

Design and Testing of a Sensing System for Aero-Engine Smart Bearings [†]

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Abstract: Smart bearings incorporating self-powered sensors and wireless data communications with intelligence in monitoring bearing conditions can help to detect early faults in aero-engine bearings. This paper presents the challenges in design and development of a sensing system with compact and low-power consumption sensors and the procedures for sensor performance evaluation under the requirements of aerospace standard. Industrial standard DO160 testing is necessary for preliminary testing of the smart sensing system prior to being installed in aero-engine, thus a laboratory test procedure has been developed for sensor performance evaluation for the smart aero-engine bearings in this project. As a case study, this paper presents the details and results of the accelerometer evaluation following the requirements in DO160.

Keywords: smart bearings; aero-engine; fault detection; sensors; vibration

1. Introduction

While smart bearings have been widely used in a range of applications such as automotive and rail bearings, no smart bearings have been developed for aero-engines due to the challenging operating environment [1,2]. This project aims to develop integrated intelligent bearing systems with self-powered, multi-sensor systems, as well as wireless communication capability and intelligent detection capability. Five sensors have been selected to measure bearing vibration, temperature, load, cage and shaft speed in an aero-engine. The selection is based on subscale testing using equivalent Ndm ratio for full scale tests and are suitable for rotational speeds in the range between 25,000 rpm and 30,000 rpm and temperatures between 150 °C and 220 °C [2]. Prior to being applied onboard an aero-engine, all components have to be subjected to assessment/testing according to the requirements defined by DO160 [3]. Due to the extreme cost of the standard DO160 testing, it is for the first time a laboratory experiment procedure is designed to evaluate sensors chosen for the smart bearings to ensure that they satisfy the requirements prior to being tested at system level. It consists of an initial sensor performance evaluation, then sensors are subject to environmental conditions (high temperature and oil immersion tests) following the DO160 definition and finally the sensors are tested under room temperature. The performance of the sensors after the testing is evaluated by comparing with its original performance as supplied. The laboratory component level testing can help to make informed decisions on the suitability of the individual components before being integrated onboard in an aero-engine. Bespoke test procedures have been designed and developed

for different sensors according to their operation principal. For example, the cage speed sensor has been tested on a retro-dynamics rotating machine, while for the strain gauges have been tested on an Instron-Machine where cyclic loading can be applied under controlled temperatures. Two case studies, the evaluation of the accelerometer and evaluation of eddy current probe chosen for smart bearings in this project is presented.

2. Evaluation of the Accelerometer

A broad operating frequency (>20 kHz) piezo-electric accelerometer meeting all environmental and operating requirements has been selected [2] for its light weight, small dimension as well as high temperature and frequency range. To evaluate its performance, subject to a DO160 temperature profile, the sensor response is initially measured at room temperature using a back-to-back vibration calibration set-up (shown in Figure 1a). The set-up is shown in Figure 2. Over the frequency range of 10 Hz to 10 kHz, the responses of the sensor are found to follow the calibration curve provided by the supplier (shown in Figure 3a). To evaluate the sensor’s sustainability, two types of testing have been conducted to avoid total loss of the sensor without a clear understanding of the causes, (a) high-temperature testing; (b) immersed in a standard aero-engine oil and endurance testing. After each test, the accelerometer performance is evaluated on the back-to-back calibration setup prior to proceeding to the next level. Details of the three levels of tests and the test results are given below.

- (a) The accelerometer was placed in an environmental testing chamber, where the temperature on the sensor is controlled and measured as shown in Figure 1b,c. After the heating process, the sensor performance is re-evaluated using the same back-to-back calibration setup (see Figure 3a) and it has been shown that the sensitivity of the sensor, although has a small change (~3.5%), it falls within the sensor specifications ($\pm 5\%$).
- (b) The accelerometer was then fully immersed in a standard aero-engine oil and heated up to a maximum temperature of 155 °C for a period of 24 h shown in Figure 2. The re-evaluation concluded no change in sensitivity and frequency response.
- (c) For endurance testing, the accelerometer was placed at 65 °C for 160 h in dry air. No change in sensitivity and frequency response was observed after endurance testing.

Overall, it is concluded that accelerometer meets the demanding requirements and will be installed on a subscale test rig for the 3rd stage of development of the smart bearing system.

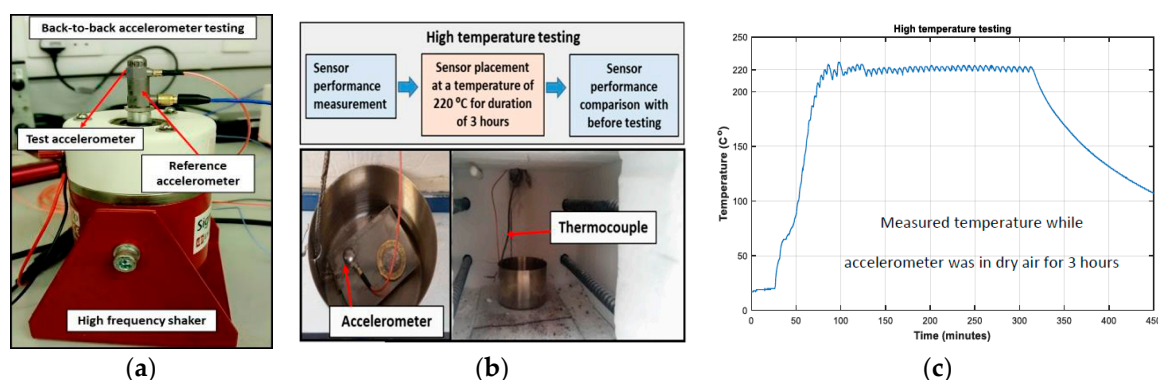


Figure 1. (a) Back-to-back accelerometer testing to measure performance spectrum of test accelerometer with respect to reference accelerometer. (b) Schematic and photograph for high temperature testing. (c) Measured temperature for accelerometer high temperature testing inside furnace.

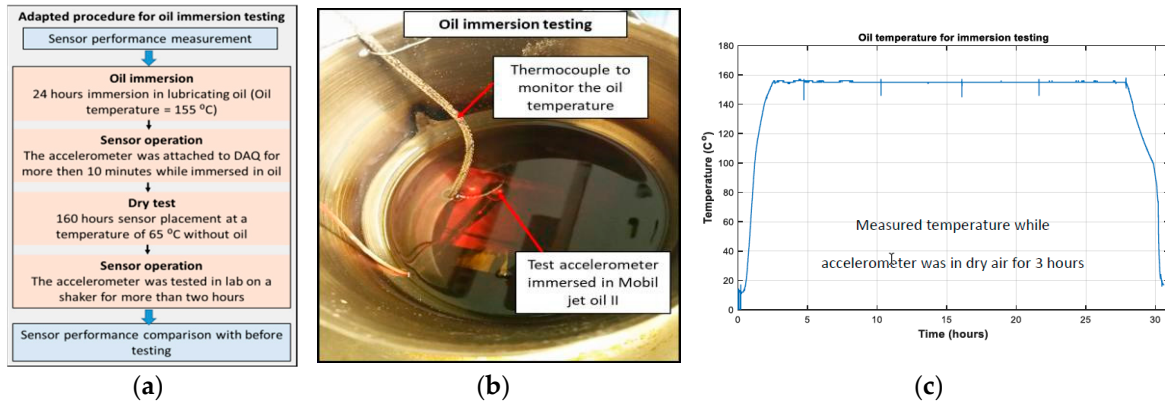


Figure 2. (a) Schematic for adapted methodology for oil immersion and endurance testing. (b) Photograph for accelerometer immersed in oil. (c) Measured oil temperature for accelerometer immersion testing.

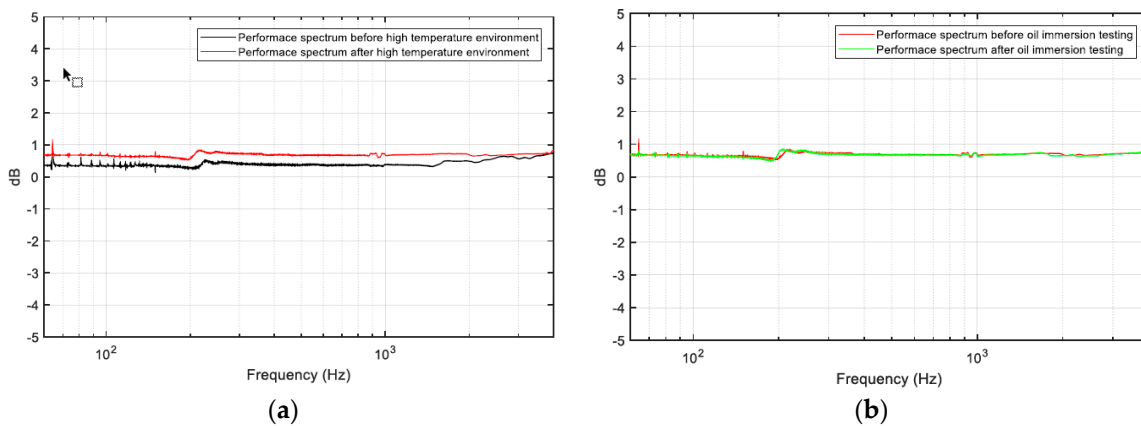


Figure 3. Comparison between measured performance spectrum for accelerometer before and after. (a) high temperature testing. (b) oil immersion testing in simulated aero engine environment.

3. Evaluation of the Eddy Current Probe

An Eddy current probe with high frequency switching capability of up to 5 kHz, having a small sensing face of 4.5 mm, stand-off distance & measuring range of 0.1 mm & 1.1 mm respectively, meeting all environmental and operating requirements [2] has been selected to measure shaft and cage rotational speed on subscale test rig. To evaluate the performance of the eddy current probe under harsh environmental conditions, it has been tested following DO160 test procedure. The high temperature and oil immersion testing procedure followed are same as given above except for the high temperature testing, the maximum temperature used was 180 °C instead of 220 °C. The performance of the eddy current probe has been evaluated at each step of before and after placing in harsh environmental conditions using two types of methods, i.e., (a) displacement calibration testing (shown in Figure 4a) (b) speed test on retro-dynamics test rig (shown in Figure 4b). The displacement measurement has carried out using a standard procedure (as given by the supplier) by moving the probe from stand-off distance of 0.1 mm to maximum measuring range of 1.1 mm with a step of 0.05 mm and record the corresponding output voltage.



Figure 4. (a) Measuring calibration curve using displacement between the target and the material. (b) Measuring speed of the gear on Retro-dynamics test rig.

Figure 5a compares the given calibration values with the calibration measurement before high temperature testing, after high temperature testing, after 24 h’ oil immersion testing and after 160 endurance testing. The regression curve for calibration data given by supplier is $(9.00 \text{ (V/mm)} + 0.5)$, measured before high temperature testing $(8.62 \text{ (V/mm)} + 0.99)$, after high temperature testing $(8.94 \text{ (V/mm)} + 0.79)$, after 24 h’ oil immersion testing $(8.88 \text{ (V/m)} + 0.85)$ and after 160 endurance testing $(8.87 \text{ (V/m)} + 0.84)$. The measured calibration curve before and after placing the probe in harsh environment is more or less similar except small differences which may have incurred due to inaccuracy in moving the probe at an exact step size of 0.05 mm from the target material. The speed measurement on retro-dynamics rig was carried out by measuring the pulses each time the gear pass by the probe (shown in Figure 4b). Data shows that the measured rotational speed using probe on retro-dynamics rig, before and after the high temperature testing is exactly the same (shown in Figure 5b). Therefore, it is concluded here that the eddy current probe not only did survive in harsh environmental conditions but also no change and effect has been observed on its performance.

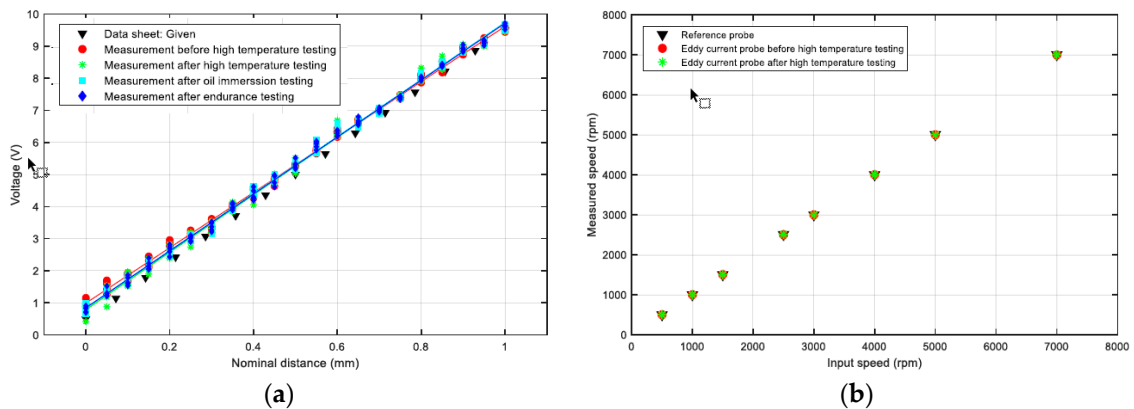


Figure 5. (a) Displacement testing to measure the calibration curve of the eddy current probe before and after placing in harsh environmental conditions. (b) Speed testing to measure the performance of the probe before and after high temperature testing with respect to reference probe.

4. Conclusions

A pre-assessment method for different sensors survivability and performance to be installed on an aero-engine based on DO160 is presented. The methodology is to measure sensor performance, place sensors in harsh environment and compare the performance with before placing in harsh environment. A piezoelectric accelerometer and eddy current probe have been tested to evaluate their performance and survivability. It has been concluded that both sensors did survive during both DO160 tests. However, accelerometer sensitivity has been changed slightly (~3.5%) after high temperature testing. Nevertheless, the frequency response didn’t show any change. For eddy current

probe, no change has been observed in speed and calibration measurement before and after DO160 testing. Overall, it is concluded both sensors meet requirements and ready to install on subscale rig.

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