Integrated smart bearings for next generation aero-engines
Part 1: Development of a sensor suite for automatic bearing health monitoring

Imran Bashir*, Ling Wang and Terry Joseph Harvey
National Centre for Advanced Tribology at Southampton (nCATS),
Faculty of Engineering and the Environment,
University of Southampton, Southampton, SO17 1BJ, UK
*E-mail: i.bashir@soton.ac.uk

Bahareh Zaghari, Alex Stewart Weddell and Neil Maurice White
Electronics and Computer Science,
University of Southampton, Southampton, SO17 1BJ, UK

Abstract

The development of smart bearing solutions will contribute to increased aircraft engine reliability, through robust health monitoring. This project aims to develop intelligent bearing systems for an Ultra High Propulsion Efficiency (UHPE) ground test demonstrator, where a fully integrated self-powered wireless sensing system will be developed for future aircraft. This paper provides a comprehensive review of the state-of-the-art smart bearing technologies and presents the structure of the integrated sensing system focusing on the parameters to be monitored and the sensor technology selection methods for the aircraft engine. Currently, most of the existing smart bearings have been developed for automobile and railway industries with very limited availability for the harsh environment a jet engine experiences, such as high temperatures and vibration levels. Initially monitoring will involve vibration, temperature, load, shaft movement, rotating speed and wear debris. Suitable sensing techniques will be selected using a rating method based on their survivability under the extreme environment inside the engine, as well as their size, weight, sensitivity, operating bandwidth, mounting methods, data processing demand and power consumption for energy harvesting and wireless transmission.

1. Introduction

Rolling elements bearing is one of the most important parts in Jet engines[1]. Condition monitoring of jet engine bearings can help detect bearing faults and predict bearing life[1,2]. On-line condition monitoring can be achieved by the development of intelligent and integrated sensorized bearing called as Smart Bearings consisting of miniaturised and low power consumption sensors, self-power ability for the operation of a wireless communication and data transfer[3]. Smart bearing vision takes on-line conditional monitoring into a new level. However, most of the existing smart bearing technologies have been developed and implemented for automobile, railway and wind turbine applications and limited development has been achieved for jet engines due to the complex and challenging environmental and operating conditions involved[4]. These include the extremely high shaft rotational speed, high vibration and high temperature.

The bearings for jet engine main shaft and turbine are exposed to the temperature of approx. 200 º C and 300 º C respectively[5]. The high temperature lubrication oil also presents an aggressive environment for sensors. Other challenges include the availability of limited input power, limited space, wired tunnelling and the unavailability of commercially available high temperature resistance electronic components. In addition, magnetic based sensors or materials are strictly restricted around jet engine bearings due to the potential of clogging metal debris. In jet engines, bearings are encapsulated in metallic enclosure, which significantly restrict the wireless data transmission[6]. Therefore, even with the significant advancement in technology during recent years, the development of smart bearing for jet engine is still a challenge that needs to be addressed.

The first stage of this work is to identify a sensor suite for bearing health monitoring in the harsh jet engine environment as well as the integration of the sensors in a smart bearing that can measure a range of parameters that indicate bearing health. In parallel, an energy harvesting technology is identified and developed to enable wireless data collection and transmission as a key part of the Smart Bearing. The main goals of this project are:

1) To identify and implement commercially available sensor technology that are suitable for jet engine bearing health monitoring, especially those can survive and operate in high temperature and in immersed aggressive jet engine oil environment.
2) To identify low power sensor to reduce power consumption.
3) To identify and develop suitable energy harvesting technologies in the jet engine environment.
4) To optimise the energy consumption of the sensing system and develop an energy distribution strategy.
5) To develop a wireless communication system for data transferring through the metallic enclosure of the jet engine.

To validate the chosen techniques and the smart sensing system, a range of tests will be carried out at component and sub-scale bearing levels in laboratories. A test head is being designed for the sub-scale bearing test rig to simulate real jet engine environment. This paper focuses on the study of a sensor suite for the smart bearing development. Firstly, a review of existing smart bearing technologies is given followed by a discussion of the challenges of sensing in jet engine environment. The methodology developed in this study for sensor selection, as well as the architecture of a smart bearing, are described before a summary of the conclusions is given.

2. Review of Smart bearing technologies

Over the past thirty years, a significant amount of work has been conducted in developing sensorized bearings. Initially, the focus was on placing a few sensors on a bearing that can measure parameters that indicate bearing condition, while vibration, speed and temperature were identified as the most important parameters for online health monitoring of bearings[7]. This has later on been extended to include load and lubrication monitoring[8].

Mounting of a smart unit has always been an important aspect of the smart bearing development and has moved from attaching a sensor unit to the bearing housing, to embedding sensors in the bearing ring[9]. Most of the commercially available bearings consist of sensors attached through wired and retrofitted-ring systems. These bearings are mostly available for automobile and rail industry such as Axlebox bearing unit ready-to-install cartridge with integrated sensor, which has been developed for rail industry[10]. Overall, significant progress has been made in the development of sensorised bearing technologies. However, until now a limited number of commercial products have been available, such as Alexbox bearings, NSK Motion & Control, Active Sensor Bearing, and Integrated Rotation Sensor Bearings. The focus has been moving from sensorised bearing (wired sensor unit) to a smart bearing (wireless and self-powered sensing system). Wireless sensing systems and self-powered sensor units for energy harvesting gained popularity in order to remove the need for having a power supply for online monitoring of smart bearings[11]. However, a smart bearing consisting of self-powered and wireless sensing system is still in research and development phase and no commercial product available up to date. Similarly, the development of thin film sensors and MEMS has shifted the focus towards embedding the sensors in the outer and inner race of the bearings[12]. Most of the sensorised and smart bearing technology development has been carried out for rail and automobile industry and jet-engine bearings have been given less attention. Jet engine bearings are traditionally monitored by measuring vibration and oil-debris monitoring. The purpose of this work is to build on the knowledge on existing smart bearing technologies and jet engine bearing operating conditions to develop an integrated intelligent bearing system for the new generation jet engines.

3. Challenges in the development of smart bearings for jet engines

As mentioned above, although smart bearings have been developed for other applications, no smart bearings have been used in jet engines due to a number of major challenges. During the initial exploration in this study, the challenges have become clearer, which has helped the identification of suitable sensor technologies for the jet engines.

Jet engine bearings are operated at high rotational speed (3,000 rpm – 10,000 rpm) under high temperatures (> 200˚C) and high turbulent conditions (vibration> 100 g). In addition, the jet engine remains in the so-called heat soak back state where heat is stored and cannot escape even after the engine stops, which raises the temperature of the bearings to as high as 250 °C[5].

To simulate a jet engine environment, planned testing for the bearing will be carried out in the temperature range of 150 °C and 250 °C. This is a huge challenge to most of the existing electronics since they can typically only survive as high as 80˚C environment. Finding the appropriate sensor and associated technologies suitable for the high temperature has been the major barrier in smart bearing development for jet engine bearings. More than 90% of accelerometers are designed and manufactured for applications below 80˚C.

The second biggest challenge posed by the jet engine is the high shaft rotational speed (3000 rpm – 10,000 rpm), which creates a high turbulent environment and high amplitude vibration. This not only adds difficulty for the sensors' survivability but also poses significant challenges for measurements such as vibration and cage rotational speed (see more details below). Furthermore, to simulate the performance of a jet engine, the subscale bearing rig uses a smaller bearing hence a much higher rotating speed (between 25,000 rpm – 30,000 rpm) will be adopted to achieve a higher pitch diameter similar to that of jet engines.

Apart from the temperature restrictions, sensors for jet engine smart bearings require low energy consumption in order to enable wireless power and data transfer using suitable energy harvesting techniques. There are further restrictions within the jet engine environment, for example the low power requirement leads to limited on-board data processing and data storage, less space for sensor mounting, inflexible engine design for adding customized solution, magnetic sensors can't be employed due to debris clogging, and optical sensors are restricted due to the use of oil, which can foul the optics.

For sensors that meet the requirements of the high temperature, it should also be tested for its suitability of being exposed to jet engine oil at such a high temperature (e.g. 180˚C). Jet engines normally use gas turbine lubricants and/or High Thermal Stability (HTS) oils. These oils are aggressive and can induce chemical attack on sensors (especially those with polymer materials[18]) at high temperature for a prolonged duration. Lubricating oils can also damage connectors and cables of the sensors in the engine.

Related to the high temperature, if a sensor needs to be glued to the bearing/housing, a suitable glue or epoxy has to be selected since most of bonding materials cannot survive the high temperature environment. The impact of the aggressive oil environment on the glue should also be examined prior to application. To validate the selected sensors and their connectors and cables, pre-tests are conducted in high temperature lubricating oil environment in this study before they are integrated in the subscale bearing test rig.

4. Sensor selection

One of the most important tasks in developing an integrated intelligent bearing is to carefully select commercial off-the-shelf (COTS) sensors that are suitable for jet engine bearing operating conditions. Initially, the sensors are to be mounted on the test-rig bearing housing before a fully integrated smart bearing with sensors mounted/embedded in the bearing is developed. As discussed above, sensors providing measurements of vibration, temperature, cage speed, shaft displacement and load are considered for the smart bearing development.

To ensure the best-suited sensors are selected for the smart bearing, a methodology has been adopted for the selection of COTS sensors illustrated in Figure 1. COTS sensors based solutions are getting increasing attention in order to reduce cost for aerospace industry[19]. Any COTS sensor which are to be deployed in jet engines need to meet the high-performance standard as given by the aerospace industry. The selection of sensors has been carried out based on information and knowledge on bearing monitoring from the literature and standards, bearing design, bearing environment and operating conditions and other requirements. The selection process can be divided into two parts, a) identification of appropriate method and technology b) identification of most suitable sensor for the given technology. The first part identifies the particular suitable technology for the measurement of a particular parameter. For example, to measure bearing temperature, there are many techniques available, e.g. thermal couples, MEMS techniques, etc. For this application, thermocouples are chosen over MEMS because they don't need input power and can measure temperature over a wide range. The second part focuses on the selection of a specific sensor (model and make) based on the technology identified in the first part.

The following subsections provide details of the selection of sensors for vibration, cage rotational speed and load measurements for a smart bearing on a jet engine.

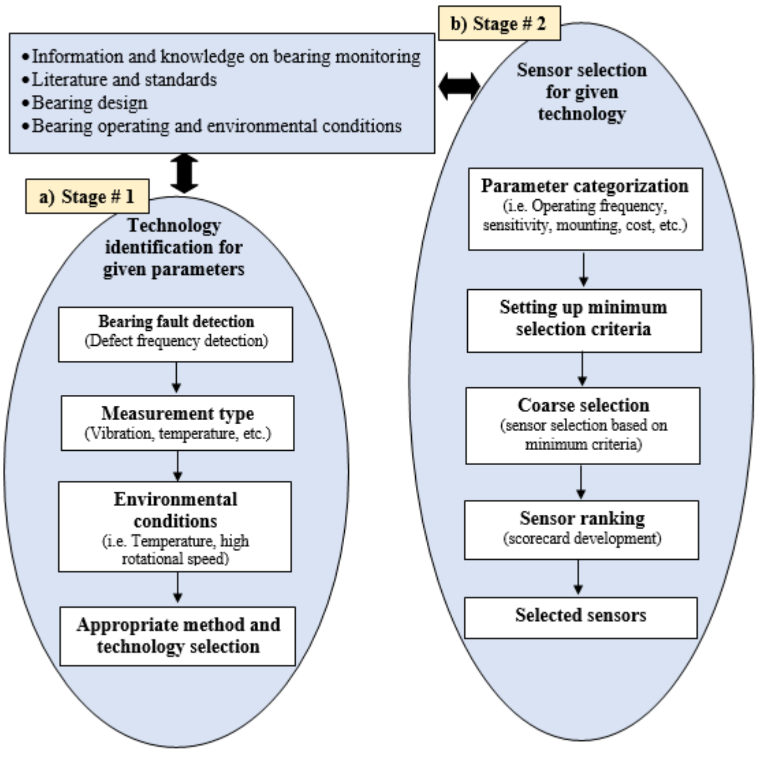

Figure 1: Methodology for technology and sensor selection for smart bearings.

4.1. Vibration

Vibration monitoring is one of the most important and commonly used methods for bearing health monitoring especially due to the fact that it can provide diagnostic information that identifies faulty components based on the bearing specific characteristic frequencies[20,21]. The existence of even tiny defects on the mating surfaces of a bearing can lead to failure if not detected quickly[22]. The rolling element bearing defect produces specific frequencies that depend on the rolling element bearing geometry, number of rolling elements, and shaft speed. The expected defect frequencies can be calculated using formulas as given in[16]. The detection of these frequencies can help to predict the bearing life in jet engines[17]. For planned bearing test, the expected defect frequencies have been calculated, based on bearing design and shaft rotational speed. These calculations informed the selection of appropriate sensor to be used for test bearing.

To measure vibration effectively, sensors should be mounted on the bearing close to the contacts (near the load-zone), where the bearing rolling elements have direct contact with the races. By putting a sensor close to the load zone, it is also exposed to the high temperature zone of the bearing which can be as high as 250 ºC in jet engines. Jet engine rotates at a very high speed and resulting defect frequencies are also very high. Therefore, the charge mode accelerometer technology meets these requirements, while the displacement and velocity-based vibration technologies are unsuitable.

Apart from the demanding requirements on temperature and frequency range for an accelerometer, the sensor's resonance frequency is also very important. For the required frequency range (> 25 kHz), the resonant frequency must be at least the two or three times the operating frequency of the accelerometer[23]. This means that the resonance frequency of the accelerometer should be at least 50 kHz or more. The resonance and operating frequencies are inversely related to the sensitivity of the accelerometer i.e. higher the resonance frequency, the lower will be the sensitivity and vice versa. In this case, the preference is given to higher resonance frequency as the sensitivity can be controlled with the help of the amplifier.

The mounting method is another factor to be considered during sensor selection. To ensure an accelerometer strongly fixed to the bearing in the high vibration and high temperature environment, only stud and screw mounting sensors are suitable. It is not feasible to stick the accelerometer by an adhesive mounting since this will not only lower the operating and resonance frequencies but also act as a vibration damper. Furthermore, due to the high temperature environment, adhesive will degrade over time thus cannot survive for long term operation.

After screening through few hundred COTS accelerometers from a wide range of manufacturers, following the criteria defined in the methodology, only eight sensors met the requirements for the operating frequency, resonance frequency and other characteristics. The shaft is rotating at a very high speed (25,000 rpm – 30,000 rpm); therefore, the expected defect frequencies are also towards the higher end of the spectrum. In this case of 5 and 10 harmonics, the expected defect frequencies are 28 kHz and 56 kHz respectively[14]. All these accelerometers have the operating and resonance frequency of greater than 15 kHz and 45 kHz respectively. Two of the accelerometers with highest resonance frequency i.e. 90 kHz and 100 kHz have been selected. The operating frequency of these two accelerometers is 20 kHz. There was another sensor with better operating frequency of 30 kHz. Although, the given operating frequency is highest compare to other accelerometers but the resonance frequency of the lies within the harmonics produced by bearing defect frequencies. This make the accelerometer impractical to be used and was not selected for testing.

4.2. Cage rotational speed

Bearing elements which are rotating at a very high speed inside jet engines, the skidding between the raceways and rolling elements can cause early failures[24]. Skidding can cause significant amount of surface shear stresses between the mating surfaces. For high speed rotating bearings, skidding causes the rolling elements to rotate slower than the theoretical rotating speed. The skidding effect cannot be detected by vibration monitoring but can be monitored through measurement of cage speed[24].

Cage speed can be measured using non-contact methods such as eddy current, capacitive sensors, magnetic, and optical sensors. The jet engine harsh environment however limits the use of magnetic, capacitive, and optical sensors due to a number of reasons, e.g. magnetic components are not allowed to be placed in air-oil sump due to the danger of accumulating of wear debris on magnetic sensor. Optical sensors are not able to make accurate measurement in this application due to light diffraction and scattering in the bearing lubricating oil environment. Capacitive sensors have limited measuring ranges and their measuring accuracy can be significantly affected by the presence of oil.

In principle, eddy current sensors meet all the requirements for the measurement of jet engine bearing cage speed including the high temperature, high rotational speed and the space available around the bearing in the engine. The cage rotational speed is measured by counting each ball passing-by the eddy current probe. As depicted in the Figure 2, each time a ball passes the probe, it produces a distorted square wave due to interference with the magnetic field. The rate at which the pulses are generated is called the switching frequency, which is calculated by multiplying the number of balls with the cage rotational speed. For the bearing on the subscale test bench, the theoretical cage rotational speed is approximately half of the shaft rotational speed[25] which is between 12,500 rpm and 15,000 rpm and the number of balls is 20. The resultant switching frequency is between 250,000 and 300,000 rpm. Measuring such a high switching frequency is challenging for most COTS sensors. Combining with other factors to be considered, such as temperature, range and response time of the probe, surface area of the balls and oil immersion, selecting a suitable eddy current sensor for the jet engine bearings becomes very challenging.

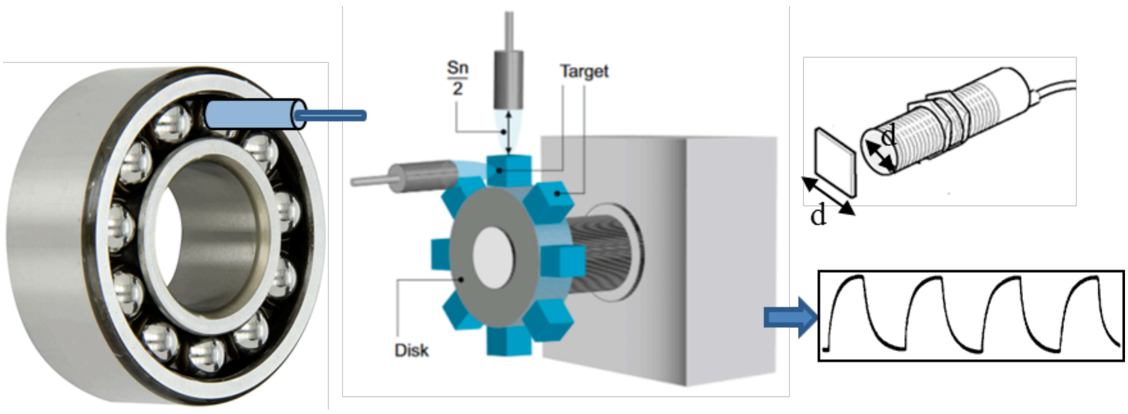

Figure 2: Cage speed measurement using switching frequency.

The temperature around the bearing in the oil-air sump can be as high as 200 ^{o}C. A typical eddy current sensor consists of a sensing unit connected with electronics, which can only survive up to 80 ^{o}C. The solution to this problem is to separate the sensing unit and electronics using a cable, but unfortunately this significantly reduces the response time of the sensor and can reduce the switching frequency. Most of the available high temperature eddy current sensors can only operate with a switching frequency of up to a few hundred hertz while the required switching frequency for jet engine cage speed measurement is in the order of a few thousands of hertz. One of the possible solutions to this problem is to introduce an extrusion in the cage that is detectable by an eddy current sensor at every cycle. Nevertheless, this depends on the feasibility of changing the existing design of the jet engine bearings.

An eddy current probe selection is often based on its measuring range, size of the probe-face and size of the target. Also, the measuring range and the size of the probe are directly related, i.e. as the size of the probe increases, the measuring range also increases and vice versa. However, for a given target, the recommended probe size is to be smaller or same as the target (See Figure 2). To maximise the detection, the shape of the of the target (e.g. the cage) is best in rectangular (See Figure 2). In a case of a ball bearing, the surface area visible to the eddy current probe is very small thus a smaller probe is preferred. However, this will in turn reduce the measuring range of the probe. This can be accommodated if the sensor can be mounted close to the bearing. Furthermore, high speed rotating cage may exhibit a small amount of displacement in the axial direction, which requires the sensor to be mounted further away at a safe distance to avoid any risk of being in contact with the bearing during operation.

Combining all the challenges in the selection process, only two types of eddy current probes have been found to meet the requirements and are selected for the smart bearing development. They will be tested on the subscale bearing test rig to evaluate their capability of measuring the cage rotational speed of the bearings. The project will also explore the feasibility of incorporating a purposely designed cage at a later stage.

4.3. Load

Load on a jet engine bearing is applied in both axial and radial directions. Real time monitoring of the load on the bearing can help understand the dynamics of the engine under complex operating conditions. Load is usually measured using load cells, however it is not suitable for the jet engine bearings due to their heavy weight and large size as well as the impracticalness. An alternative method that estimates load through the measurement of the elastic deformation of a stationary bearing race using strain gauges is thus chosen for this application. Strain can be measured using various methods and three are potentially suitable for the harsh environment in jet engines, including resistive strain gauge, fibre Bragg gratings and surface acoustics wave devices. The fibre Braggs gratings measurement system is large and need significant power to operate. Similarly, surface acoustic wave sensors need further development before it can be considered to measure strain in harsh jet engine environment.

Therefore, a resistive strain gauge has been selected to measure strain on jet engine bearings in this project.

In order to measure elastic deformation of the outer race, it is proposed to mount the strain gauges directly on the outer race (stationary) of the bearings. The strain gauges should be mounted on the outer side and along the circumstantial side of the bearing to measure the radial and axial strain respectively. On the outer race, the strain gauge is exposed to higher temperature zone of up to 250 ^{o}C. As discussed above, suitable glue (or bonding materials) has to be selected to achieve long durability sensing. Also, chemical attack by lubricating oil can also weaken the gluing over time. Hence the gauge must be protected against aggressive lubrication oil. In the case of oil seeping between the strain gauge connectors, it can instantly cause the malfunctioning of the sensor.

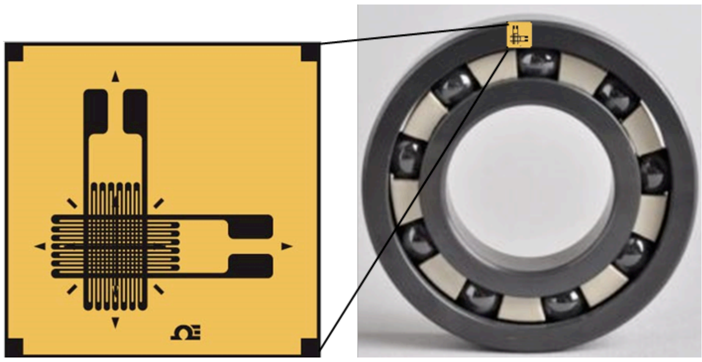

Figure 3: Strain gauge mounting to measure strain on the outer race of the bearing.

Furthermore, in a jet engine bearing, the outer race experiences significant temperature variations during operation and strain measurement has a strong dependence on the temperature of the environment it is in. In order to obtain accurate strain measurements, temperature compensation must be applied. This is achieved by using a T-rosetta (cross) strain gauge (see Figure 3) that measures differential strain by constructing a half bridge circuit. However, this introduces another challenge due to the limited space available on the bearing race (especially on the side of the race). Figure 3 shows that the strain gauge should be mounted on the outer side of the race to measure radial strain. However, for planned to test the total width of the outer race is only 5.5 mm. Considering all the restriction and requirements, only two types of T-rosetta strain gauges have been identified for the test bearings. The dimensions of the two strain gauges are of 5.6 mm x 5.6 mm (rectangular) and 5.4 mm (circular).

5. Conclusions

Through the initial investigation, it has become clear that the harsh jet engine environment presents significant challenges for the development of a smart bearing. Apart from the two major challenges of high temperature and high rotating speed, there are many other challenges that also limit the selection of suitable sensors for jet engine bearings. Based on the work described in the literature and industrial experience, the most important parameters for jet engine bearing monitoring are chosen to be vibration, temperature, cage speed, shaft displacement and load. A methodology has been adopted for selecting suitable sensing technologies for aerospace bearings. After a comprehensive screening of COTS sensors, only a limited number of suitable sensors were found to meet the requirements. Future work will focus on the pre-testing of the selected sensors under high temperatures and in immersed oil conditions prior to being tested on a sub-scale bearing test rig.

Acknowledgements

This study was carried out in the framework of Clean Sky 2 Joint Undertaking under the European Union's Horizon 2020 research and innovation programme. The authors wish to thank the Clean Sky 2 project to fund Integrated Intelligent Bearing Systems for UHPE Ground Test Demo (I^2BS) project.

References

1. Tandon, N. & Choudhury, A. A review of vibration and acoustic measurement methods for the detection of defects in rolling element bearings. *Tribol. Int.* **32,** 469–480 (1999).
2. Qiu, H., Luo, H. & Eklund, N. On-Board Aircraft Engine Bearing Prognostics: Enveloping or FFT Analysis? in *Volume 2: 29th Computers and Information in Engineering Conference, Parts A and B* 1247–1252 (ASME, 2009). doi:10.1115/DETC2009-86141
3. Keong, R. L. C. & Mba, D. Bearing Time-to-Failure Estimation using Spectral Analysis Features. *Struct. Heal. Monit.* **13,** 219–230 (2014).
4. Gousseau, W. & Griffaton, J. Vibration signature evolution of an aircraft engine rotating at low speed with a damaged bearing. in *Surveillance 8, International Conference* (2015).
5. Nishikawa, T., Hayashi, N. & Hayakawa, A. *Technical Trend of Aircraft Bearings, NTN Technical Review*. (Machining Tool/Aerospace Engineering Dept, NTN coorp, 2014).
6. Yang, D.-X. *et al.* Through-Metal-Wall Power Delivery and Data Transmission for Enclosed Sensors: A Review. *Sensors (Basel).* **15,** 31581–605 (2015).
7. Michael L. French, Jason W. Melvin, J. A. T. Bearing with sensor module. (1997).
8. Minoru Sentoku. Sensor-mounted roller bearing apparatus. (2005).
9. *DODGE Smart Bearings*. (2009). doi:http://www.baldor.com/mvc/DownloadCenter/Files/FL302
10. FAG-Schaeffler. FAG Axlebox Bearings with Integrated Sensors in the V250 for HSL-Zuid, Netherlands. Available at: http://www.schaeffler.com/remotemedien/media/_shared_media/08_media_library/01_publications/schaeffler_2/publication/downloads_18/wl_07521_de_en.pdf. (Accessed: 19th April 2017)
11. Aktiebolaget-SKF. SKF launches SKF Insight^{TM}, groundbreaking intelligent bearing technology. (2013). Available at: http://www.skf.com/group/news-and-media/news-search/2013-04-08-skf-launches-skf-insight-groundbreaking-intelligent-bearing-technology.html. (Accessed: 20th March 2017)
12. Saskia Biehl. *Piezoresistive thin-film sensor system in direct rolling contact in*

bearings.
13. McFadden, P. D. & Smith, J. D. Vibration monitoring of rolling element bearings by the high-frequency resonance technique — a review. *Tribol. Int.* **17,** 3–10 (1984).
14. Saruhan, H., Sandemir, S., Çiçek, A. & Uygur, I. Vibration Analysis of Rolling Element Bearings Defects. *J. Appl. Res. Technol.* **12,** 384–395 (2014).
15. Lacey, D. S. J. *An Overview of Bearing Vibration Analysis*.
16. Orhan, S., Aktürk, N. & Çelik, V. Vibration monitoring for defect diagnosis of rolling element bearings as a predictive maintenance tool: Comprehensive case studies. *NDT E Int.* **39,** 293–298 (2006).
17. Marble, S. & Morton, B. P. Predicting the Remaining Life of Propulsion System Bearings. in *2006 IEEE Aerospace Conference* 1–8 (IEEE). doi:10.1109/AERO.2006.1656121
18. Matoux, J.-L. & Thomas, E. W. Elastomeric solutions to seal jet oils at high temperature with fluoroelastomers and perfluoroelastomers. in *Polymers in Defence and Aerospace Applications,Toulouse, France* (2007).
19. Charlotte Adams. Product Focus: COTS Operating Systems: Boarding the Boeing 787 - Avionics. (2005). Available at: http://www.aviationtoday.com/2005/04/01/product-focus-cots-operating-systems-boarding-the-boeing-787/. (Accessed: 4th April 2017)
20. Randall, R. B. & Antoni, J. Rolling element bearing diagnostics—A tutorial. *Mech. Syst. Signal Process.* **25,** 485–520 (2011).
21. Patil, M. S., Mathew, J. & RajendraKumar, P. K. Bearing Signature Analysis as a Medium for Fault Detection: A Review. *J. Tribol.* **130,** 14001 (2008).
22. Shah, D. S. & Patel, V. N. A Review of Dynamic Modeling and Fault Identifications Methods for Rolling Element Bearing. *Procedia Technol.* **14,** 447–456 (2014).
23. Dumont, M., Cook, A. & Kinsley, N. in 61–71 (Springer International Publishing, 2016). doi:10.1007/978-3-319-30249-2_4
24. Zheng, D., Wang, L., Gu, L. & Yuan, Z. High speed rolling bearing cage rotation speed monitoring using optical fiber sensor. in (eds. Zhang, Y., Xiang, L. & To, S.) 84173O (International Society for Optics and Photonics, 2012). doi:10.1117/12.978271
25. Liu, Z., Xu, C., Li, M., Wang, Q. & Liu, H. Study on the rotational speed of bearing cage based on ultrasonic measurement. *Proc. Inst. Mech. Eng. Part K J. Multi-body Dyn.* 146441931769785 (2017). doi:10.1177/1464419317697855