Multi-parameter Fibre Optic Sensing System for Remote Condition and Operation Monitoring of Gearbox Bearings in Rack and Pinion Jacking Systems

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ABSTRACT

In a world where more than ever "time is money", there is a continuous push for new technologies that enable condition and operation monitoring of critical industrial equipment in often inaccessible locations and very harsh environments, thus minimising the need for corrective actions, down-times and at the same time providing better insights about their operation. In this paper, we demonstrate the technical feasibility and the inherent advantages of Fiber Bragg Grating (FBG) based fiber optic systems to remotely sense, in real-time, multiple performance parameters of critical gearbox bearings inside rack and pinion jacking systems.

The bearing condition and operation monitoring system jointly developed by Smart Fibres and SKF includes numerous FBG-based optical sensors to monitor temperature and both dynamic and static strain, which were deployed in various points inside the outer race of the sensing bearing. Smart Fibres' SmartScan 04 FBG interrogator acquired real-time measurements of all the aforementioned parameters, which thanks to SKF's data analysis expertise and its knowledge of bearings and loads were combined and transformed into meaningful insights about the condition and operation of the gearbox's bearing and the jacking system as a whole.

An innovative method to instrument rolling element bearings was put in practice during this project. For the gearbox bearing instrumentation on this jacking system, two FBG arrays, each containing 15 strain sensors and 1 temperature sensor were fixed in a groove machined on the outer race of the bearing's structure. This allowed us to measure real-time temperature, rotational speed and dynamic/static loads at multiple points around the bearing's structure. Not only did this provide a more direct indication of the bearing's condition than conventional strain gauge based load cells, but it also provided valuable information about the alignment and loading of the bearing both in running as well as in stand-still conditions. Some of the intrinsic characteristics of fiber optic sensors make them particularly suitable for this type of application. Complete immunity to electromagnetic interference enabled our sensors

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to conveniently operate very close to electric motors without being affected by currents. Passive sensors and low optical power levels allowed the sensors to operate in hazardous and flammable environments without bulky and expensive shielding. The ability to combine several sensors on a single fiber means that the size and cost of cabling can be minimised and the good signal transmission properties of optical fibers allow the sensors to be interrogated over long distances. The very low profile and high flexibility of optical fibers allowed us to place the sensors inside the bearing and within the jacking system's gearbox, in contrast with previous approaches based on conventional load cells. This combination of multi-parameter real-time remote measurement inside one of the gearbox's bearings permitted SKF to get a much closer look at the rack and pinion system, discovering unforeseen features. This helped to better understand the interactions between different components and obtain a much more precise analysis of the actual behavior, condition & operation of the entire jacking system, leading to a safer and more efficient operation by its user.

INTRODUCTION

Project Partners

- SKF - Is a Swedish leading bearing manufacturing company that produces and supplies bearings, seals, lubrication systems, maintenance & mechatronics products, power transmission products, condition monitoring systems and related services globally.

- SMART FIBRES - Is a UK-based leading producer of FBG-based fiber optic systems for various sensing applications in the aerospace, oil & gas, wind energy, medical, marine and civil engineering industries.

The Sensing Technology – Fiber Bragg Grating (FBG) Sensors and Wavelength Division Multiplexing (WDM) Interrogating Platform

Smart Fibres' fiber optic sensing technology is based on Fiber Bragg Grating (FBG) sensors, each of those with a characteristic Bragg wavelength, which are then connected to a Wavelength Division Multiplexing (WDM) interrogating platform that acquires the sensor readings (wavelength shifts) that are later converted into engineering parameters by specialised software (SmartSoft).

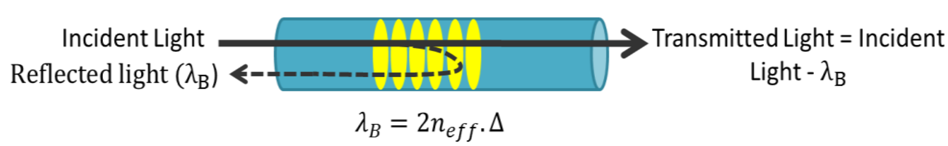

Figure 1. Diagram describing an FBG written inside the core of an optical fiber, including the Bragg wavelength condition.

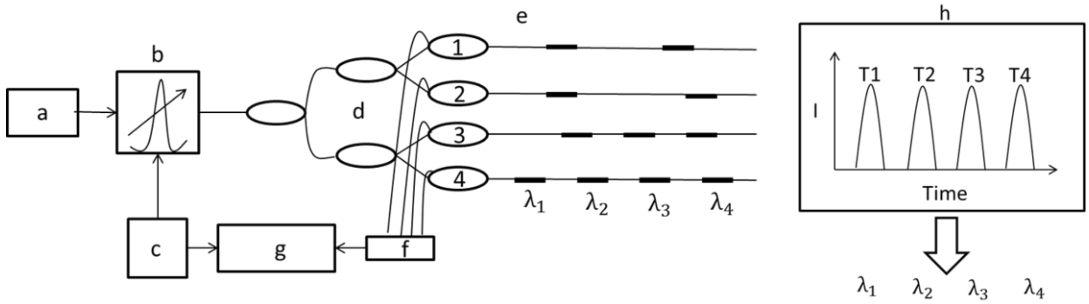

Figure 2. Schematic of a WDM FBG interrogator. Components: a) light source, b) scanning filter, c) scan generator, d) couplers, e) FBG sensor arrays, f) photo-detectors, g) processor, h) example of time varying response of channel 4, showing times Tx converted into Bragg wavelengths. [1].

In the case of this project, two arrays of 16 FBGs, 15 for strain sensing plus 1 FBG for temperature sensing and compensation, were produced and deployed inside a groove on the outer race of the gearbox bearing.

In a WDM interrogating platform, multiple FBG sensors can be placed inside the same optical fiber channel and read out every 400 μs or less, provided that they have a different Bragg wavelength. The Smart Fibres WDM technology is based on a tunable laser that interrogates all the FBG sensors at 2.5 kHz over a 40 nm window on the C-band. The Bragg wavelengths reflected by the sensors are then captured by a series of photo-detectors. The schematic in Figure 2 explains the concept.

The interrogator used for this project was the Smart Fibres' SmartScan 04, which is a highly-dynamic 4 channel interrogator, with a capacity of up to 16 FBG sensors per channel.

Application – Load Sensor Bearings for Rack and Pinion Jacking Systems

SKF delivers sensor bearings to measure load, vibration, speed, position for the shaft and temperature. These sensing bearings are operated in the heart of all rotating equipment and therefore bring crucial operating value. In this article the usage of load sensing bearings for rack and pinion jacking systems is shown. For this specific sensor bearing, SKF and Smart Fibres together integrated 32 Fiber Bragg Grating sensors into one bearing to measure static and dynamic loads on the bearing.

Jacking systems are commonly used to jack-up and jack-down ships, drilling platforms or any other structure which needs to be temporarily fixed on the sea floor, but still must be able to re-locate during its lifetime. The frequency of these jacking operations depends on the specific application. For deploying and maintaining wind turbines, jacking could be needed up to 200 times per year. In contrast, for oil rig operations, the frequency may be reduced to 3 times during the whole lifetime of the structure.

Figure 3. A jacking rig with three “legs” in the application for oil production in the sea. In total 18 or 24 motors per pillar are used for driving [2].

The most commonly used jacking method is rack and pinion, where there are 3,4 or 6 “legs” placed on an application and these “legs” function as the rack, while there will be 18 or even 24 pinions connected to it for driving the platform up and down. Figure 3 shows a total jacking system on a rig with three legs, each leg consisting of 18 racks in combination with 18 pinions to drive platform up and down. In Figure 4, a schematic zoom-in of this rack and pinion combination is shown for one of the legs [3]. The blue parts are the motor gearbox combinations with a pinion at the end of the system. The rack and pinion jacking system is shown in Figure 5, where the fiber optic load sensing bearing has been implemented. The details about the bearing design will be discussed in section 2, but the fiber optic sensing bearing was designed to measure dynamic and static load, temperature and rotational speed.

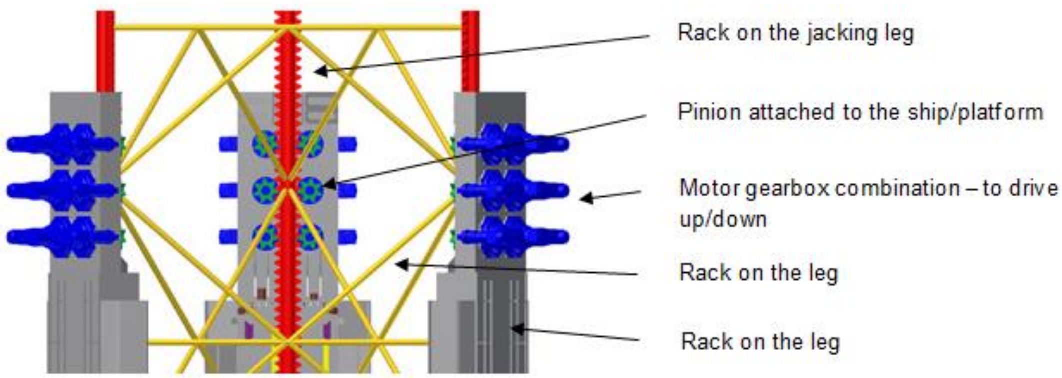

Figure 4: Schematic drawing of one leg of a rack and pinion jacking system.

Figure 5: A typical jacking drive unit, starting with an electro motor, drives a four or three spur gearbox. Indicated by a red circle is the position of the fiber optic sensing bearing for static and dynamic load measuring in the jacking drive units [4].

Benefits – Value of fiber optic bearing sensing for jacking systems

As mentioned on section 1.3, the fiber sensing bearing is used to sense both condition and operation parameters of the bearing. For this application, we will specifically focus on the load. The need to know load both during the jacking up/down and in static conditions is crucial for the operation of jacking systems. When driving, there are multiple reasons to measure load:

- Is the rig/ship well balanced?
- Are all motors connected correctly?
- Do the motors carry the load evenly?
- What is happening with the motor gearbox combination and most importantly what is the condition of the pinion (the "workhorse") of the jacking system?

Normally the electrical motor current is used as a reference to calculate the load, but it is not information taken at the pinion position as there are two gearboxes in between and furthermore, measuring motor current does not work at stand-still. The main reason to measure at stand-still is to have control of the total rig/ship during its operation: either drilling for oil production or when placing or repairing a wind turbine. For example, when the rig is standing on its long legs on the sea bed during operation, the operator needs to make sure that it remains stable during production. The legs touch the sea bed at 100 meters below the surface and they are surrounded by strong currents, creating a very dynamic environment where a leg can sink away due to the unstable nature of the sea bed (i.e. sand can be washed away by the currents). Therefore, for operation safety and stability, the jacking system operators want to control the load on the different legs to make sure that the rig remains stable or to be able to correct things before the entire rig "collapses" into the sea by the sinking of one or more legs. Around 10-15% of these jacking systems "collapse" into the sea during their lifetime, with disastrous consequences such as: months of repair needed, the associated production loss and in the worst cases human casualties. To prevent this from happening, jacking rigs equipment manufacturers and designers are constantly looking for ways to measure the static load on the legs. There are two commonly used ways:

1. Install a strain gauge load cell on the top of the 6 motors, gearbox pinion combinations
2. Install individual strain gauge based load cell at the end of the pinion shaft.

Both solutions have four general disadvantages: they are extremely expensive, have huge corrosion problems (electronics in combination with sea climate) and must be re-calibrated after 1 or 2 years of operation, which is not possible when a system must be 10 years in service at one location. Besides these general disadvantages, the first solution has only the combined measurements of 6 pinions, so the individual problems of the pinions cannot be seen in isolation. The second solution has the problem of being close to the electrical motor, so the stray currents negatively affect the load-cell measurements. To overcome these problems, Smart Fibres and SKF have equipped two prototype bearings for static and dynamic load sensing in a jacking system, where the main advantages of the fiber sensors cover the disadvantages of the more traditional solutions and bring new benefits:

- High integration density of sensors, which means reduced re-calibration needs and higher absolute sensing accuracy for static measurements.
- Optical signal, which means EMI immunity and no stray current problems associated.
- Overall it is a less costly solution than the usage of custom made load-cells as described above.
- With the correct jacketing, no corrosion and hydrogen problems are expected on the optical fiber sensors.

Low profile and high flexibility, which allowed us to access parts of the machinery that are much closer to the loads we are intending to measure and were previously inaccessible for traditional load cells.

The Bearing Instrumentation Process

In a previous project, Smart Fibres and SKF integrated Fiber Bragg Gratings (FBG) inside bearings that were always rotating during the measurement process [7]. An example of that integration is shown in Figure 6 below.

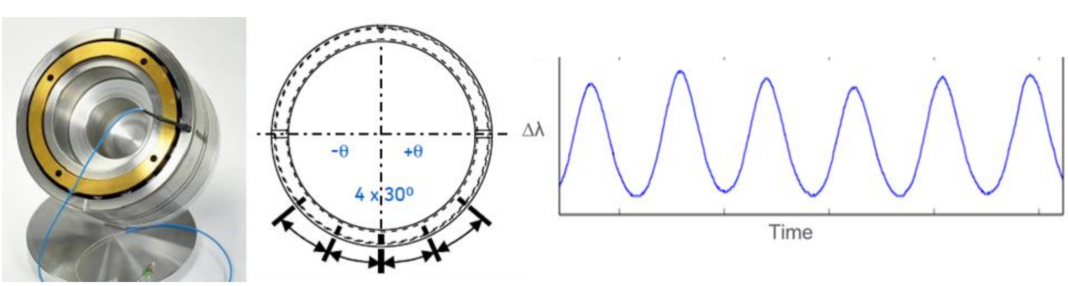

Figure 6. On the left a fiber sensor bearing for subsea applications, in the middle the sensor deployment for that specific bearing and on the right strain signal (wavelength shift) of a single FBG sensor versus time [5][6].

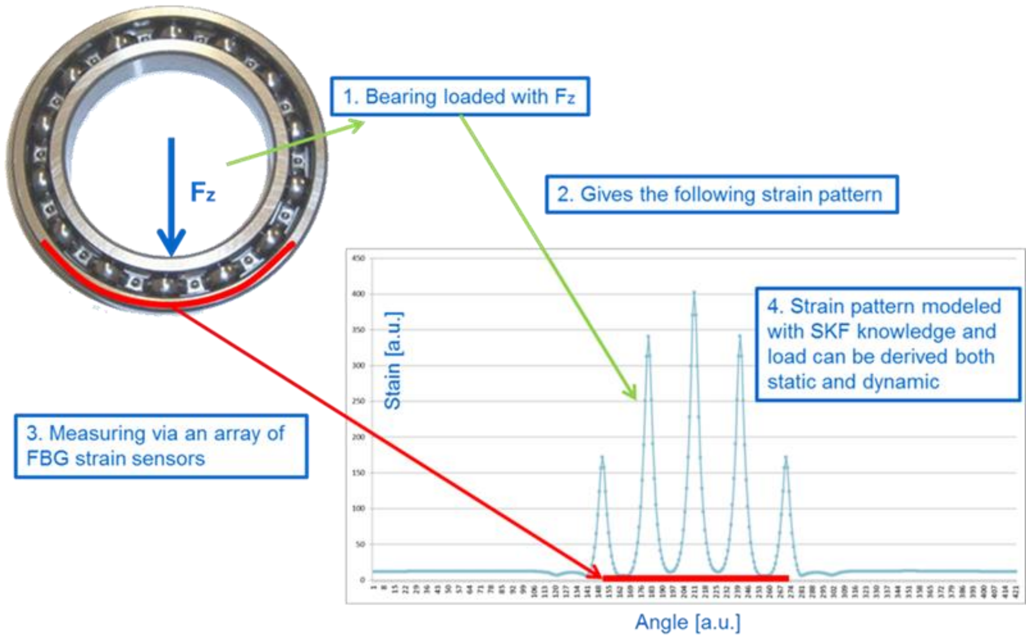

Figure 7. Explanation of how to measure static load on a bearing: A bearing "sees" load Fz (1) via a shaft, this load transfers strain via the inner ring and balls to the outer ring, giving a strain pattern (2) . Then via integrating many FBG sensors in the bearing (3), one is able to re-create the strain pattern by sensing and measuring the static load (4).

The pictures on the left and center show how the FBG sensors were integrated into the bearing and their relative position respectively. The diagram on the right shows the wavelength shift of one specific FBG sensor versus time. Only part of this design approach could be used for the application described on this paper. Since the static load also had to be measured, more sensors were needed. Therefore, the number of FBGs in the bearing had to be increased from 5 in the former application as shown above, to 32 for this project. This can be explained by the fact that there must be so many sensors to "catch" at least 2 rollers for a correct load measurement. This can be explained by the fact that there must be so many sensors to "catch" at least 2 rollers for a correct load measurement. This is explained in Figure 7, if a load is applied to the shaft, the load is transferred via the inner ring towards the bearing balls and so through the outer ring where our sensors are placed (the red line) [6]. The load is always carried by more than one ball and therefore a strain pattern is shown as indicated in Figure 7. To develop a solid absolute load estimate via sensing, this pattern must be recreated with the use of the sensing values of the FBG sensors. Therefore, we measure the wavelength shift and relate this directly to strain and then combining this data from at least 3 to 5 FBG sensors one is able to estimate the absolute static load of the system as wanted by the end customer.

In Figure 5, the location of the fiber sensing bearing is shown. This position was chosen due to practical reasons of integration. This bearing is in the middle of two gearboxes and has a well-defined loaded zone; therefore the sensing part of the bearing is focused on two areas of the bearing. As indicated above, each FBG array was formed by 15 strain sensors, which were FBGs (written on standard telecoms fiber) separated by about 3 mm and directly bonded onto the metal surface of the bearing, and 1 temperature sensor that was also used for temperature compensation on the strain sensors. This temperature sensor was an FBG placed at the tip of the array and encapsulated inside a loose tube probe to ensure complete isolation from strain. The temperature sensor was calibrated to traceable standards before installing the arrays on the bearing. The two arrays were installed inside a groove machined on the outer race of the bearing, each of them covering a section of the bearing's circumference. The optical fiber array was bonded to the bottom of the groove by means of an epoxy glue, which was carefully selected for its mechanical properties (to provide the best bonding to the metallic bearing surface and optimal strain transfer to the FBG strain sensors), rated for the operational temperature conditions and resistant to the mineral oil present inside the gearbox. The groove was then filled with an adequate sealant material to prevent oil ingression. The arrays were later connectorised to a jacketed fiber optic cable which connected the sensors to the SmartScan 04 interrogator and PC, placed outside the jacking system, through an egress fixture purposely built into the bearing.

In Figure 8, details of integration of the FBG sensors on the bearing are shown. Due to the expected temperature and strain range and to prevent overlapping of the reflective peaks from the 40 nm bandwidth of the SmartScan 04 interrogator, the Bragg wavelengths of the 15 strain FBGs sensors and the 1 temperature FBG had to be carefully chosen [1]. Once the instrumentation process was finished, the bearings had to be temperature cycled in the oven, to settle down all the materials and a final performance check was conducted to make sure that all the sensors were working as expected.

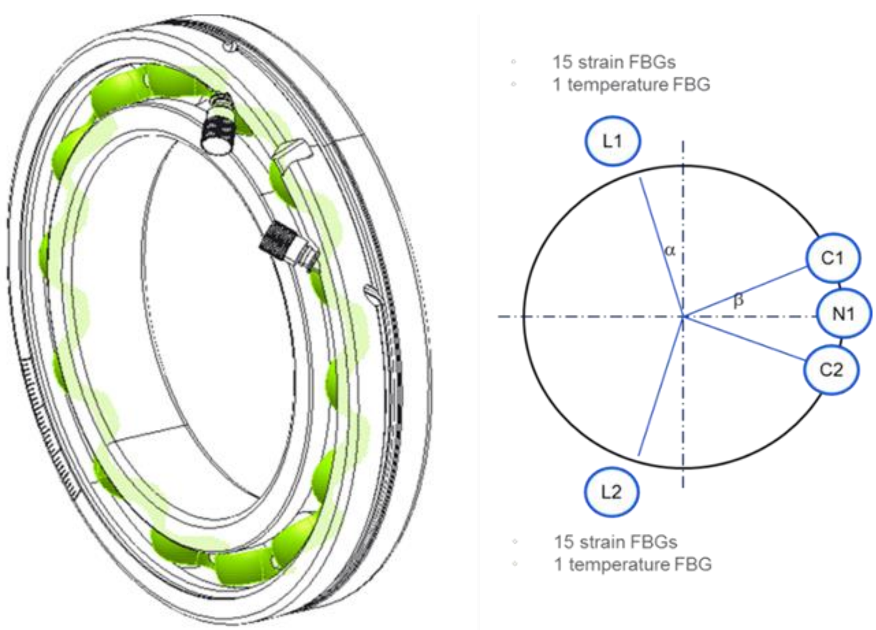

Figure 8. Detailed integration of sensors in the bearing; on the left the connectors shown and how the fiber is positioned via a groove into the bearing outer ring, with on the right the schematic location of the sensor zones (L1, L2), connectors (C1, C2) and fixation notch (N1).

Figure 9: Installation of the fiber sensing bearing in the jacking system gearbox.

The high integration density of the FBG sensors was one of the challenges to overcome during the design and instrumentation phase. The other main challenge was to mount the highly flexible but relatively fragile optical sensing assembly onto the bearing and inside the gearbox. Figure 9 shows how challenging this mounting process was and how close the fibers were to the rotating gears and bearings. Besides this, the gearbox is filled with mineral oil to lubricate the bearings and gears. All of this combined created a very harsh environment to implement and install the optical sensing bearing.

TEST DESCRIPTION

Test Rig Description

To validate the calculated sensing accuracy and to offer a higher level of confidence to the jacking rig OEM, the bearing was installed in a jacking test rig as shown in figure 10. This test rig consists of two motor, gearbox and pinion combinations and can both perform dynamic and static jacking tests. One of the motors is the driving end and makes sure that the rack is moving, whilst the other

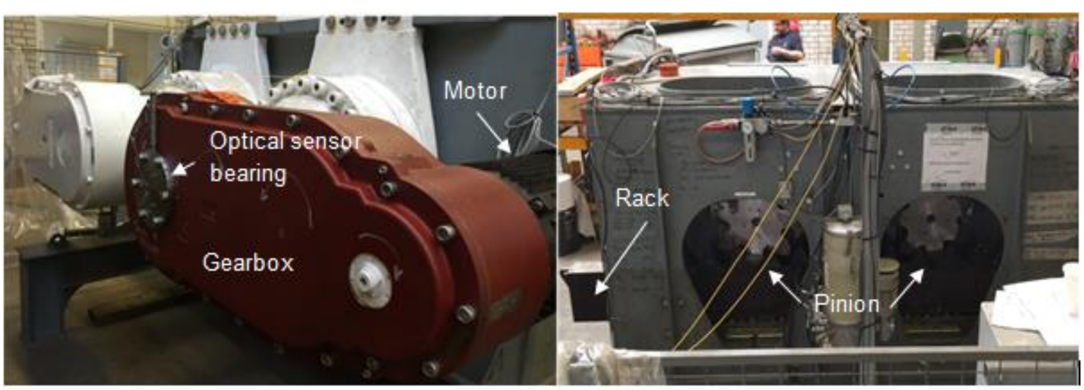

Figure 10. The jacking drive test rig. The picture on the left shows the back of the system, with the gearbox and the motor, which is where the sensing bearing was integrated. On the right it is the front of the system with the rack pinions driving the rack during testing.

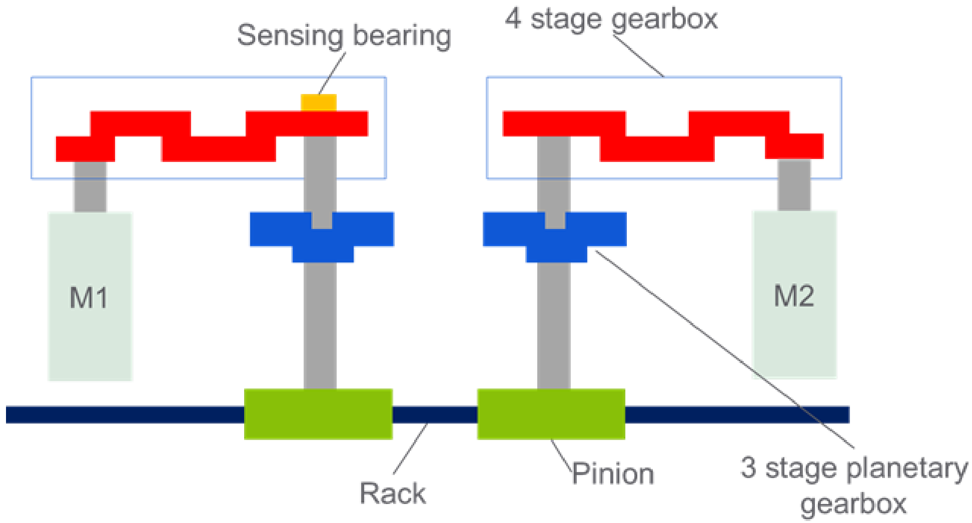

Figure 11: schematic top view of the test rig

motor is used for control purposes to keep the rack within the test rig and to ensure constant speed. Since the bearing was located between the gearboxes, shown in figure 11, the motor current of motor one (M1) was used as a reference and via calculations this was transferred to expected load on the bearing. The fiber optical test bearing was calibrated for both static and dynamic operation at SKF and showed and absolute accuracy of <3% for both static and dynamic loads.

The rig is a slow rotating system, which was also operating for a shorter period of time than in the real application, therefore the focus of the test was solely to determine the absolute load accuracy for static and dynamic bearing load, which relates via a relatively simple calculation to pinion load, the final parameter the jacking system operator wants to know. The main test conditions used are shown in table 1.

TABLE I. LOAD CASES FOR TESTING CORRESPONDING TO A REAL-LIFE JACKING PROJECT

Different load scenarios				
Test Case #	Scenario	Description	Load [kN]	Speed [rpm]
1	Leg handling	Normal leg weight	-3,4	90
2	Leg pulling	Maximum upward load	-14.1	0
3	Normal jacking	Maximum dynamic load	15.3	60
4	Pre load holding	Maximum static load	21.9	0
5	Severe storm	Class requirement	29.2	0
6	Prototype	Test load case	32.9	0

Description of SKF’s data visualisation and data analysis systems

In Figure 12 the total measurement system is shown. It consists of the fiber sensing bearing, the patchcord from the bearing to the interrogator (placed outside the gearbox) and the PC, where the data acquisition occurs via an Ethernet cable and a

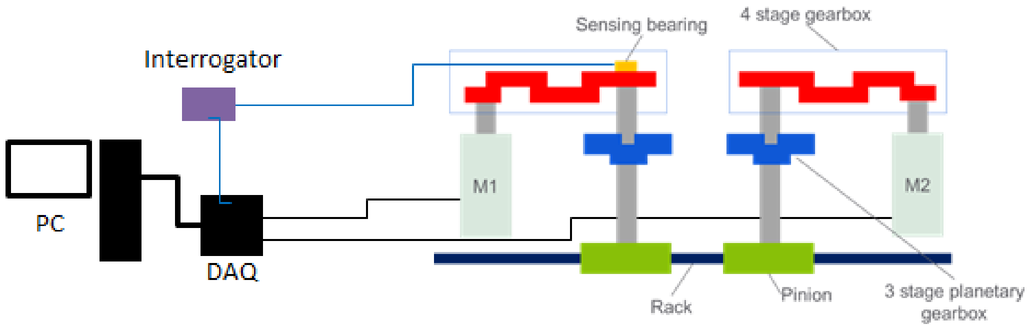

Figure 12. Total test system

software suite performing data storage, processing and visualisation of the data. Besides the fiber sensing bearings, the reference motor currents from both motor 1 and motor 2 are also included in the data acquisition system.

DISCUSSION OF RESULTS

In this chapter both the dynamic and static measurement results are discussed. First the dynamic test results are shown and then the static.

Dynamic testing

During the dynamic testing, the test cases #1 and #3 from table 1 were used during 7 days of testing to determine the absolute load values.

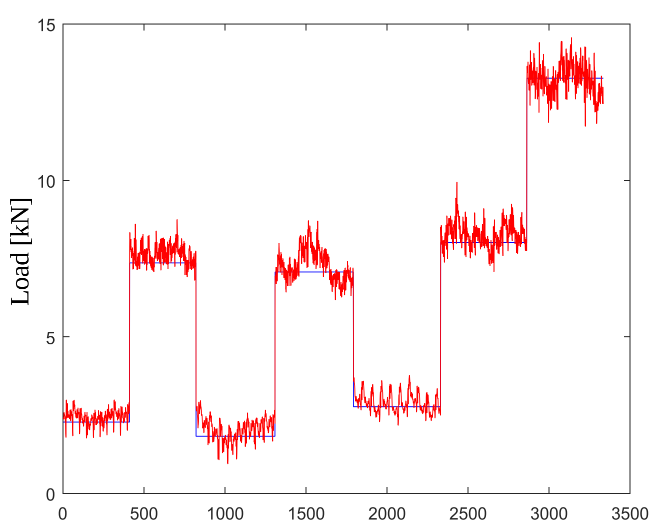

Figure 13: Validation set from result presentation. The blue lines are the used reference values of the dynamic motor one, the measurement noise on these lines is less compared to the red line coming from the fiber optical load sensing bearing.

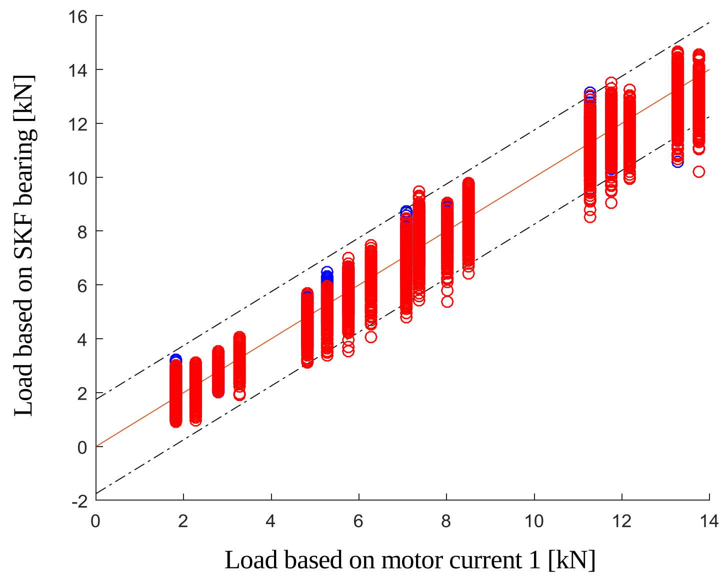

Figure 14. All dynamic measurements in one plot, on the horizontal axis the load on the bearing calculated from the motor current and on the vertical axis the measured load via the optical sensing bearing. The dotted lines indicate a ±5% full scale accuracy.

In Figure 13 an individual load measurement is shown, where applied load is indicated on the horizontal axis and measured load on the vertical. For the applied load, the motor current was used as a reference, while for the measured load the fiber optical sensing bearing load measurements were used.

In Figure 14 all the dynamic results can be seen via the motor current measured load versus the fiber optical sensing bearing load. The variation of the dynamic load compared to the reference load was <4%, which is well within specification for what the customer needs. The measurements were conducted over a period of 6 months and no signs of drift were detected, so no re-calibration was needed during all the testing.

Although the absolute accuracy of the dynamic load sensing bearing is <4%, the motor currents are a more stable measurement for the torque on the motor. Compared to the motor, the bearing is in the middle of the jacking system and gearboxes, which can be regarded as mass-spring systems. Therefore, an investigation was conducted to explain this difference from a total of 50+ measurements collected in Figure 15. The sensing bearing is between motors one and two, and both motor currents are measured, one for driving one for control. In Figure 16 this is shown in a graph, were both motor currents are plotted and the measured load via the optical sensing bearing.

In Figure 15 it is clearly shown that the actual load measured by the bearing does not follow the motor current 1, constantly used as reference, but exactly follows the shape and fluctuations of the load calculated from motor current 2. This motor current has a sinusoidal behavior since it is used as 'control motor' to make sure that the rig remains at a constant speed. Consequently, the control loop of that motor is seen on its current. As expressed the bearing "sees" this control loop in the load measurement as an additional influence, causing a repeatable fluctuation on the constant load it captures from motor one. The graph of the measured load is, for clarity reasons, placed on top of the motor current graph, so the absolute fluctuations are not as large in reality as in the figure.

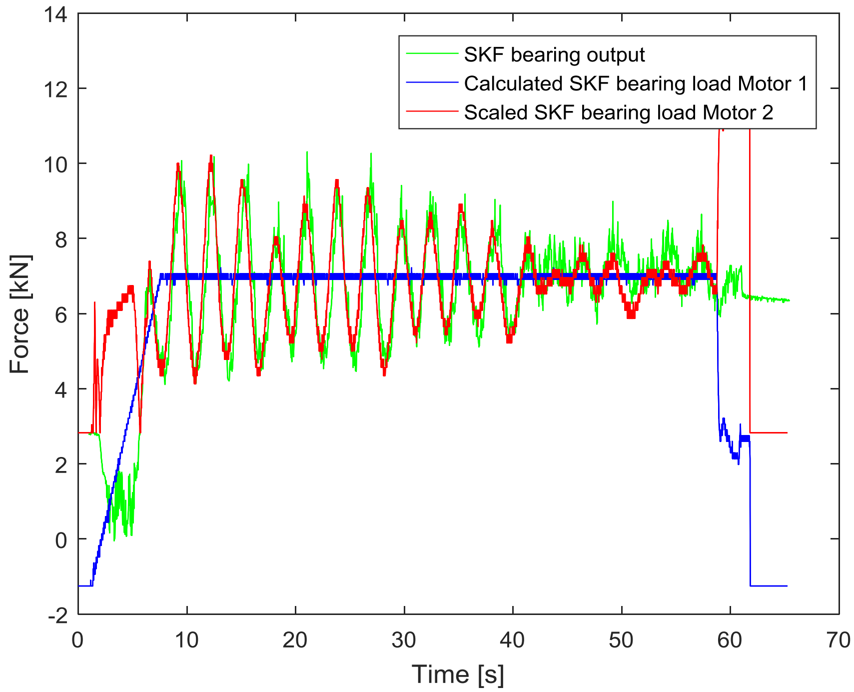

Figure 15: The load measured by the sensing bearing (green) compared to the calculated motor current from motor 1 (blue) and scaled calculated motor current from motor 2 (red).

It can be concluded that, although reaching an absolute dynamic measurement accuracy of <4% full scale, the sensing bearing captures all the stimulus generated by the entire system. This effect was unknown for the jacking system OEM and gave them valuable insights into their design and operation. Therefore, measuring at the bearing gives more insights on the total dynamic behavior of the system and for this application brings crucial knowledge on the pinion, the crucial part of the jacking system, and friction of the pinion/rack combination.

Static testing

The main objective of the mutual test campaign was to determine the absolute static load accuracy. For this purpose, the motors as shown in figure 10 were replaced by static load cells with manual driving, to enable precise and exact driving of static load on the pinion, with the bearing still in between the gearboxes. In Figure 16 a measurement of 1900 seconds is shown with static load on the pinion. The blue line is the calculated bearing load based on the load cell measurement at the position if motor 1. The red line is the measured load via the optical sensor bearing in the loaded zone and the yellow line is the load measured based on strain in the non-loaded zone. The measured load following the expected load from the calculation except for the exact steps height, it seems there is a hysteresis effect in either the optical sensing system or in the complete jacking system. Another interesting effect is the yellow line, which shows a reduction of load in a non-loaded area of the bearing. This effect should not be there, but can be explained by the fact that we base the load measurement on the deformation or strain of an outer ring.

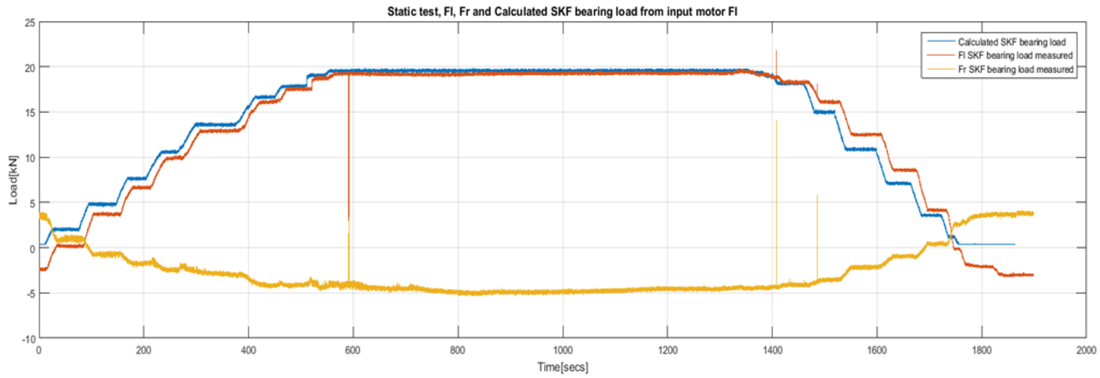

Figure 16: A 1900 second static measurement, where the blue link is the theoretical calculated load, the red line the measured static load by the optical sensor bearing and the yellow line the load on a non-loaded location of the bearing indicating there was a global bearing deformation happening at this test, influencing the measurement accuracy.

Therefore, the outer ring is becoming more of an “egg” shape, known to happen at high load and loose fit, and then this is seen back in the load signal. This represents another lesson learned from this testing exercise; to implement sensors around the bearing to map the total deformation of the bearing; another important parameter for designing and learning more about the system.

Figure 17 shows the entire static load testing measurements combined into one graph, depicting one week of continuous testing and all the associated results. All the green points are measurements from that week and the dotted lines are ±10% error lines, showing that the absolute values are not within ±10% accuracy of the calculated load. There are multiple causes for this and from a sensing perspective, it makes sense to measure the complete outer ring with sensors to compensate for general ring deformations in a loose fit application. Furthermore, the calculated load is without friction and jacking system deformation and looking at Figure 16, there are hints that the system shows signs of hysteresis. The data demonstrates that when measuring load at the bearing, only possible via FBG sensors, new insights about the bearing’s and complete system’s behavior are found. Although the ~10% absolute accuracy is large, it is still sufficient for the jacking application, since the end customer is more interested in the relative load change: is a leg “sinking/falling” or not. These relative load changes are in the order of 10 or even 100 times the normal load, making the optical sensing bearing well suited to be used as a control input for the operation of the jacking applications.

CONCLUSSIONS

In this document the integration of two FBG arrays, consisting of 16 sensors each, into a gearbox bearing was explained. These fiber optical sensing bearings are used for dynamic and static load measuring of rack and pinion Jacking systems. Jacking systems are used to fix construction platform or oil rig in waters with a depth of maximum 200 meters as shown in Figure 3. Measuring load, both dynamic and static, is crucial for the safety and operation of these jacking systems. In total 10-15% of

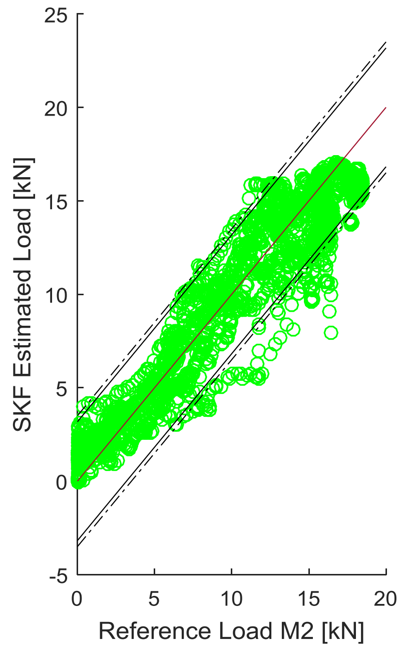

Figure 17: The results of a week testing with on the horizontal axis the calculated reference load and on the vertical axis. The dotted lines are ± 10% error lines and the green points are all the measurement data.

these systems will "fall" and get seriously damaged at least once during their 20 years' operating lifetime.

The goal to implement FBG sensors into bearings for this application was to determine whether the fiber sensing technology could be used for this application. Until now, no satisfactory solutions existed, which could perform these crucial operating parameter measurements without showing problems such as electromagnetic interference, high cost, corrosion or need for re-calibration. These disadvantages can now be overcome using optical FBG sensors. By integrating these FBG sensors into the bearing, Smart Fibres and SKF have created a unique system. These sensors can maximize production time, safety and predictability of the complete jacking units including the legs with the rack for a lower cost than the current conventional load cells.

Two prototypes of the described fiber optical sensor bearings were tested in a jacking test rig, shown in Figures 9 and 10. Weeks of testing were required to determine both the accuracy of the dynamic load on the bearing in the rig compared to the reference motor current, and the static load of the bearing compared to a load cell. In table 2 the absolute accuracies are shown for these measurements, indicating that dynamic accuracy is <4% and static load accuracy is ~10%, with a load sensing range from -35 kN to 35 kN. The period of testing was about 6 months in total and no re-calibration was needed to maintain the aforementioned accuracy levels, suggesting the possibility of a stable load measurement system with no need for recalibration.

The relatively high inaccuracies, compared to the calibrated value of 3%, are explained by the fact that more effects are observed on the test rig than the theoretical calculations indicate. Examples of that are: friction, fit difference, deformations and other effects.

TABLE II. COLLECTED ACCURACY RESULTS OF BOTH STATIC AND DYNAMIC TESTING CAMPAIGN ON THE JACKING SYSTEM TEST RIG

Load situation	CI 95% [%] (100%=35kN)	CI 95% [kN]
Static	10 %	+-3.5 kN
Dynamic	3.7%	+-1.3 kN

During the static testing, hysteresis of the system is shown; the deformation of gears and bearing outer ring are elements that influence the absolute load measurement. During dynamic testing, the behavior of the control loop of motor two has huge influence on the measured bearing load. Signs of rack and pinion friction moment are also shown in the bearing load dynamic measurements. These effects contribute to relatively lower measurement accuracy, but on the other hand, they also show that this new sensing methodology provides insights into the dynamic behavior of the total jacking system, which can be simulated as a mass-spring system. This is the first time that both SKF and the jacking system OEM have seen this high fluctuating load behavior. These fluctuations have huge influence on the condition and lifetime of both the bearings [9] and the complete jacking system.

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8. Alten seminar 2016 – Sensing the bearing – H. van Genuchten
9. RBC 6000 – SKF bearing catalogue - SKF