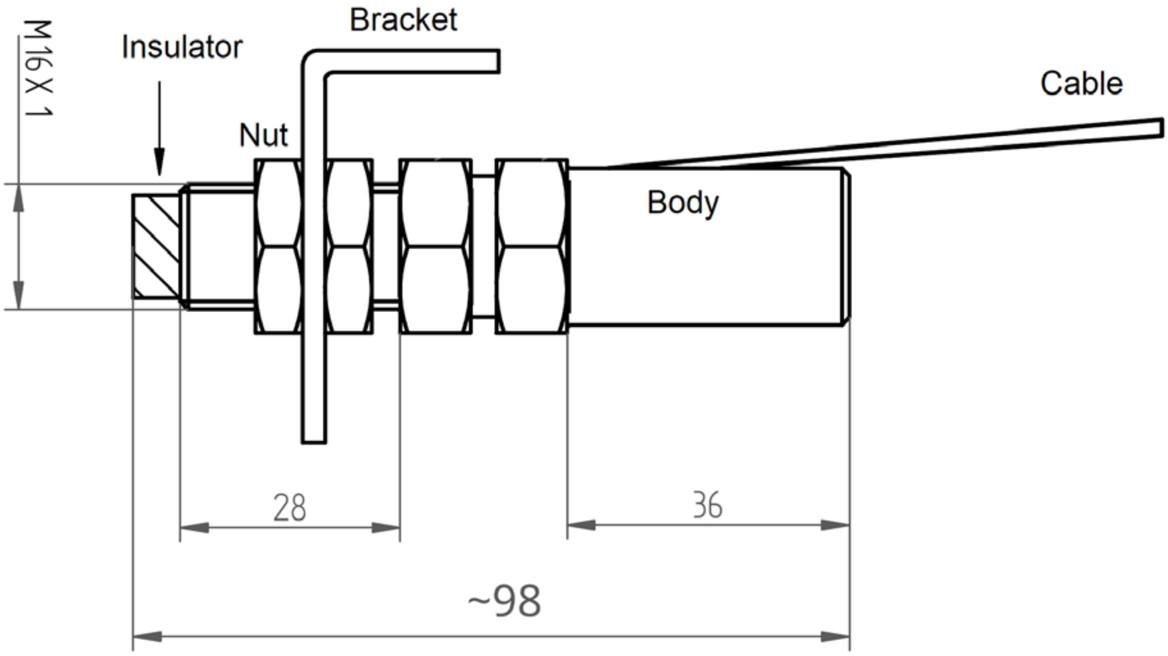


Figure 2. Inductive sensor

Figure 3. Inductive sensor photo

2.3 Magnets

Strong permanent magnets (PM) are made from alloys of rare-earth elements (Coey 2002, Liu 2019). Among the available types of magnets, ferrite and neodymium magnets do not work at temperatures above 200 ° C (Table 1). They lose a lot of their magnetic field event at a moderate temperature as high as 125°C (Fernandez et al. 2015). All magnets demagnetize when heated to the Curie temperature or a strong electromagnetic field from an AC electromagnet is applied (de Almeida and Landgraf 2019).

Table 1. Permanent magnet properties

Magnet	Ferrite (HF)	AlNiCo	SmCo	NdFeB
Pull force	moderate	medium	high	very high
Curie temp. °C	450	900	750	310
Max. operating temp. °C	250	520	520	100
Corrosion resistance	very high	very high	high	low
Machining	no	diamond cutting, grinding	no	no
Demagnetization with AC electromagnet	medium-resistant	not resistant	very resistant	resistant
Cost	low	high	very high	acceptable

The presented sensor uses two cooperating magnets (Rokicki et al. 2012): measuring AlNiCo and supporting samarium (SmCo). The magnets are positioned on the sensor axis along which the temperature gradient occurs. The AlNiCo magnet works at a higher temperature, but is supported by the field of the larger samarium magnet. This solution makes it difficult to demagnetize the AlNiCo magnet, and the temperature is a factor that strengthens its field. Strong permanent magnetic fields and elevated temperature are used in the manufacturing of permanent magnets to improve their performance in the process known as magnetic thermal annealing or artificial magnetic ageing (Sanford 1944, Skomski et al. 2006).

Two-magnet designs ensures that the signal parameters are maintained if the temperature of the external part of the sensor does not exceed 400ºC. This can happen when the engine is shut down, when airflow ceases and the structure is not cooled. Such states in sensors with a single magnet caused their irreversible destruction. In the presented two-magnet sensor, moderate overheating stabilizes and strengthens the measurement magnet.

2.4 Sensor installation

During operation in a gas turbine, the probe comes into contact with gas at a temperature of up to 1100ºC. Therefore, it should be mounted in such a way that makes heat dissipation possible so that the temperature of the external part of the sensor does not exceed 150 - 200ºC during normal operation. The cooling medium may be bleed air or bypass air in a turbofan.

The sensor is installed manually in the turbine casing. It is mounted by screwing the sensor into the socket prepared in the engine nozzle to the appropriate distance from the blade. After positioning the sensor, it is fixed with a nut and connected to the configured amplifier.

Installing the sensor is the riskiest moment for its health and durability, especially for the cables and the insulator. Personnel handling sensors should be properly trained and should use the proper tools. The threads should be made so that it is not necessary to use high torques for fastening. The cables should be carefully fastened in conduits so that they are not exposed to abrasion and erosion. Fitting sensors requires removing the outer casing of the engine and usually costs much more than sensors.

2.5 Sensor durability

Turbine operators are interested in achieving the durability of the sensors for at least 5-6 years of continuous operation, which is the typical time between overhaul (TBO) of turbines, but it is difficult to simulate and prove in laboratory conditions. In steam turbines, the operating temperature is moderate (about 100 °C), but the main problem is a humid environment and corrosion (Przysowa et al. 2017). In case of mechanical damage to the insulator, the sensor loses its tightness and the winding and magnets corrode. In a damaged sensor, the response of the electromagnetic circuit to the blade transition decreases and gradually disappears, which is manifested by a lower signal-to-noise ratio of the output signal.

During the operation of a gas turbine, there are noticeable changes in the stand-off distance between the blades and the sensor due to rotor vibrations and thermal expansion. This is why the ceramic insulator should be flush-mounted and must not protrude into the abrasive layer. If the stand-off clearance is too small, the sensor may be rubbed and damaged (Przysowa and Rokicki 2015, Sridhar and Chana 2017).

Further work is required to predict sensor health and detect symptoms of signal deterioration. Fernandez et al. (2018) tested performance of PMs subjected to cyclic magnetization and demagnetization in temperature up to 135 °C. They found that magnets' cycle life decreases with operating temperature. In practice, the known methods for assessing the waveform quality are used, such as monitoring and statistical analysis of pulse amplitude, signal-to-noise ratio, rise time and the number of missing and surplus blades.

3.0 METHODS

3.1 Rig testing

A commercial rotor rig (Bently Nevada RK-4 Rotor Kit) was adapted to test TT / TC sensors. A test wheel with 9 steel blades and a diameter of 120 mm was mounted on the shaft. The motor control unit was used to set the desired speed up to 10,000 rpm. The NI PXI-1065 computer equipped with PXIe-6358 module and software developed in LabView was the data acquisition system (DAQ). The block diagram of the measurement system is shown in Figure 4.

Two sensors were mounted around a test wheel. Figure 5 shows the tested sensor heated with a blowtorch on the right and the reference sensor in the bottom left corner. The temperature of the probe was measured with a thermocouple, which was attached to the ceramic insulator by means of glass silk thread, resistant to temperature up to 1060 °C. The test consisted in heating the sensor until the selected temperature was reached and measuring the sensor signal for 3 minutes at a constant speed of 7000 rpm. This procedure was repeated a few times for temperature raised from 50 to 1100 °C. The bladed wheel was moved away from the sensors during heating but it was moved back for spinning.

A series of measurements were made with gradually increased temperature (Figure 6). The signals from the sensors were fed into the multi-stage adjustable amplifier of the conditioning system. The amplified signals were sampled with frequency of 500 kHz. For each temperature point, 20 second of data was recorded in the pcm format and processed in Matlab.

3.2 Signal processing

For each temperature, the Hilbert transform *H{x(t)}* was calculated for sensor output *x(t)*, for the data frame of 20 seconds. It was used to get the signal envelope *e(t)* as the modulus of the analytic signal:

$$e(t) = |x(t) + i\,H\{x(t)\}| \tag{1}$$

The average envelope voltage of the hot sensor was then related to the cold sensor's one.

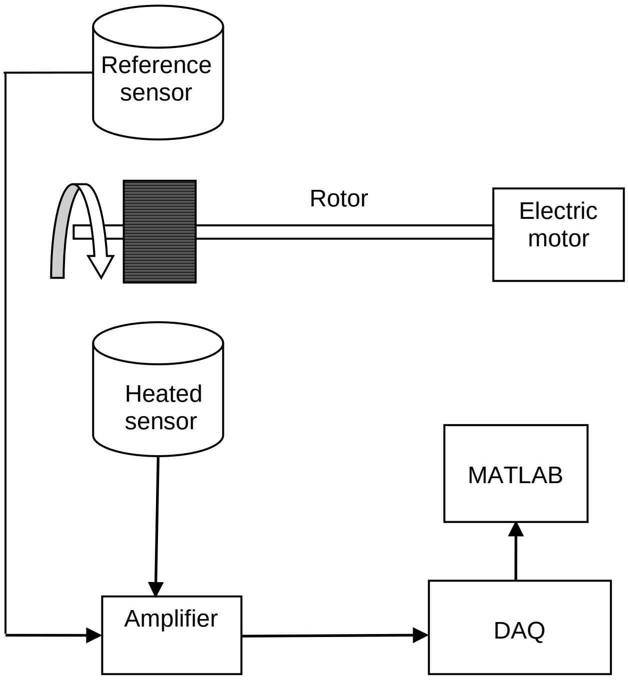


Figure 4. Scheme of the rotor rig and data acquisition

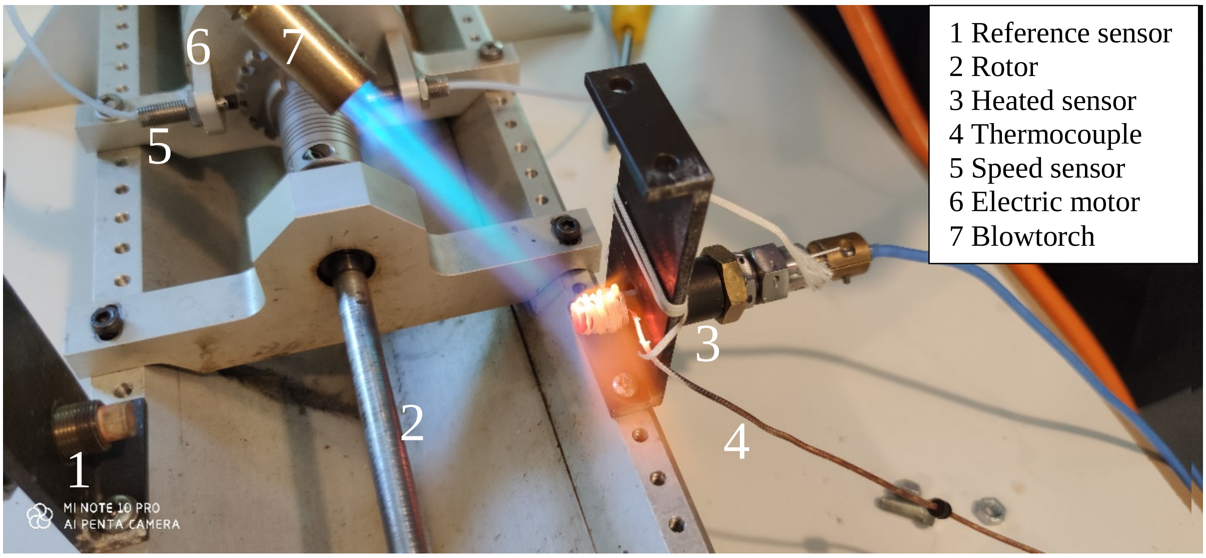
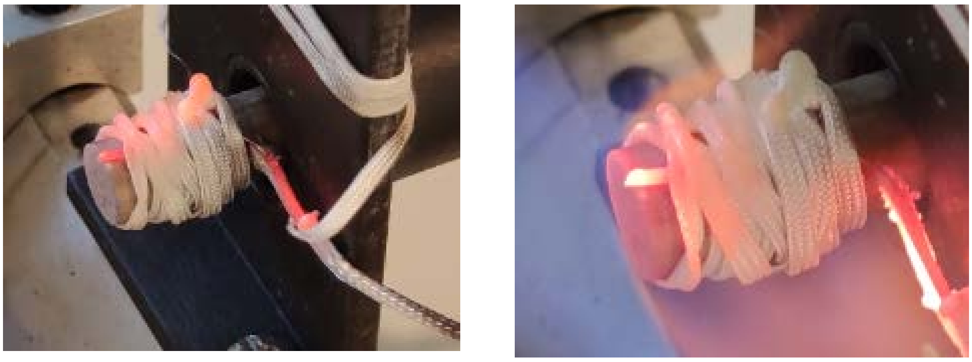


Figure 5. Inductive probe fired at the rotor rig

a) 500 °C

b) 600 °C



c) 700 °C

d) 900 °C

Figure 6. Probe at gradually increased temperature

4.0 RESULTS

Across the whole tested temperature range (50-1100 °C), both sensors generated measurable pulses in response to passing blades. Figure 7 and 8 show the heated probe and its output signal at 1100 °C.

Figure 7. Probe and a thermocouple heated to 1100 ˚C

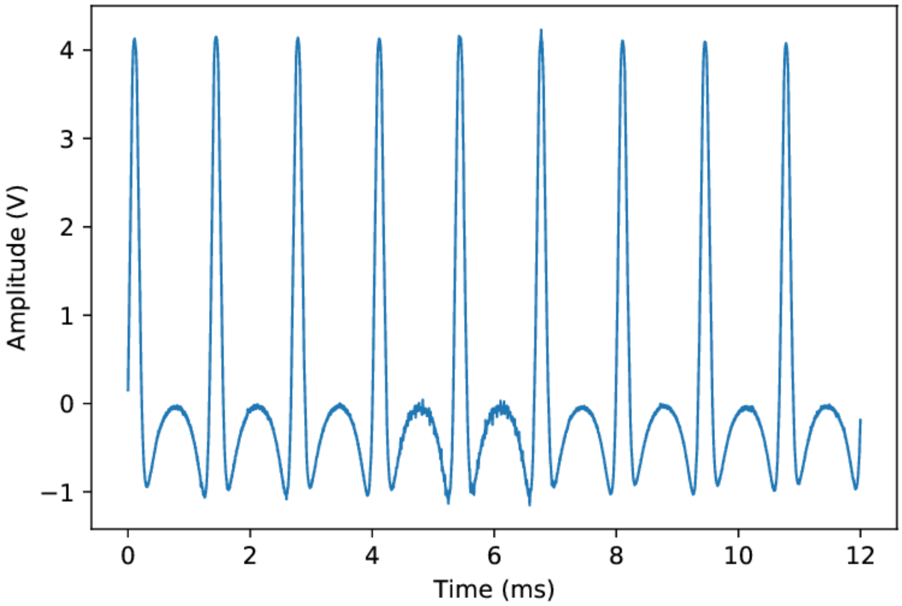


Figure 8. Output signal at 1100 °C

The voltage level of the signal was determined for several temperatures. Figure 9 shows the voltage ratio of the heated sensor signal in relation to the cold sensor. It can be seen that the sensor maintains its primary performance even at 1100 °C.

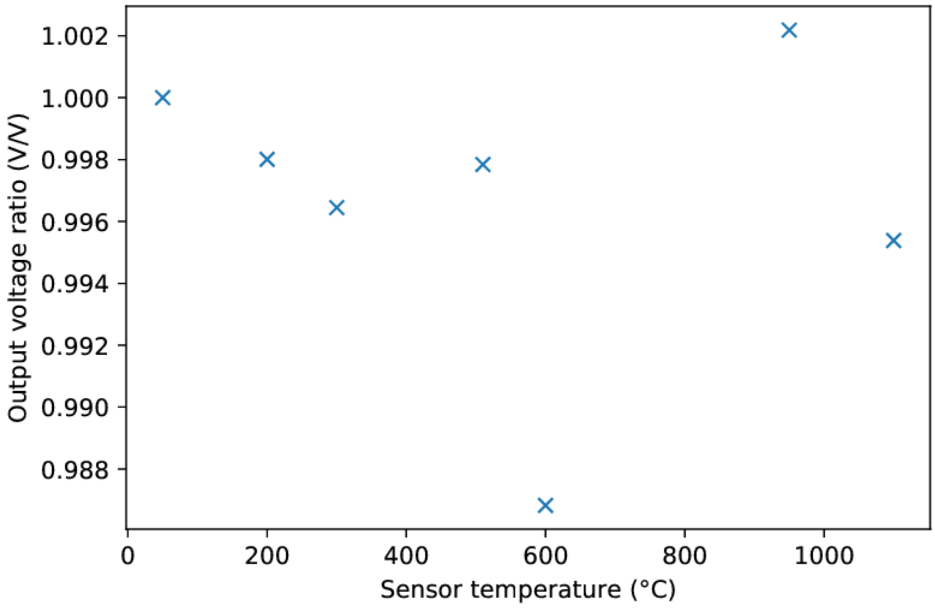


Figure 9. Hot sensor output voltage related to cold probe

Finally, six sensors were installed in the turbine of the SO-3 turbojet and tested (Figure 10). Output signals were acquired with 1 MHz sampling. All the sensors produced readable signals for the entire test. Figure 12 and 13 show some initial data gathered at the idle (7200 rpm) and takeoff speed (15600 rpm). There are 83 turbine blades, so the corresponding blade passing frequencies are 9960 Hz and 21580 Hz. The rising edge has a low rise time, so it can be used for time-of-arrival measurement. Further engine testing is planned.

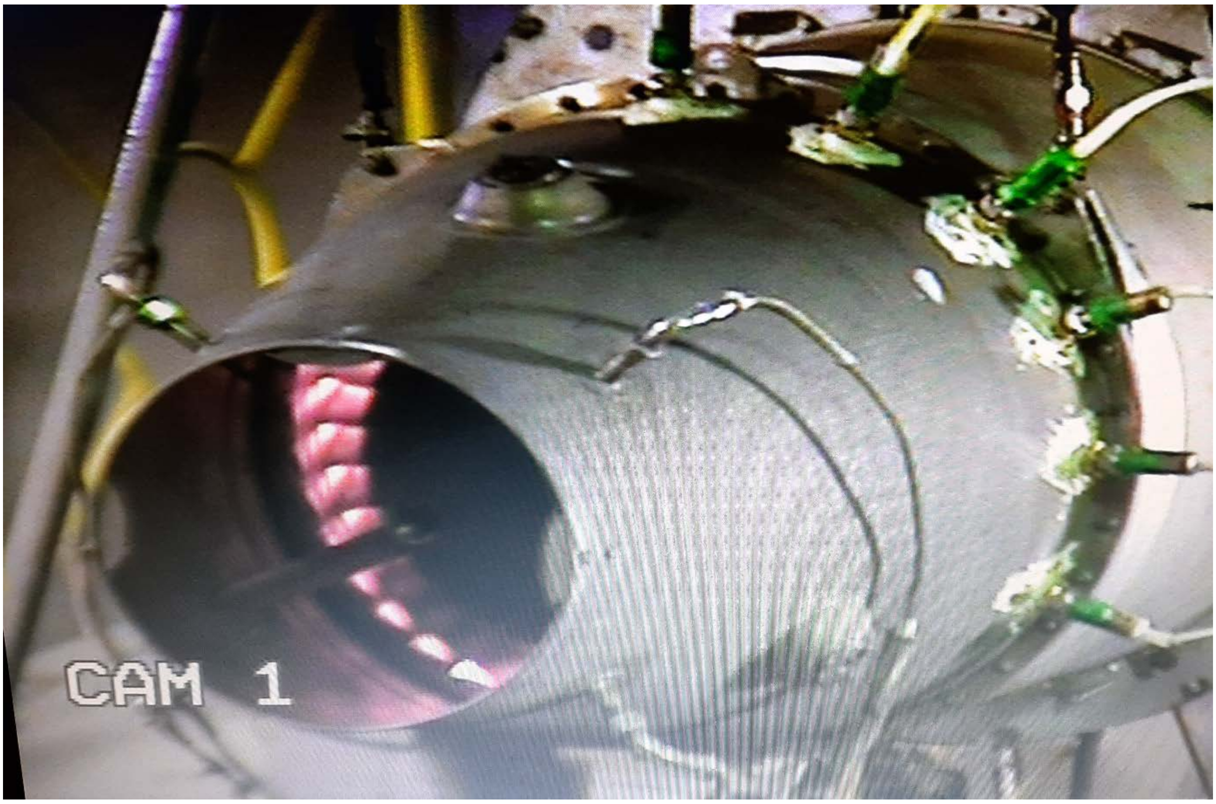


Figure 10. Sensors operated in a SO-3 turbojet

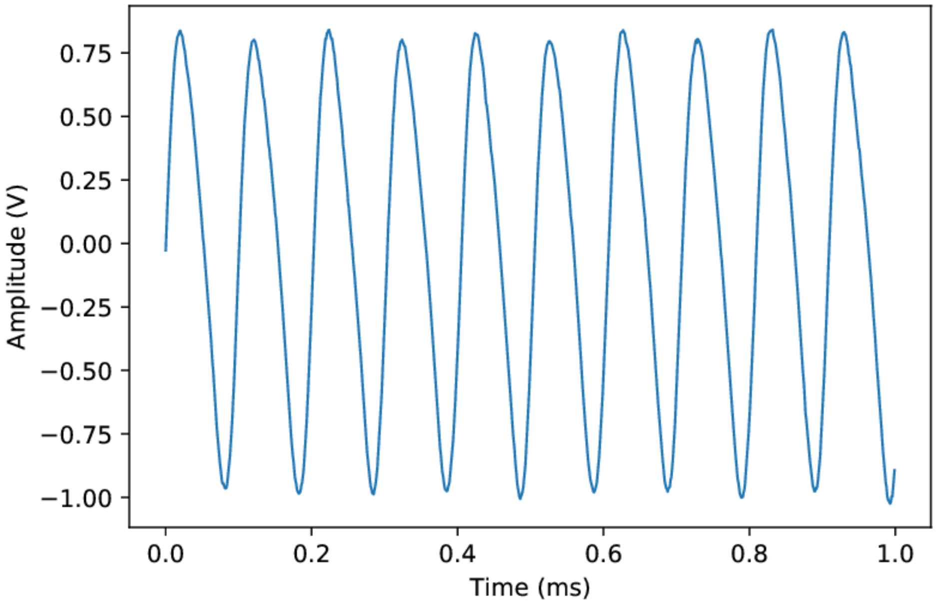


Figure 11. Sensor 2 output for the SO-3 turbojet at idle

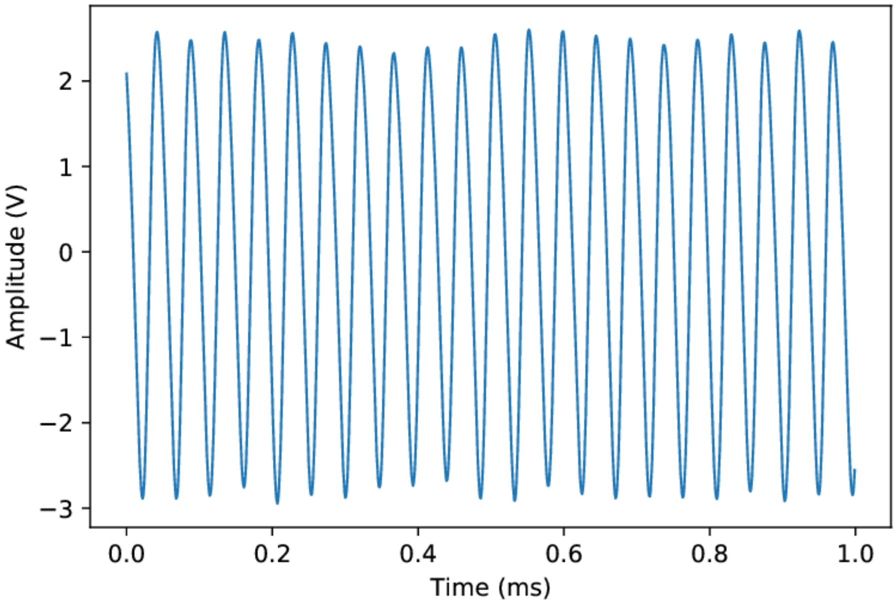


Figure 12. Sensor 2 output for the SO-3 turbojet at the takeoff speed

5.0 CONCLUSIONS

The paper presents the design and validation of a high-temperature magnetic sensor for blade health monitoring. It discusses the selection of components and technologies to build a robust and durable sensor as well as challenges related to its installation in a turbine and ensuring trouble-free operation.

The permanent-magnet sensor was tested at a temperature of up to 1100 ºC to evaluate its waveform quality and confirm the possibility of using it in the BHM systems of gas turbine blades. It was found that the signal level changes by only a percent as a result of heating. In real-engine applications, sensor performance will depend on how the sensor is installed and the available capability for heat dissipation. The proposed design of the inductive sensor is suitable for blade health monitoring of the last stages of compressors, steam turbines as well as previous generation gas turbines operating below 1000°C, even without a dedicated cooling system.

The presented design solutions overcome most problems related to the operation of inductive sensors in elevated temperature. They can be also implemented in other types of magnetic sensors used to measure speed or distance in the hot section of the gas turbine. The increased temperature capability of sensors and their electronics offers more flexibility in the design of the engine health management and control system which can be thus made in a distributed architecture. Robust magnetic sensors which need less wires, power and cooling are more likely to be widely implemented in future military engines.

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