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# FIBER OPTICAL SENSING OF BEARING PERFORMANCE AND PUMP CONDITIONS

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## ABSTRACT

Fiber optical sensing (FOS) is an emerging alternative technology for monitoring pumps, compressors and other rotary machinery, and their processes. This can be done with optical sensors that are external attached to the equipment, integrated into the equipment or inserted into parts of the equipment (for example the bearings). The sensing is done in either precise single or multiple points in the optical fiber or by using the complete fiber as a continuous sensor. These methods are insensitive to electric and magnetic fields, and can transmit signals over very long distances, several of them are intrinsically safe. The methods applied are highly sensitive to strain, temperature, angular or distance changes. FOS is therefore an ideal technology to apply in oil & gas installations, as for example included in many static applications today e.g. for down-hole, pipeline and structural monitoring. In addition, FOS is becoming available as a technology for monitoring rotating equipment such as pumps, gear trains and screw compressors. Fiber optical load and temperature monitoring of rolling and hydrodynamic bearings is expected to be generally available in the near future in combination with temperature and pressure monitoring of the processes. This combination of optical sensing will enable monitoring of pumps and compressors and utilizing the data for process equipment optimization (PEO) by interacting with variable speed drives (VSD) and process settings. In this way a third new online proactive method of monitoring compared to the traditional reactive and predictive methods is added:

- Reactive: Instant protection of single equipment at occurring failure;
- Predictive: Broad avoidance of instant failures by monitoring of early signs of coming failures; and
- Proactive: Process Equipment Optimization that may give significant reduction in operating expenses (OPEX) by tuning the equipment to work under optimized conditions and by so avoiding the failure causing conditions.

For example a significant reduction in OPEX due to 20-50% lower energy consumption and much improved mean time between

repair (MTBR) are anticipated. The MTBR reduction is expected to come from tuning the equipment, e.g. pump, compressor or motor, to work under known and favorable mechanical conditions. This should ensure higher reliability and availability of an installation. In addition, fiber optical sensing is potentially very favorable from capital expenditure cost (CAPEX) due to anticipated lower installation costs (especially in cabling) and equipment costs for use in: explosive atmospheres (EX), magnetic and electric fields, submerged or enclosed areas.

## INTRODUCTION: LOAD MONITORING OF BEARINGS

The occurrences and shapes of stress fields within rolling bearings was first determined by using an optical method that visualized photo-elastic stress patterns from transparent bearing models being under loads as seen in Figure 1 (Münnich et al, 1968). These visualizations could then be used to see the influence on bearing and housing designs, shaft and housing fits, and load cases. However, at that time it was difficult to translate the knowledge of these optically established stress fields into a method to monitoring loads on bearings in real process equipment and in real installations.

Instead, the later established shock pulse method, it was developed by Yhland and Johansson (1970) and further refined by Botö (1976), did become extremely popular for detecting early bearing failures and monitor them to failure. The method used sensitive vibration sensors of piezoelectric type that were coming commonly available. The shock pulse method has within the process industries, after further developments, become a very versatile tool to catch failing bearings and other parts before a catastrophic failure occurs.

Load measurements through the rolling bearings have been slow to take-off as an enhancement to the shock pulse method. Strain gauges, being the obvious first solution, have been applied in several manners for example on external bearings surfaces, within housings and on measurement plates. They have also been inserted within bearing rollers with wireless transmission of the strain signals to an external receiver (Bankeström, 1994). These methods are mainly applied in verification of designs (rollers with strain gauges) or in processes where ample space are available (housing or measurement plates with strain gauges) and temperatures are stable. The cost of a system in these cases are also of less importance.

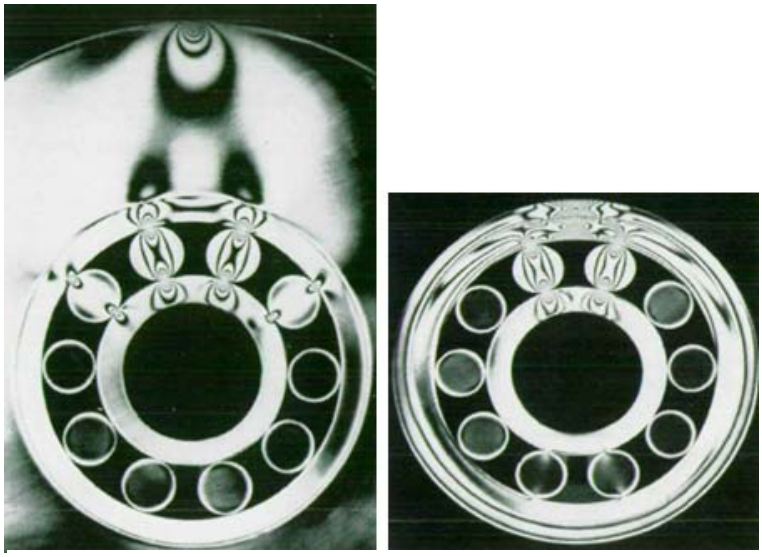

*Figure 1. Photoelastic stress patterns of a roller bearing in thick (left) vs. thin (right) circular housings (Münnich et al, 1968). Note the change from 4 to 2 load carrying rollers within the loaded zone.*

For rolling bearings, a new commercial development is the recent introduction of equipment using surface acoustic waves (SAW) technology (SAW, 2012). Vibrations are generated by a transmitting probe into the outer ring of the bearings and reflected waves are picked up by a separate receiving probe. This technology has been applied to estimate the axial load seen by single row angular contact ball bearings (ACBBs) in pumps (Meisenbach, 2016). The SAW equipment estimates the axial force acting on an ACBB by measuring the operating speed of the ball set (cage speed) in comparison with the real speed of the shaft. These two speeds enable an estimation of the operating contact angle of an ACBB and is then compared with the free contact angle i.e. the bearing contact angle seen at no load, in a calculation giving the bearing speed ratio. SAW equipment has, by using the bearing speed ratio method, been applied in commissioning and monitoring of multi stage pumps to establish the load direction and magnitude of the axial forces acting on pairs of angular contact ball bearings.

The bearing speed ratio method has earlier been applied by Phillips (1979) with optical sensing probes. It was used to investigate the variation in bearing loads vs. lubrication with oil and greases. The study by Phillips gave a good agreement under normal bearing

conditions between speed measurements that calculated the axial load vs. actual applied pure axial load and oil lubrication. However, if skidding was encountered within the bearing the calculated axial load vs. the real applied axial load was shown to give large discrepancies from the bearing speed ratio vs. load curve.

In addition fiber optical sensors have been applied to get static and dynamic bearing load measurements on hydrodynamic bearings by incorporating these in tilting pads of the bearings (Perez and Ibanez, 2001). However, this technology is, as far as known by the authors, not yet widely applied in the monitoring of hydrodynamic bearings. The optical monitoring track of bearings has later been followed by Hoffman et al (2007) and Reedman and Yang (2009) that developed methods using optical strain gauges (fiber Bragg gratings). These where directly attached to the outer ring of a roller bearing by Hoffman et al (2007) and enabled monitoring of both vibrations and load in a test rig of a gearbox. The Reedman and Yang (2009) work enhanced the sensitivity and simplified the mounting of them by using grooves with a slit for the fibers. This enables the reading of distinctive load (strain) signals created by a single roller but also using signals from several rollers to reconstruct the loaded zone within the bearing. It gives a method to estimate the total load on the complete rolling bearing. Additional retrieved bearing information was outer ring temperature in one position, rotational speed and direction, damage signals, etc (Feenstra and den Haak, 2012).

## INTRODUCTION: FIBER OPTIC SENSORS IN PUMPING

A few earlier studies using FOS on bearings and pumps have been published. For example Phillips (1979) used multiple optical fiber probes to measure speed variations in bearings for pumps and later Phillips (1987) applied an enhanced probe version of the technology to make vibration analysis on rolling bearings. In the two papers Phillips does not describe the optical technology in detail but it seems clear that a Fiber-Fabry Perot Interferometer (FFPI) cavity probe was used as the measurement principle (Figure 2). The later enhanced design avoided reflection issues coming from fretting damage on the outer ring and lube oil contamination by applying an enclosed cavity within the tip of the probe. The light was reflected within the probe and by this design it avoided the disturbances seen from variable reflections on the outer ring. The focus in this case was on performing vibration measurements.

A third paper, by Conkey et al (2003), showed an additional development of FFPI probes by measuring within a cavity of the housing for the rolling bearing. A thin wall in the housing separated the outer ring of the bearing from the end of the probes. In this paper, FFPI probes were inserted, one in the area with the highest expected loaded and the second in the low loaded zone. This enabled detection of load patterns created by the bearing in the housing. For example it was demonstrated that, by applying a slow rotation under load, load information could be gathered from the load effects coming from interference fits, the rotor dead load, misalignments, pre-loads from the drive, and load variations caused by installation issues and belt load changes. In summary the three different FFPI probe

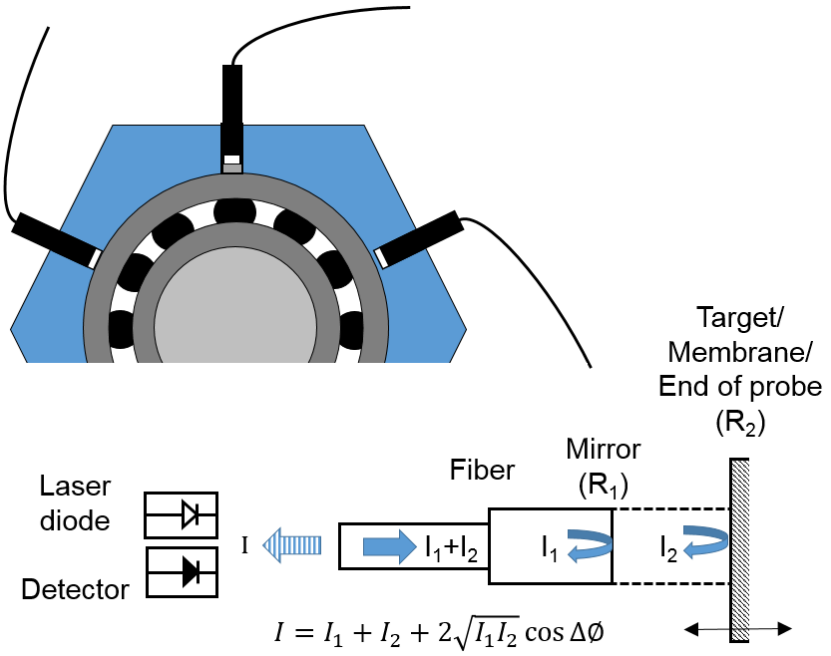


*Figure 2. Three method to apply FFPI probes on a bearing. Top left: Cavity with measurement direct on bearing surface (Phillips, 1979). Top middle: Cavity in closed probe (internal measurement in the probe) with direct contact on the surface (Phillips, 1987). Top right: Measurement in closed cavity in the bearing housing (Conkey et al 2003). Bottom: The optical behavior of a FFPI cavity created by two mirrors $R_1$ and $R_2$ (after Sathitanon and Pullteap, 2007).*

designs for measuring bearing vibrations, speeds and loads are shown in Figure 2.

For pumps in general FFPI cavity sensors have been applied as pressure probes and been demonstrated as a method to detect cavitation by Perez et al (1998). In this case the FFPI sensors were applied at the inlet and outlet of a centrifugal pump. It was possible to detect occurrences of pressure spikes at different pumping conditions both at suction and discharge. For example, high frequency pressure spikes from vapor bubble implosions in the suction part of the impeller were detectable by the FFPI sensors up to $NPSH_A/NPSH_R = 2$. Pressure spikes were also detected at flows 50% below the best efficiency point (BEP), due to internal re-circulation and suboptimal flow distributions in the impeller and casing. To our knowledge, there has not been any in-depth analysis done on what can be achieved with FOS and the frequencies required to monitor for example cavitation, surge and stall. However, it can be expected to require a broad sensing window from single Hz, to half the blade passing frequency and up to 1 MHz (Cudina, 2003) depending on FOS method applied and type physical parameter measured. It is known that cavitation is typically present in centrifugal pumps up to $NPSH_A/NPSH_R = 5$ to 6.

The design of an almost complete fiber optical network structure for a smart pumping system has recently been demonstrated in the development of a large twin screw sub-sea pump system (Williams et a, 2010a and Williams, 2010b). In this case a fiber optical system, utilizing fiber Bragg grating (FBG) technology, was applied to monitoring the 3.5 MW electric motor of the pump and the 90,000 barrels (10400 $m^3$) per day screw pump as described by Staveley (2011) and Feenstra and den Haak (2012). The pump was designed to give a 2400 psi (16.5 MPa) differential pressure and enable the pumping oil viscosities ranging from 2 to 2,000 cP.

The radial bearings in such a screw pump see various combinations of high and low loads at high and low speeds. It was therefore decided to design and develop a special toroidal roller bearing and integrate FBG strain and temperature sensing within these bearings as described by Kahlman (2011) and seen in Figure 3. The bearing was manufactured in a special corrosion, fatigue and stress cracking resistant bearing steel, as reviewed by Kahlman (2016), and equipped with optical fibers that had well defined and integrated FBG sensor positions. These were located in two parallel grooves (2 grooves x 5 measure points) of the outer ring plus a single point for the actual operating temperature of the bearing. This made it possible to measure strain cycles from individual over rolling rollers in multiple measuring points in one fiber and to distinguish between misalignment and loads. The distance between the sensors in the pump and the analyzing instruments (FBG interrogator etc.) was at a length of 6.2 miles (10 km) through fibers on a coil.

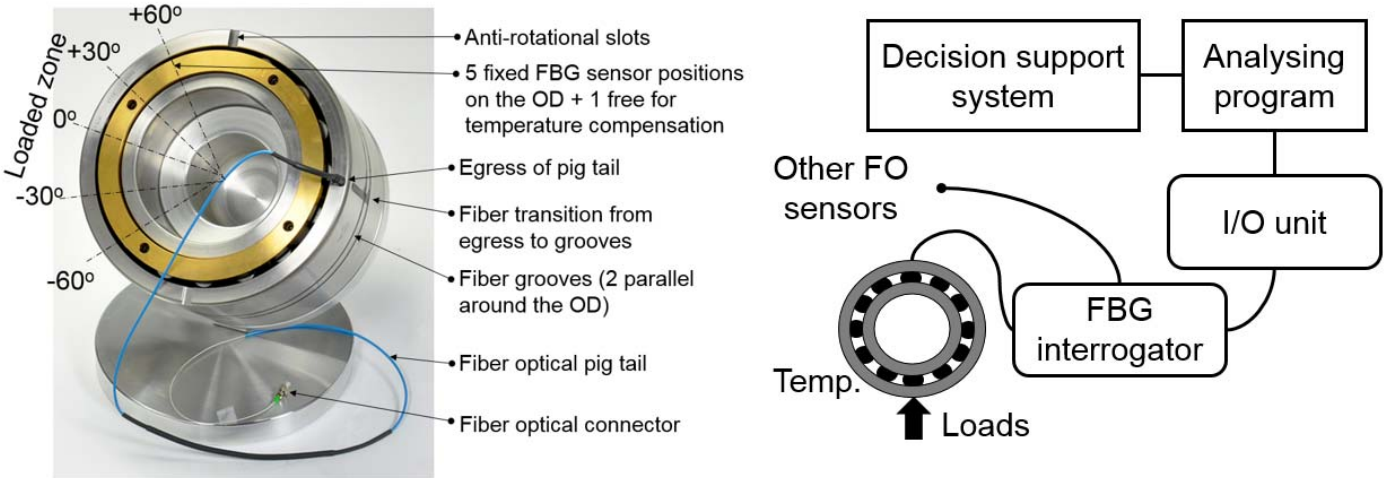


*Figure 3. Left: A toroidal roller bearing (CARB®) with a bore size of 160 mm (6.3"), for a sub-sea screw pump, fitted with fiber optical monitoring for radial load measurements. Right: A schematic of the architecture of the complete FOS system.*

The distinct load signature of each bearing, in fact each bearing roller, and the loaded zone were established (Figure 4) and pure radial bearing loads could be measured within an accuracy of about 5% by calibrating the bearings before mounting. The load measurements showed very high repeatability. Thus, it was possible to detect an 0.8 tenth (2 micron) wide and deep scratch parallel with the length of the roller by either strain enveloping (Figure 5) or by analyzing the load signature from each individual roller. The length of the

scratch was about 1 inch (2.5 cm) on one side of a single roller. The rotational speed on the bearings was derived through the strain pulses seen at the FBG positions and compared to the known tachometer speed in the pump string test rig with high accuracy as seen in Figure 6. In addition to the sensing within the bearings the temperatures of motor windings, oil system pressures and overall vibration levels of the housings were measured by FBG sensing.

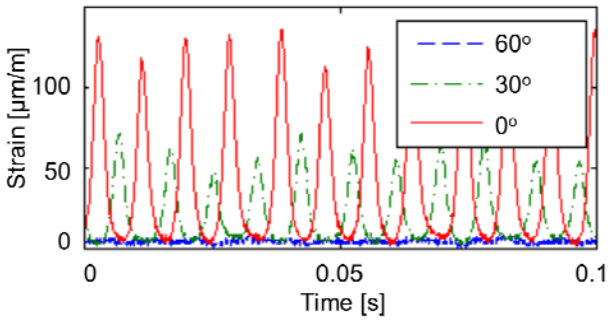


*Figure 4. Load peaks from 3 different FBG sensor positions within the loaded zone of a toroidal roller bearing tested in a pilot test of a sub-sea screw pump (Feenstra and den Haak, 2012).*

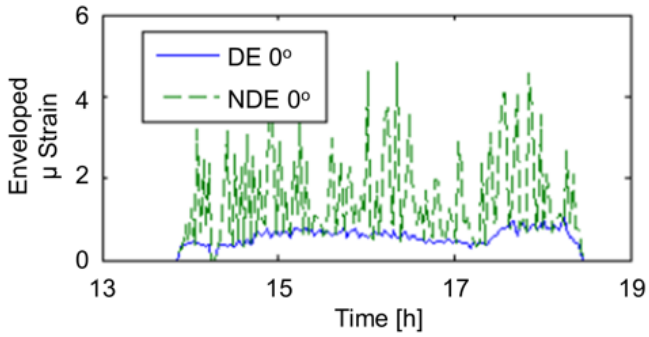


*Figure 5. A comparison of the enveloped FBG strain signals from the same toroidal bearing design in two different positions on the same shaft: drive-end (DE) and none drive-end (NDE). The NDE bearing showed peaked enveloped strain signals due to a small scratch on one side of one roller (Feenstra and den Haak, 2012).*

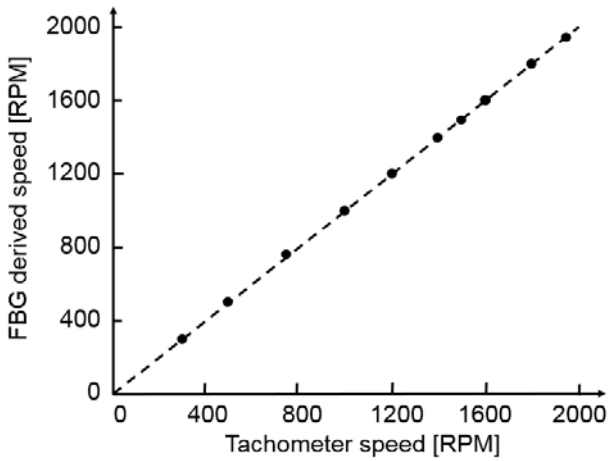


*Figure 6. Conventional measured tachometer speed vs. FBG derived in speed.*

## INTRODUCTION: FIBER OPTICAL SENSING METHODS & NETWORK

As reviewed in the previous chapter several different types of fiber optical sensor technologies can be applied in the monitoring of pumps, compressors and other rotary machinery. In Table 1 the fiber optical methods are divided into a few groups with some common characteristic that can act as a guide to the available technologies (e.g. Culshaw, 2000). However, it should be emphasized that this is a large field with many sub-technologies so the overview is only a highlight. The focus is on technologies that are judged to be relevant for PEO of rotary machinery and being mature.

*Table 1. FOS methods with potential for rotary machinery.*

| Typical name | Physical parameter measured | Sensor location | Physical effect | Decade |
|---|---|---|---|---|
| Fotonic | Proximity | Fiber tip | Intensity | 60s |
| Sagnac effect | Gyroscopic / Angle velocity | Fiber coil | Interferometry / Phase | 70s |
| Fabry Perot cavity | Proximity / Vibration [1] | Fiber tip or single fiber point | Interferometry | 80s |
| Brillouin (acoustic) & Raman (temp.) scatter | Acoustic & Temperature | Distributed along fiber | Time-domain reflectometer (scatter) | 80s |
| Faraday rotation | DC current | Fiber coil | Phase shift | 70-90s |
| Fiber Bragg grating | Strain (stress & Temperature) [2] | Multi points in fiber | Shift of reflected wave length | 80/90s |

[1] Also used for pressure measurement via movement of membranes.
[2] Also used for multitude of other parameters such as pressure, vibrations, chemical compositions etc. by transferring a physical parameter to strain.

*Fotonic Based Proximity Sensors*

Fotonic sensor (bifurcated fiber bundles), or intensity modulated systems, is originally based on the principle that you are sending light through an emitting bundle of fibers to a surface that reflect this light back. The intensity of the reflection is picked up by a receiving bundle of fibers and gives a measurement of the proximity to the reflecting surface. Two receiving fiber bundles are applied, as shown in Figure 7, to compensate for changes in the reflectivity of the target. Further developments, of this old technology, have led to applications today that apply a few single fibers combined with a high intensity light emitted by a diode. The fotonic sensor has the capability to get a resolution in the 0.0005" (micro meter) range (Culshaw, 2000).

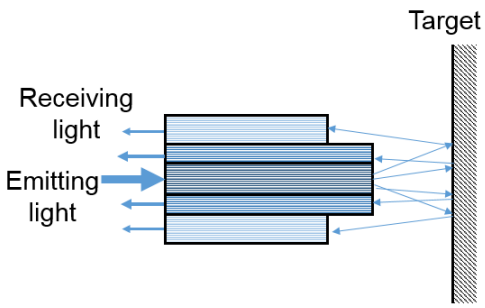


*Figure 7. The principle of a fotonic sensor that measure the proximity of a target by measuring the intensity of the reflection, and the difference in intensity for two receiving fiber bundles.*

*Fiber Optic Gyroscopic (FOG) Sensors – The Sagnac Effect*

An optical gyro is created by using a laser source that inserts light in both ends at the same point of a long fiber that is coiled up in a number of loops. In this way the so-called Sagnac effect (phase / interferometry effect) can be used to measure the angular velocity of the coil's rotating moment. The light is inserted by the use of a beam splitter. The beam splitter will separate the light beams before being inserted and after traveling through the single fiber in two directions it will reunite them. This is where one light beam will travel longer through the glass fiber, than the other light beam, and will get a different phase shift if the refractive index is different from one. These sensors are some of the most sensitive and accurate ones available. It is possible to just increase the length of the fiber to get a better resolution. This has led to the use in some cases of many miles (kilometers) of optical fibers. However, much shorter fiber lengths can be used if the requirement of the accuracy is lower. This type

of sensor is commonly applied to create highly accurate gyros etc. But it has also been suggested, e.g. by Siraky (2010), to be used in rotary machinery as a highly accurate sensor for encoders. This is suggested to be achieved by winding the optical fiber coil around the end of the shaft. A laser injects light into the coil through the end of the shaft and by using a receiving device on the shaft that splits the light into two beams it will travel in opposite direction in the fiber coil on the shaft.

*Interferometry Based proximity Point Sensors – Fiber-Fabry Perot Interferometer (FFPI)*

Optical fiber interferometry is seen as a very sensitive sensor technology and can be used, for example, to measure with single mode fibers (e.g. Islam et al, 2014):

- The strain within a fiber in a single point,
- Measuring the distance to a free surface at the end of the fiber, or
- The vibrations of a fixed surface.

These measurements are done by creating a FFPI cavity, created by two mirror locations, that reflect back the light from a laser diode. An internal single point fiber cavity (intrinsic FFPI) is created by two closely located dielectric mirrors. The more common alternatively, as seen in Figure 2, is to use the end of the fiber (extrinsic FFPI) with reflections from a mirror at the fiber-end and from an external mirror surface. One example of use is that the fiber-end proximity measurement is used to measure the distance to a mirror attached to a pressure membrane. This enable the creation of small optical pressure probes. FFPI works by that the reflected intensities from the two mirrors and the number of fringes in a period of time can be related to a displacement value as described by Sathitanon and Pullteap (2007). They reported an accuracy in the steps of 755 nm, depending on interference fringes created, with a measurement range from 0.0005” to 0.0038” (1.2 to 96 micron).

*Distributed Acoustic & Temperature Sensing – Brillouin & Raman Scatter*

Distributed sensing by Optical Time Domain Reflectometer (OTDR) is a technique which is distinctive to fiber optics (Culshaw, 2000) and is extensively used to characterize and troubleshoot optical fiber networks. It is based on that a forward traveling light beam can interact within a fiber seeing a physical parameter field and create returned scatters continually along the fiber (Figure 8). Scattering sites are microscopic variations in density, composition or structure of the glass fiber material. Typically, the physical fields sensed are temperature (DTS – Distributed Temperature Sensing) or strain (DAS – Distributed Acoustic Sensing). A time-domain reflectometer that enables distributed sensing relies upon sensing these backscatters and sensing the traveled time of the light pulse. The three backscattering processes are Rayleigh, Brillouin (B-OTDR) & Raman (R-OTDR) scatters with the last two being the most commonly used. This is in spite of the fact that the Rayleigh scatter gives the highest signal. If a laser with high linewidth, e.g. 50 kHz, is applied the Brillouin and Raman scatters will reflect at broad linewidths but the Rayleigh one only at a narrow linewidth (Bao and Chen, 2012). This makes integration of the intensities possible for Brillouin and Raman scatters but not for the Rayleigh scatter. The acoustic sensing coming from the Brillouin scatter is an offset frequency spectrum related directly to the phonon spectrum in the fiber. The temperature sensing coming from Raman scatter that probes the optical phonon spectrum. The B-OTDR and R-OTDR methods enable reading in fiber on tens of miles (tens of kilometers distance) with a possibility to locate the measurement within about 1.3 to 3.3 feet (0.4 to 1 meter). For B-OTDR the reported accuracies are in DAS mode about 0.0024” (60 µm) strain and in DTS mode about 3.5-5.5 $^{o}$F (2-3$^{o}$C) and for R-OTDR in DTS mode about 1.5 $^{o}$F (0.8 $^{o}$C). Thus making a combination of these methods popular for surveying and protecting oil & gas wells, pipelines, power cables, sewage pipes etc.

*Faraday Rotation – Current Measurements*

It is a bit surprisingly, for us outside optics, that it is possible to measure currents (via magnetic fields) and voltage (via electric fields) by fiber optics (Culshaw, 2000). The principle of how to design a magnetic field measurement device using a fiber optical coil was outlined by Day et al (1982). It uses the Faraday rotation, a magneto-optical phenomenon, that showed light being related to electro-magnetism. The method has been perceived as a precision measurement method for currents in high voltage installations and is today used in actual products on the market (Brändle and Stierlin, 1990).

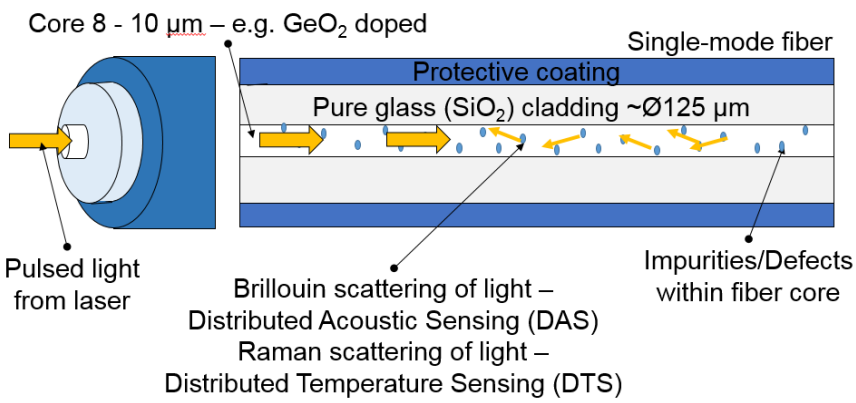


*Figure 8. Fiber optical sensing by DAS and DTS.*

*Multi Point Strain Sensing – Fiber Bragg Grating (FBG) Sensors*

The FBG method, as described by Hill and Meltz (1997) and invented by Hill in 1978, utilize the precise reflective effect of a grating etched, normally done with an excimer (UV) laser, into a fiber sensing position (Figure 9). It is then possible to monitor the strain seen in the specific location caused by a local temperature or stress field i.e. the FBG is basically acting as an optical strain gauge. The sensing is done by sending in light from a broad wavelength light source into the fiber in which the FBG returns a specific wavelength via Bragg reflection. This reflection will have a change in the wavelength accordingly to how the strain changes the optical path length of the period of the FBG (Figure 10). By having a broad light source, it is possible to measure about 20-30 FBGs as long as the strain is not eating the wavelength budget i.e. the FBGs start to shadow each other in the returned wavelengths. These strain readings can be done at very long distances. One example was the use of a 6.2 miles (10 km) long optical fiber to read 12 FBGs in a string test of a bearing installation for sub-sea pumps, as described by Staveley (2011). The FBG sensing technology is currently a popular sensing method as it is often a simple and easy to apply technology. In practice it can measure most physical properties if these can be transferred to a local strain within a component or in a sensor probe. This has enabled for example force, temperature, vibration, pressure, viscosity, chemical, humidity, corrosion and current FBG sensors to be invented and demonstrated.

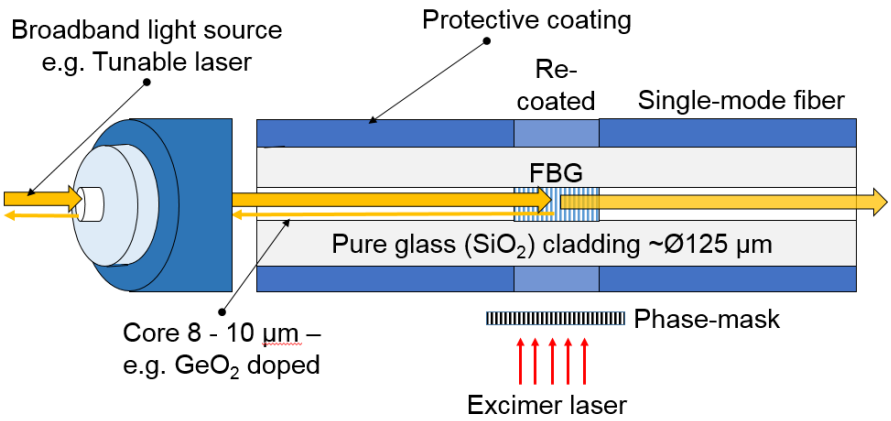


*Figure 9. The manufacturing of a FBG with excimer laser and strain sensing with a broadband light.*

The local strain at the FBG location, $\varepsilon_{total}$, in a rolling bearing consists of a sum of different contributing effects as summarized in the below schematic equation:

$$\varepsilon_{total} = \varepsilon_P(P) + \varepsilon_{temp}(T_{act}) + \varepsilon_{fits} + \varepsilon_{pre\text{-}loads,\ external} + \varepsilon_{pre\text{-}loads,\ internal} + \varepsilon_{misalignments} + \varepsilon_{deformations} + \varepsilon_{other}$$

where the bearing load, *P*, is:

$$P = X\,F_{axial} + Y\,F_{radial}$$

$F_{axial}$ is the axial force on the bearing and $F_{radial}$ is the radial force on the bearings if the bearing is designed to take a combination of axial and radial loads. The X and Y factors are bearing design constants given for the specific bearing design, size, and load conditions (ISO, 2007). In this case the centrifugal forces are not taken into account. The other strain contributions are dependent on internal and external geometrical conditions at installation but may see changes at: the actual operating temperature, $T_{act}$; speeds; and loads. As seen it becomes a very demanding task to take all these factors into account if you want to measure the external bearing loads with high accuracy. Therefore, the challenge is to locate and design the FBG locations in such ways that several of these effects are minor in the total strain picture and are accurately compensated for with algorithms. For example, the bearing temperature can be measured in separate FBGs that are detached from other influences of strain. Thus the temperature influence can be deducted from the strain measurement.

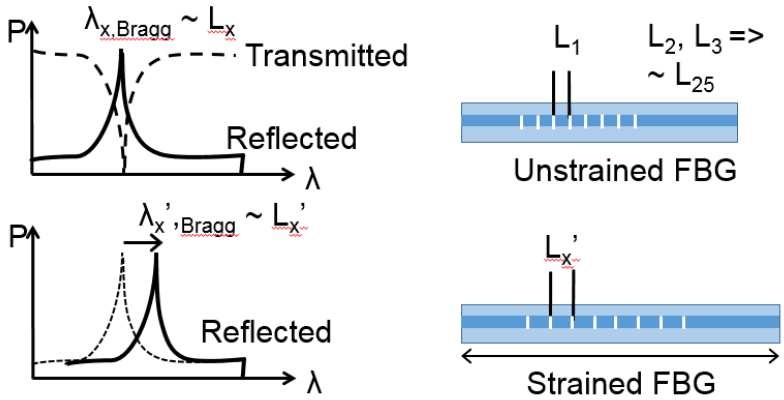


*Figure 10. The reflection of wavelengths in a FBG in unstrained and strained state.*

*FOS Network design – Explosive Atmospheres*

Fiber optical sensor methods are becoming mature and the experiences of laying local and long distance optical network are well established within the telecom industry (ITU, 2009). However, fiber optical communication and sensing have not had the large attention, as it deserves, within the control and monitoring communities of the process industries. For example, fiber optics sensors and networks are not mentioned within the main governing industrial standard (API 670) for machinery protection of oil & gas installations (API, 2014). This standard focuses on conventional electrical networks and with the latest version to some extent including wireless ones too. It is very similar to the lack of fiber optic guidance within standards coming from ISO, EN, API, AMSE etc. that deal with the design and use of measurement probes for pressure, temperature and flow. However, a very important step is the recent release by IEC (2015) of the standard "*Explosive atmospheres – Part 28: Protection of equipment and transmission systems using optical radiation*". This standard should be able to advise and guide potential sensor suppliers, network designers, installers and users to set limits but also review tests of environments vs. light sources. It should be noted that fiber optic sensor networks are not by default intrinsically safe, as this will depend on the radiated power (mW) or the irradiance (mW/mm$^2$) being the "*radiant power incident on an element of a surface divided by the area of that element*" potentially emitted from a fiber onto surface or into a gas o dust cloud. If an installation passes the optical requirement for not igniting, then it is designated being "*inherently safe optical radiation*" with the highest optical protection class and stated as "*OP IS*". OP IS enable use within the highest protected gas and dust EX areas. The IEC levels for the OP IS class are given in Table 2 in comparison with the emitted power from a typical OP IS FBG laser diode source.

*FOS Network design – Fiber types, Damping, Connectors, Communication to PLC/DCS*

The design and construction of fiber optical (sensor) network including layouts, connectors, fiber length, types and interpretation of signals is a large topic (ITU, 2009 & 2012) and it is mainly outside the scope of this paper. But some comment should be made. The used fiber type of FBG and DAS/DTS systems is the single mode fiber with a thin main transmitting core (about 8 to 10 µm diameter) surrounded by a larger outer glass body (125 µm diameter) as seen in Figure 9. This glass structure is then coated by a protecting polymer layer. The composition of the glasses can vary from the ones commonly used in telecom to more specialist ones to enable use at high temperatures and chemical resistance, especially against hydrogen. It is the same for the outer polymer layer which can be from the conventionally used ones for telecom to more advanced one such as PEEK to give chemical (e.g. lube oil and gas),

temperature and wear resistance. These coated fibers can either be used as they are, or inserted in protecting/guiding polymer or metal tubes, or inserted into to a strengthening fiber bundle e.g. of aramid fibers within a protecting cable jacket. It can be a single fiber, or more often, multi optical fibers within such a strengthening cable jacket with each fiber color coded to simplify connectivity. It can be expected that at each machine it will be an optical junction box connecting the various optical sensors into one cable for communication to a more central point within a non-EX area or cabinet that may survey several machines. Various fiber optical connectors and splices (mechanical or fused) are foreseen to be used in these network as within the telecom industry (ITU, 2008 & 2015). At long distance it will be necessary to take into account the fiber length, bends and number and type of connections/splices to ensure that the signal strength is high enough. It is expected that number and type of connectors and splices used will be the limiting factors for the sensing distance. Such calculations are common within the telecom industry and use dB reduction per fiber length and per connection, bending radius etc. For a sensor system it can be noted that the light has to travel twice through the system before coming back, after being reflected, to the detector.

*Table 2. The optical requirement for not igniting all type of atmosphere are designated being "inherently safe optical radiation", the highest optical protection class given ("OP IS") by IEC (2015).*

| Radiated power[1] | Irradiance[2] | For following atmospheres | Remarks |
|---|---|---|---|
| mW | mW/mm$^2$ | – | – |
| ≤ 15 | – | All atmospheres | No limit to the involved irradiated area |
| – | ≤ 5 | All atmospheres | No limit to the involved irradiated area |

[1] No irradiance limit applies.
[2] No radiated power limit applies.
Comments: A typical FBG light source is a continuous wave (CW) laser, Class 1M, with a maximum power of 2.5 mW (OP IS ≤15 mW i.e. no limitations in EX areas). The source is similar in power of to light emitting diodes (LED) used in some local networks. A semiconductor laser light source for optical transmission has a maximum power of about 100 mW i.e. optical protection needs to be considered in EX areas.

## MONITORING OF BEARINGS, PUMPS AND COMPRESSORS BY FBG SENSORS

A key development to enable high quality fiber optical monitoring of centrifugal pumps and oil-flooded screw compressors, is to ensure the possibility to measure the axial and radial loads on the main thrust bearings in these equipment. The most common rolling element bearing type to be used is the ACBB (Figure 11) in typically back-to-back (pump) or face-to-face (compressors) arrangements under the approximate conditions reviewed in Table 3.

It is challenging to measure with FBG containing fibers on these ACBB pairs of bearings, especially for pumps. This because combined axial and radial loads; fiber location; housing and shaft fits; axial clamping; and centrifugal forces affect the measurement. However, it has been possible to devise design rules by using a combination of programs for simulation of bearing application, finite element method (FEM) stress analysis and measurements. These findings will be verified in a test program under 2017 in test rigs and in pumps and compressors. In the test rigs it is possibility to apply variable speeds, different fits and change the lubrication of the bearings. The first bearing under evaluation is a 7320 test bearing (a 40 degree ACBB design with 100 mm bore) with multiple fiber locations incorporated on optimal fiber locations from sensing point. For example, the tests are expected to verify "good locations" for fibers that gives consistent results independent on magnitude of load, relationship between axial and radial loads and induced errors e.g. from variations in housing fits. Simulations are used to search for and compare different potential FBG fiber locations as shown in Figure 12.

The fiber locations, number of required fibers, and FBGs in a fiber are to be fully confirmed. However, it seems possible to achieve a measurement error in the range of ±5 to 10% for a single fiber and below ±5% by using two fibers with some margins. It should be

noted that the repeatability is likely to be better than these values. Feenstra and den Haak (2012) demonstrated this in the past by showing that a minor roller defect gave detectable and repeatable changes in the load spectra and strain enveloping spectra. In the end the full capability of FOS ACBBs will be clear when real pump and compressor tests have been done. It is expected that misalignment, unbalance of impeller, cavitation, deadheading, face seal issues, wear of impellers, casings and wear rings, instability of cutwater, lubrication issues etc. could possibly be to detect at different speeds and process conditions. In addition, it will be possible to detect bearing parameters such as speed of rotation, direction of rotation, skidding (low loads), high loads etc.

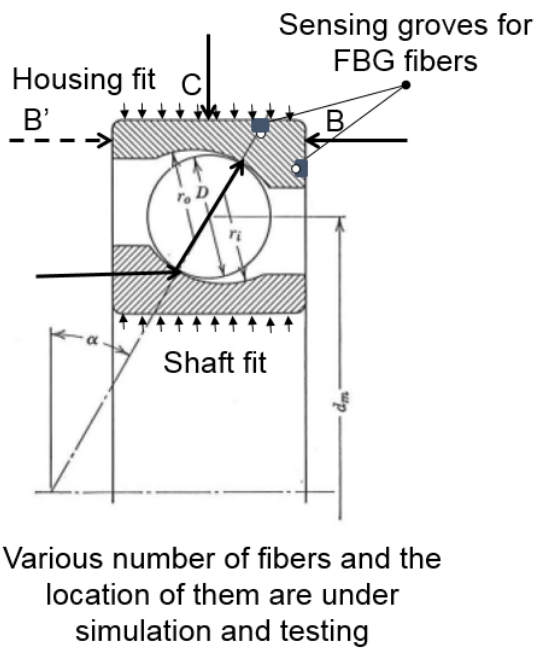


*Figure 11. Some ACBB design and application parameters to be consider for location of fibers and the development of sensing algorithms. B – Main axial bearing force; C – Main radial bearing force; and B' – Clamping force.*

*Table 3. Typical design parameters for single row Angular Contact Ball Bearing (ACBB) arrangements within centrifugal pumps and oil-flooded screw compressors.*

| Typical Design Parameter | Centrifugal Pump | Oil-Flooded Screw Compressor |
|---|---|---|
| Standards | API 610 / ISO13709 | API 619 / ISO 10440 |
| Bearing arrangement | SRACBBs (locating) Back-to-Back | SRACBBs (locating) Face-to-Face |
| Location | Drive end side | Discharge side |
| Bearing designs | 40° contact angle, Machined brass cage | 40° contact angle, Machined brass or PEEK cages |
| Thrust bearing sizes | 7308 to 7320 Bore 40 to 100 mm | 7308 to 7320 Bore 40 to 100 mm |
| Max speed (API) ($n\ d_m \leq 0.5x10^6$ mm/min) | ≤ 3600 [1] rpm (7320) ≤ 8300 rpm (7308) | ≤ 3600 rpm (7320) ≤ 8300 rpm (7308) |
| Lubrication | Oil splash (rings) or Oil mist | Oil jet |
| Housing/Shaft fits | G7, G6, H6, K7 / k5 | Radially free / k5 |
| Internal | Normal axial clearance (CB) | Light pre-load (GA) |
| Loading | C/P = 12 (3 to 20) | C/P = 12 (3 to 20) |
| $F_{axial}/F_{radial}$ | 3 to 20 (mainly thrust) | Pure thrust |

[1] Up to 3600 rpm is often not practical for larger rolling bearings (e.g. 7320) from general cooling point, and the energy density requirement in API 610 (< $4x10^6$ KW/min).

An interesting monitoring possibility of rolling bearings with FBGs is to measure the temperature of the outer ring at many different locations under different running conditions as seen in Figure 13. In this case a bearing in a marine gearbox (propulsion thruster) has been monitored by load sensing FBGs in different locations of the outer ring of a spherical roller bearing. By using a special algorithm, it has been possible to derive the temperature increase in the different FBG locations and plot them over time. The colored ring shows the differential temperature towards the start condition at a specific time of a test cycle (the red line). It the test the temperature could varies with about 14°F (8°C) along the outer ring of the bearing. This could potentially affect the lubrication condition of this bearing in an unexpected manner. It therefore seems desirable to incorporate a type of lubrication warning based on the lubrication condition seen within a measured bearing. A lubrication warning could use the temperature to calculate the (local) "kappa ratio", $\kappa$, as defined by ISO (2007) or by the bearing manufacturer. It is done by applying: the rotation speed, n, and bearing pitch diameter, $D_{pw}$, to calculate the reference kinematic viscosity, $\nu_1$. The actual kinematic viscosity, $\nu$, is given by the viscosity of the oil at the actual operating temperature, $T_{act}$:

$$\kappa = \frac{\nu\,(T_{act})}{\nu_1(n, D_{pw})}$$

For ACBBs in pumps and compressors it is generally regarded that a kappa ratio below 1 gives poor lubrication conditions and the ratio should preferably be above 1.5.

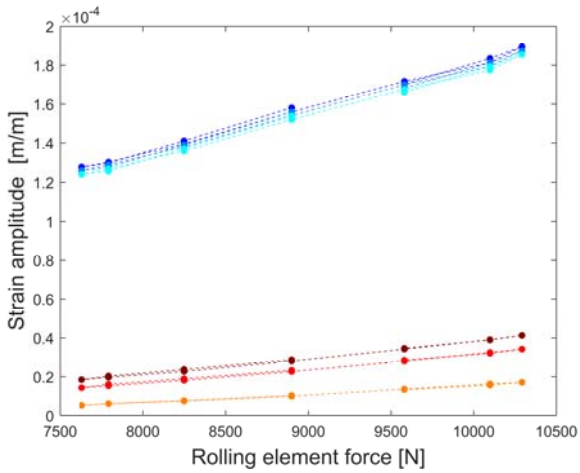


*Figure 12. Simulations showing behavior of two fiber locations (Blue and Red) for a single fiber vs. three different typical housing fits (max, mean and min) for pumps. The blue good location gives a high strain amplitude with good response vs. force with low spread against housings fits. The red bad location gives a low strain amplitude with low response vs. forces with high spread against housing fits.*

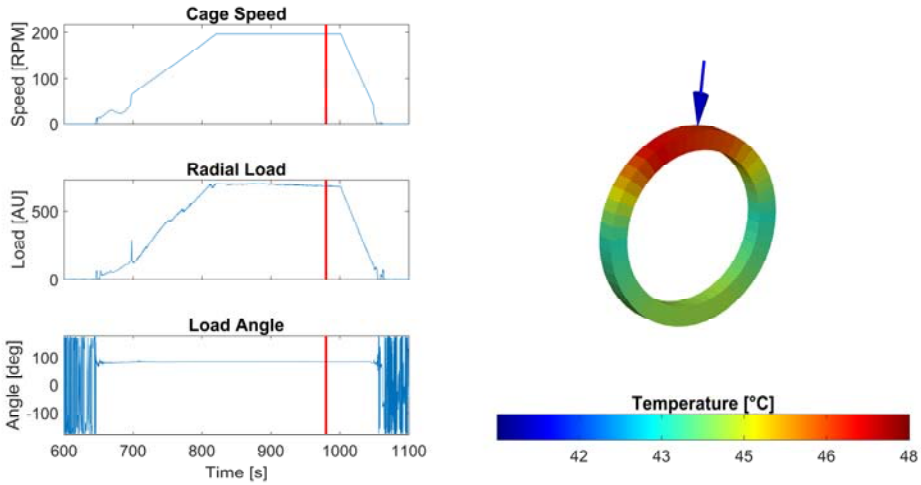


*Figure 13. An oil lubricated spherical roller bearing in a gearbox for a marine propulsion system Left: Part of the by FBG fibers measured Speed (cage) – Radial loads (AU – arbitrary unit) – Load angle (blue arrow) cycle. Right: The delta temperature map of the outer ring after 990 seconds (red lines, left diagrams) after the start with load angle (blue arrow).*

**THE VISION: SMART PUMPING WITH FIBER OPTICAL MONITORING**

The use of a combination of fiber optical process sensors (pressure) and bearing sensors (loads, pulse loads, temperature, rotational speeds etc.) should open up the possibility to fulfill the vision of *"smart pumping"* as foreseen by Stavale et al (2001) by making a broad spectra of measurements available from a single source. FOS should enable smart pumping if measured data of the pump and bearing conditions can be communicating to a programmable logic controller (PLC) or a distributed control system (DCS). The controller could then optimize the running conditions vs. process requirement (pressure, flow and speed), quality ensure the set-up of the pump (alignment, couplings, seal flushing, mountings etc.) and continues monitoring the pumps through their lifetime. Thus enable:

- Energy efficient pumping (optimized flow conditions);
- Safe pumping (stable flow and pressure regimes);
- High quality set-up of pumps (avoid installation faults); and
- Reliability control of pumps (monitoring of wear and unforeseen incidents).

By utilizing PEO by VSDs, as shown in Figure 14, it should be possible to achieve a much prolonged service-life of the bearings, seals and general equipment. This is in combination with a significant increase in energy efficiency of pumps and screw compressors. It should be noted that the energy savings in pumping can be in the range of 20 to 50% if the flow is regulated along the system curve interacting with the BEP by using a VSD (DOE, 2004 and 2006), as seen in Figure 15. The electric energy bill is the dominant life cycle cost for the operation of most pumps. At the same time this gives smoother pumping compared to using a throttle valve and avoids the equipment working in a failure creating regime e.g. with cavitation, vibrations or large bearing forces (Bloch, 2011). Gomez (2015) has suggested that most early pump failures are due to issues with the process or set-up of the equipment that can be addressed if these are known i.e. the contributing factors (failure causes) occurring at installation of the pump should be detected before failures of components start to occur, as seen in Figure 16.

Smart pumping, with monitoring by fiber optic sensing, can address the above issues and should be ideal for oil & gas installations that often see issues that limit the use of electric and wireless sensors and electric cabling in:

- EX & workers HSE areas (refineries, gas plants, off-shore etc.);
- Electro-magnetic fields (electric motors, power cables etc.);
- Fluids (process gases, sub-sea or within lubricants);
- High and low temperatures (hot or cryogenic running);
- Faraday cages structures (tanks, bearing housings, pressure vessels etc.); or
- Over long distances (sub-sea, tank farms, pipelines, dispersed equipment etc.).

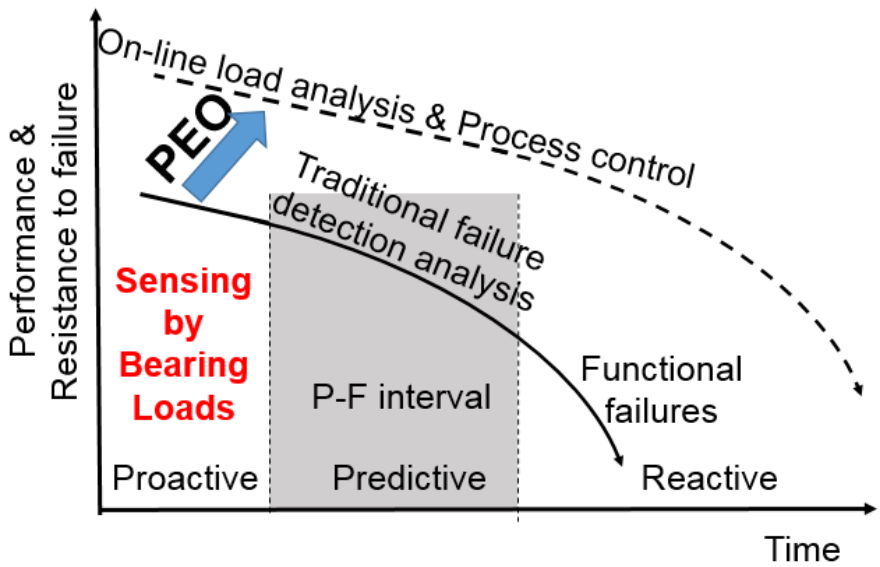


*Figure 14. Process Equipment Optimization (PEO): Fiber optical load and process monitoring should enable work in a proactive mode instead of being predictive or reactive. This will enable control of processes so higher performance, higher reliability and higher energy efficiency can be achieved.*

It can be foreseen, that in the near future FOS will be developed to be applicable as on-line process and equipment monitoring systems for pump and compressor skids. An example of such an on-line system, that is

under development and utilizes FOS by FBGs, is shown in Figure 18. In the show design sketch a pump and its process can be monitored hundreds of yards away without use of electric cabling or conventional sensors. The fiber optical communication to the sensors at the pump skid is done along the high voltage power cord. This remove the need to provide extra cable racks in the facility for sensor cables. A fiber optical junction box is located at each pump skid that will enable bundling of the individual sensor cables into one single cable with multiple fibers. At each junction box the ambient temperature is monitored and this enables monitoring of the differential temperature of bearings for example, an important parameter in the survey of rotating equipment. To make the installation more economical the cables from several skids can be routed into one common non EX area to be surveyed by a single control box.

A control box that contains: a fiber optical switch to enable multi skid and multi sensor monitoring; a FBG interrogator; and a "smart optical input/output unit (O-I/O)". It is foreseen that the O-I/O unit will be programmed with basic algorithms using data from the sensors to enable calculation of bearing loads, load fluctuations, speeds, direction of rotation, bearing temperatures etc. and also using sensor data to calculate pressure and temperature of the process at suction and discharge. By using bearing and pump knowledge, and using the values generated by the O-I/O, it will be possible to feed into more advance algorithms in the PLC/DCS to generate bearing, general equipment and process statuses and using these to give more advanced advice, warnings and alarms.

At the central point, yards (meters) to miles (kilometers) away, the O-I/O unit may serve several machine locations, as the sketch in Figure 18 shows. An O-I/O consists potentially of an optical switch, an optical sensor interrogator, power supply and an intelligent I/O unit. It will ideally communicate with a PLC and/or a DCS for the specific machine and in this way enable continues PEO of the machine.

An alternative is to connect to a machine health monitoring system either on-line or then needed. It makes it possible to monitor the equipment from a safe area for example at commissioning, start-up, troubleshooting, service etc. It is also expected that other FBG bearing types, such as deep groove ball, cylindrical roller and various spherical bearings, will be available over time adding the possibility to monitor gearboxes, electrical motors and radial bearings in pumps if required.

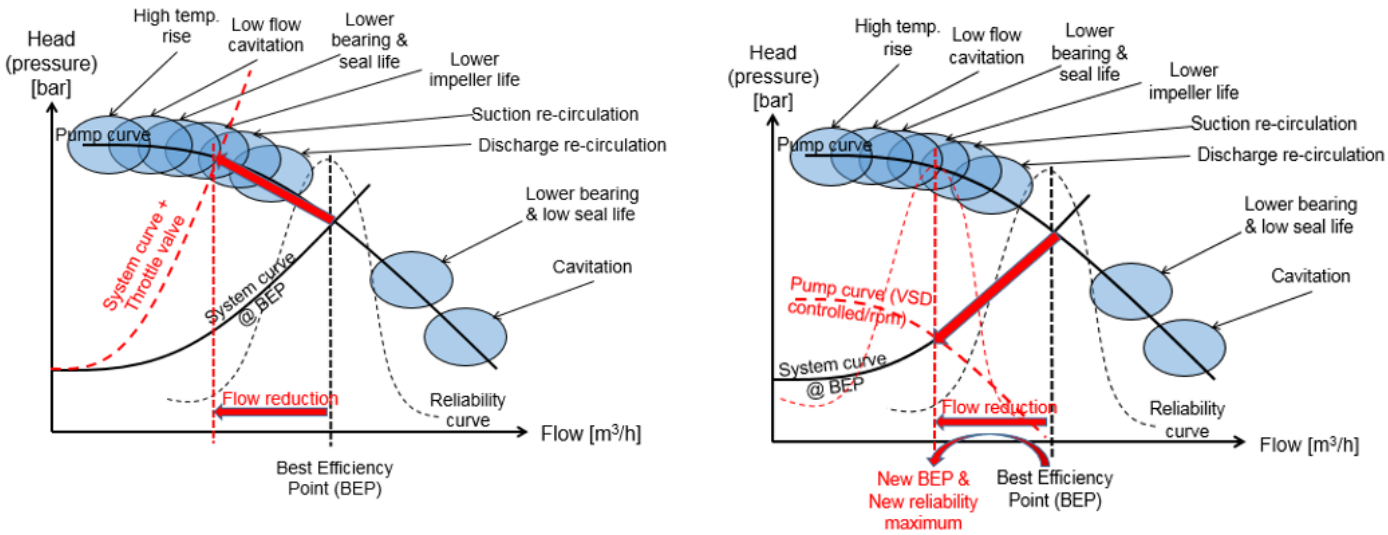


*Figure 15. Flow reduction of pumps after Bloch, 2011 and DOE 2004 & 2006. Left: Use of throttle valve. Right: Use of variable speed drive.*

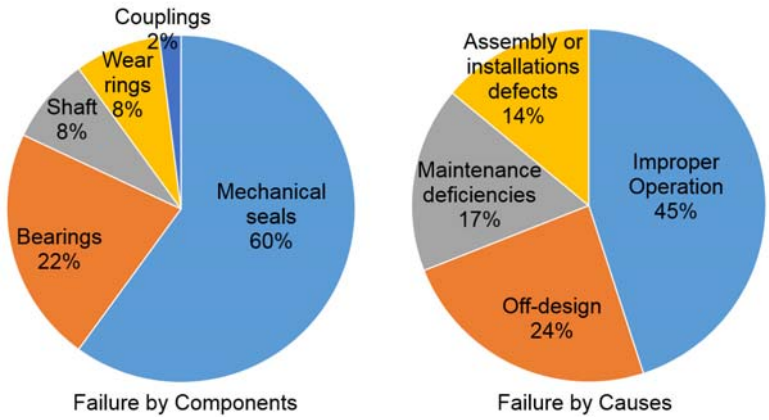


*Figure 16. Centrifugal pumps: Failure by components vs. Failure by causes (after Gomez, 2015) that can be detected by FO load sensing.*

The cost of FOS system components and FOS bearings are still at an early stage. However, the major system parts are electro-optical components that with volumes can be expected to be reduced in price. In addition, the learning in production of for example FOS ACBBs can be expected to follow the cost development of conventional electro-optical manufacturing. It is known that the cost development of this type of manufacturing normally follow a learning curve as laid out by Ghemawat (1985) and Lieberman (1987):

$$c(x) = a\,x^{-b}$$

where c(x) is the marginal cost, a is cost of first unit, x is cumulative output and b is the learning elasticity which define the slope of the learning curve. An exponent b=0.32 gives a reduction in cost to 80% if the accumulated volume has been doubled. This define a learning curve of 80%. An 80% learning curve have based on experiences be seen as a realistic one for electro-opto-mechanical manufacturing operations. Figure 17 shows, based on a spread in learning curves from 70 to 90%, the expected cost developments relative to the basic cost for a 100 mm bore size angular contact ball bearing for pumps and compressors. The relative cost is higher for smaller bearing bores. However, it can be expected that the volumes for smaller bores are potentially higher and could lead to a faster reduction in relative cost. In addition, the synergies between different bearing size can act favorable in the cost development. But at the same time it must be considered unrealistic that the relative cost will get close to 1 for FOS ACBBs as predicted for a 70% learning curve for a cumulative volume of 10 000 pcs.

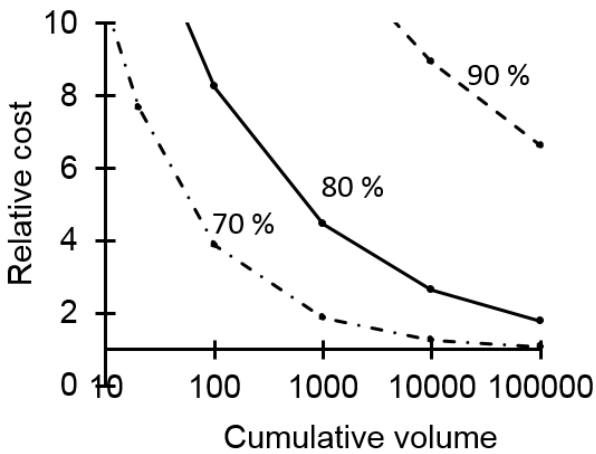


*Figure 17. Prediction of relative cost vs. cumulative volume of FOS (FBG) for a 100 mm bore ACBB (70, 80 and 90 % learning curves).*

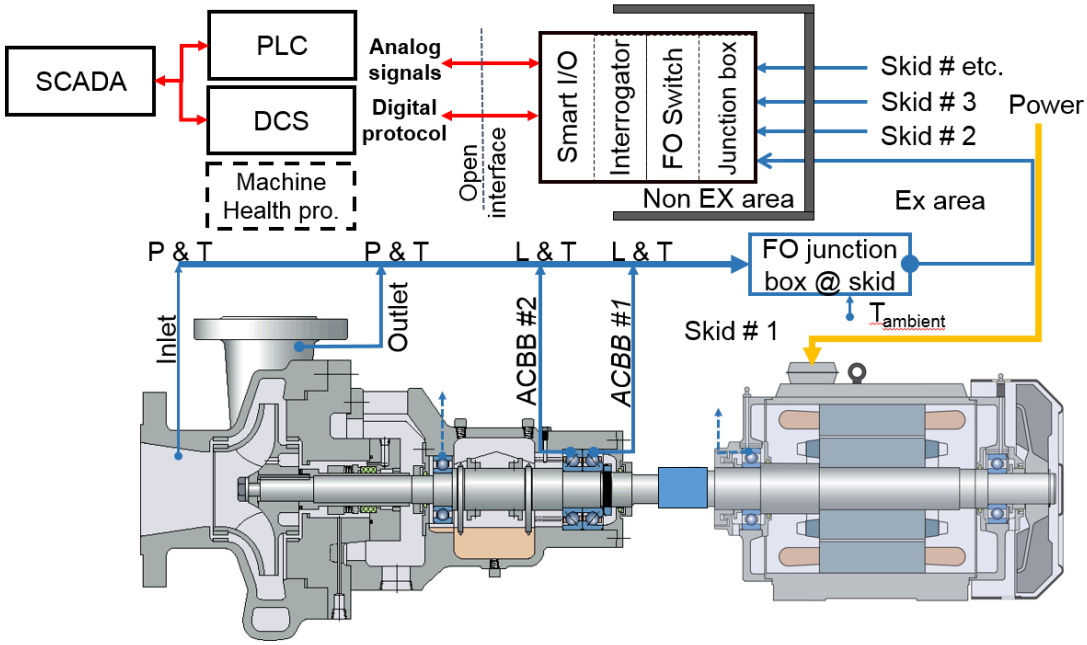


*Figure 18. A proposal for an intelligent fiber optical sensing system, using FBGs, to be used for process equipment optimization by bearing: load (L), speed & temperature (T) monitoring combined with monitoring of pressure (P) within the process.*

## SUMMARY AND CONCLUSIONS

In summary fiber optical monitoring of rotating equipment and processes, for example utilizing the fiber Bragg grating technology within bearings and process sensors, opens up a new route to on-line proactively increase process efficiency and equipment reliability. Fiber optical sensing is, of course, a much less mature technology with few established suppliers and with a technology only being introduced now compared to the much more established monitoring methods as reviewed and compared in Table 4.

Potentially, fiber optical sensing, including load monitoring, offers attractive economical alternatives and open for much more efficient use of assets by using process equipment optimization, as sketch in Figure 14. This is to be done in combination with variable speed drives and process control. The large advantages for fiber optical sensing with fiber Bragg grating are the attractive sensing capabilities of strains (loads and temperatures) within rolling bearings, the insensitiveness to electric and magnetic fields, high integration of sensors, high data capabilities and the possibilities to monitor on large distances. This in combination with the inherently safe, optical radiation (OP IS), design of the network from the sensing part to the connections to an O-I/O unit, which can be placed at distance from the sensing point and in a none explosive area close to the programmable logic controller or a distributed control system. Thus, making a full fiber optical on-line connection to a PLC/DCS possible.

Therefore, process equipment optimization with fiber optical sensing becomes a fully feasible option and may allow close interaction with the pump and system curves to create high operational reliability combined with highly energy efficient pumping.

*Table 4. Comparison of various process & equipment monitoring methods.*

| Method | Data collection | Power cables | EX issues | Active process control | Data collection | Data on distance |
|---|---|---|---|---|---|---|
| Routing | Manual | No | People & electric | No | Days to months | No |
| Strapped on | Within box | Yes or Batteries | Electric | No | Hours | No |
| On-line, electric | El. cables | Yes | Electric | Yes | Seconds or less | ~500 feet (150 m) [1] |
| On-line, wireless | Wireless HART | Yes or Batteries | Electric | No [2] | Seconds to Hours | 100-750 feet (30-230 m) [3] |
| On-line, FBG optic | Opt. cables | No | None | Yes | Seconds or less | 0.6-6 miles (1-10 km) [4] |

[1] Analog current signals e.g. 4-20 mA. High frequencies reduce cable length. Analog voltage signals have much lower measurements distances, ~50 feet (15 m), and digital ones longer. Cable to properly terminated, shielded and not routed near high-energy AC sources assumed.
[2] Due to concerns on losing the signal or hacking.
[3] Depend on amount of obstructions. In a Farady cage situation no data will be transmitted.
[4] Tentative. Depend on number and type of connectors, sharp bends etc.

## NOMENCLATURE

ACBB = Angular contact ball bearing (single row)
BEP = Best efficiency point
CAPEX = Capital expenditures
DAS = Distributed acoustic sensing
DCS = Distributed control system
DTS = Distributed temperature sensing
EX = Explosive atmospheres
FBG = Fiber Bragg grating
FEM = Finite element method
FFPI = Fiber-Fabry Perot interferometer
FOG = Fiber optic gyroscopic
FOS = Fiber optical Sensing
MTBR = Mean time between repair
$NPSH_A$ = Net positive suction head available (feet or meter)
$NPSH_R$ = Net positive suction head required (feet or meter)
O-I/O = Optical input and output (unit)
OPEX = Operating expenses
OP IS = Inherently safe, optical radiation
OTDR = Optical Time Domain Reflectometer
B-OTDR = Brillouin OTDR
R-OTDR = Raman OTDR
PEEK = Polyether-ether ketone
PEO = Process equipment optimization
PLC = Programmable logic controller
SAW = Surface acoustic waves
SCADA = Supervisory control and data acquisition (system)
VSD = Variable speed drive

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