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Thibault Tam

Ahmed Kovacevic

William J Milligan

Tong Sun

Kenneth Grattan

See next page for additional authors

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Authors

Thibault Tam, Ahmed Kovacevic, William J Milligan, Tong Sun, Kenneth Grattan, Matthias Fabian, Thibaud Plantegenet, Brijeshkumar Patel, and Sankhyabrata Bandyopadhyay

Experimental investigation of screw compressor clearance monitoring techniques

Thibault TAM[1*], Ahmed KOVACEVIC[1], William J. MILLIGAN[2], Tong SUN[3], Kenneth T.V. GRATTAN[3], Matthias FABIAN[3], Thibaud PLANTEGENET[1], Brijeshkumar PATEL[1], Sankhyabrata BANDYOPADHYAY[3]

[1] City, University of London, Thermo-Fluids Research Centre,
London, United-Kingdom
thibault.tam@city.ac.uk

[2] Howden Group Ltd, Data Driven Advantage,
Renfrew, United-Kingdom

[3] City, University of London,
Research Centre for Photonics and Instrumentation,
London, United-Kingdom

* Corresponding Author

ABSTRACT

The aim of this study is to propose new methods to monitor operational clearances in oil-free screw compressors. The motivation has been to support research into leakage flows through generating data on clearance variations, and thus to develop systems that can be used for condition monitoring and control in industrial machines. By reviewing some monitoring applications in API 619 screw compressor packages, it was found that a substantial number of sensors were employed to optimise and protect assets but that a considerable number of failures could also arise as a result of the additional system components. Although Eddy-current probes and optical fibre bundles are already used in turbomachinery to measure clearance gaps, they are experimentally investigated in static conditions. They were both found to be sensitive to the change in distance to a female and male screw compressor rotor, and further investigation in dynamic conditions could further support the advantage they show for the application. Additionally, fibre Bragg grating sensors were bonded to the external casing of a Roots blower to measure the cyclic temperature change. The linear response achieved emphasises the advantage of the approach and supports the interest in further developing such a system to measure temperatures and strains inside screw compressors.

1. INTRODUCTION

The experimental investigation introduced by this paper is part of project SECRET[1], which forms part of an innovative collaborative research project between the Royal Academy of Engineering, Howden Compressors and City, University of London. Over the course of five years, concepts that are proposed to improve the efficiency and reliability of oil-free screw compressors will be developed and tested. A key objective of project SECRET is to lead to a better understanding of the conjugate heat transfer dynamics occurring in the clearances of rotary positive displacement machines (PDM), as well as the effect that internal leakages have on the machine's performance.

Current analytical and numerical models are considered sufficient to design operational clearances, and prevent interference between solids due to thermal distortion during operation. A simplified illustration of a twin-screw compressor and its clearances is shown in Figure 1. Stosic et al. have provided extensive details on a unidimensional multi-chamber model for calculating compressor performance (2005), which can be used to compare empirical methods such as Buckney's (2011) or coupled with numerical studies such as Husak's (2019) and Rane's (2021).

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[1] Smart Efficient Compression: Reliability and Energy Targets

Stosic compares performance prediction by the multi-chamber model and the three dimensional computational fluid dynamics (CFD) model (2015). He argues the losses due to the dissipation by heat transfer are marginal compared to the input power to drive the compressor. While the study of leakage flows was not highlighted, Stosic points to heat transfer as a source of thermal deformation and a potential reliability risk.
This risk to reliability is in agreement with the analyses by Sauls, Weathers and Powell, in their three-part contribution on the analysis of an oil-flooded refrigerant screw compressor. They find that solids tend to retain the same assembly clearance regardless of operational temperature levels, but reiterate that different thermal deformation rates during transients are what cause reliability issues (Sauls et al., 2006).
The clearances between rotors are significantly affected by the thermal deformation of the rotors and housings, but do not appear to drop below the cold assembly clearance value (Powell et al., 2006). Finally, when analysing the transient deformation of the rotors and housing, Weathers et al. have estimated the smallest radial clearances to be near the high pressure cusp and discharge port of the compressor (2006).
This has recently been supported by Husak et al. (2019) and Rane et al. (2021) in their modelling of an oil-free screw compressor. Both models suggested that variations of up to 80 µm on a Φ120 mm rotor can be expected in that area while highlighting the variability of the clearance's distribution across the machine. Furthermore, by modelling the deformation of the housing, Rane et al. demonstrated that leakages through operational clearances could have a considerable effect on volumetric efficiency, indicated power and adiabatic efficiency (2021).

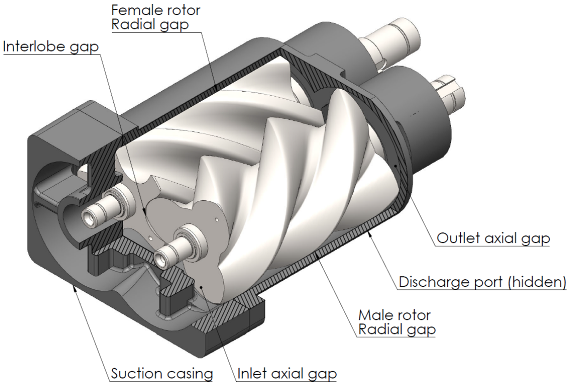

Figure 1: Section through simplified twin-screw compressor casing, indicating operational clearances

Previous work in the field established that thermal loads in oil-free screw compressors cause transient distortions in the solids, and it is suggested to be a hazard to the machine's health during start and stop operations. Though it is understood analytically for the machine's performance, it is still difficult to give experimental evidence of the correlation between thermal loads, leakage flows and the variation in clearance gaps. As a result, the validation of analytical and numerical models has been limited when the level of abstraction considered for a study is the clearance gap. Moreover, positive displacement machines are pervasive in the modern world. Stosic estimates the annual production rate of positive displacement machines to be in excess of 200 million units, and 17% of the world's electric power production committed to driving these devices(2015). Therefore, small improvements in performance could lead to significant global energy efficiency savings for demand-side assets (EESG & Group, 2020).
With this in mind, the aim of this research has been to develop a clearance monitoring system for oil-free screw compressors. The experimental investigation presented here introduces the ongoing development of this monitoring system. The paper begins with a review of screw compressor package instrumentation and its reliability. This is followed by a presentation of static displacement measurements on a pair of screw compressor rotors, first with an Eddy-current probe and then with an optical fibre bundle. Finally, surface temperature measurements using fibre Bragg grating sensors are presented as a potentially interesting monitoring technology to improve performance.

2. CONDITION MONITORING OF SCREW COMPRESSORS AND ITS RELIABILITY

2.1 Considerations when Developing a Condition Monitoring System

In reference to ISO 13374, Lu et al. list the functional requirements of a condition monitoring system to perform advisory, prognostic, diagnostic, state detection, data manipulation and data acquisition functions (2021). While they suggest the latter two or three layers of functions are typically fulfilled, the success of the ulterior analysis depends on the robustness of the sensing system and the quality of the corresponding input data. Lu et al. underline the importance of understanding the physical relevance of what is being sensed to the condition and health of the machine. Lu et al. also advise optimising detection coverage and frequency response, in order to obtain as much information as possible from a data set which is as narrow and cost-effective as possible.
Condition based maintenance is similarly well defined by Gouriveau and Medjaher (2011), by recalling ISO 13306:2001. In the same book chapter Tinga distinguishes sensors that can measure a physical parameter that directly appraises a

machine condition(e.g. vibrations or erosion), and sensors that monitor performance parameters (e.g. temperature or pressure) which can be inferred to a condition (2011). In line with the latter consideration by Lu et al., Tinga stresses the importance of having a prognostic method available to complement a condition monitoring system in order to perform condition based maintenance effectively. This implies an understanding of the physical quantity and its relevance to preserving the machine in a desired state, as well as an ability to extrapolate trends from historical data.

2.2 Monitoring Screw Compressor Packages

Milligan and Harrison illustrate well the scale at which process and machine condition measurements can be collected in a screw compressor package (2015). In addition to measuring the temperatures, pressures and vibrations of the bare shaft screw compressor, the main motor drive and gearbox are also subject to measurements in order to control the package. Evidently, process temperatures, pressures, flows and valve positions are monitored or actively controlled. Additional auxiliary systems may also typically be present, such as oil lubrication, seal systems, water or coolant supply, or even flame and gas detection. For the parameters which are safety critical, they can be monitored when integrated into a dedicated monitoring system which initiates a trip if shutdown limits are exceeded.

Milligan and Harrison caution, however, that the two-stage compressor package they described is for a highly critical application with several layers of standards compliance (2015). The demanding application is also reflected in the full integration of the monitoring system which considers environmental protection, cabling, communication and interface to the site. Milligan et al. subsequently describe how they are effectively utilising the Internet of Things (IoT) to predict performance and machine health trends (2017). They compare requirements of mass produced compressors which may feature 5-15 measurements points, while built-to-order machines that comply with stringent standards such as API619 would typically require 170 measurement points. This large amount of data places such applications favourably for prognostics modelling. A paradox is illustrated in the next paragraphs, that data is collected as a means to maximise the value of an asset but that the integration of instruments inevitably introduces other failures to the asset.

2.3 Analysis of Reliability Data

The Offshore and Onshore Reliability Data (OREDA) project, established in 1981, is considered to be the main source of reliability data which has been collected by operators on live assets in the oil and gas industry(DNV & SINTEF, 2002). In 2002, the project group released failure rates, failure mode distributions and repair times for a population of 34 screw compressor packages installed across 16 sites. An analysis of this data shows that instruments are the component that had failed in one third of the failures during the observation period, as shown in Figure 2.

A further analysis into the distribution of failure modes relating to instrument failures of that year is presented in Table 1. This data sheds light on how instruments are performing in harsh environments, as well as how their integration impacts system reliability. It also illustrates the significance of robust instruments that are designed for their operational and environmental conditions, as well as their potential to improve total system reliability by virtue of being less unreliable. Further analysis could also consider the downtime and repair time reported, and estimate the time lost and cost incurred from failures.

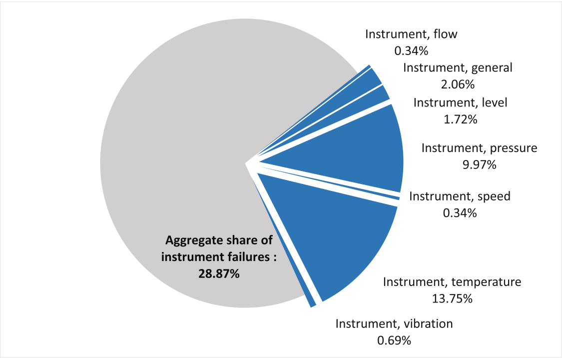

Figure 2: Percentage share of component failures attributed to instruments in screw compressor packages, using data reported by OREDA in 2002 (DNV & SINTEF, 2002)

A newer edition of OREDA was accessed with an interest to understand how the reliability of screw compressor package instrumentation has changed over a decade. Unfortunately the data set did not distinguish a specific screw compressor taxonomy group, so a comparison between data for all types of compressors was initiated. The 4th edition reported that 23.39% of all failures were of instruments, for a population size of 131 across 38 installation sites (DNV & SINTEF, 2002). The 6th edition reports this figure to be 19.83% in a population of 47, across 11 installations (DNV & SINTEF, 2015). This could hint at a general trend that instruments are becoming more reliable, but no substantiated conclusions can be drawn without a much wider appreciation of the study's parameters and other industry trends. A difficulty in doing so, is of course normalising the data sets so that they are comparable. It is suggested that an analysis

Table 1: Breakdown of screw compressor package failures described as instrument failures, by failure mode and as using data reported by OREDA in 2002 (DNV & SINTEF, 2002)

Failure mode	Abnormal instrument reading	External leakage (process medium)	External leakage (utility medium)	Fail to start on demand	Low output	Parameter deviation	Minor in-service problems	Spurious stop
Failure mode distribution of instrument failures (%)	44.89	1.27	6.42	5.11	3.84	14.10	10.26	14.10
Share of instrument failures for ea. failure mode (%)	53.04	2.47	55.66	33.25	17.64	28.21	28.82	32.36

of the failure mode distribution as done in the previous paragraph would be interesting.

3. CLEARANCE MEASUREMENT TECHNIQUES

3.1 Review of Existing Solutions in Turbomachinery

Measurements of Blade tip clearance (BTC) and Blade Tip Timing[2] (BTT) are both well established practices for non-intrusive stress measurements of turbine blades (Szczepanik et al., 2012). Although PDM and turbomachines are different thermodynamic systems and solids, there are similarities in the significance of rotor-stator clearances to machine health and performance (Wu et al., 2019). Chen et al. have reviewed the history and current state of the available techniques, and categorise four classes of instruments used: inductive, capacitive, optical and microwave (Chen et al., 2021).

Inductive probes, or Eddy-current probes, measure the change in inductance as a result of surface Eddy-currents generated by a coil. They are well understood and widely used in all kinds of defect measurements (Garcia-Martin et al., 2011; Tian et al., 1998). Numerical and experimental simulations have been carried out to explore their responses in BTC and BTT applications (Jamia et al., 2019; Mandache et al., 2013). Substantial work of a sensor development and signal-processing method is also well documented by Cardwell et al. (2008) and (Chana et al., 2016). Other projects have sought to develop passive Eddy-current probes to measure through the casing together with low-noise amplifiers (Roeseler et al., 2002; Haase & Haase, 2013). A review of these studies highlighted inductive probes' sensitivities to the material and shape of the target, as well as the presence of material surrounding the probe tip which could interfere with the measurement.

Capacitance probes are also well developed for clearance measurements. Since Chivers' proposal of a capacitive BTC system (1989), his research has resulted in impressive products which are still being developed to this day. Indeed Sheard demonstrated a self-calibrating probe (2011), and Stubbs & Shahid showcase the performance of their latest measurement systems (2020). Since these probes measure the change in capacitance between a probe and a target, the probe is sensitive to any changes to the dielectric constant in the gap (Walt, 2010).

Fibre optic bundles are commonly used during engine developments due to their high resolution, but appear to be less attractive for operational health monitoring due to the presence of contaminants and of the high temperature in turbines (Chen et al., 2021). Optical fibre bundles carry a beam through fibres, and the light is reflected back to a receiving fibre when a target passes by the probe. The reflected light is captured by a photodiode and analysed with a spectrometer, which generates a pulse whose amplitude can be measured. Garcia et al. have tested a bifurcated bundle in a live engine, and have demonstrated its ability to eliminate noise by measuring a quotient of two response signals (2013). A different optical technique by interferometry is demonstrated by Kempe et al. (2007), but has not been further considered.

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[2] Practice which characterises turbine blade vibrations from discrepancies of a blade's time of arrival.

Based on the literature reviewed and a technical risk assessment which was carried out in parallel, some of the potential limitations of available instruments were experimentally explored and presented in subsections 3.2 and 3.3.

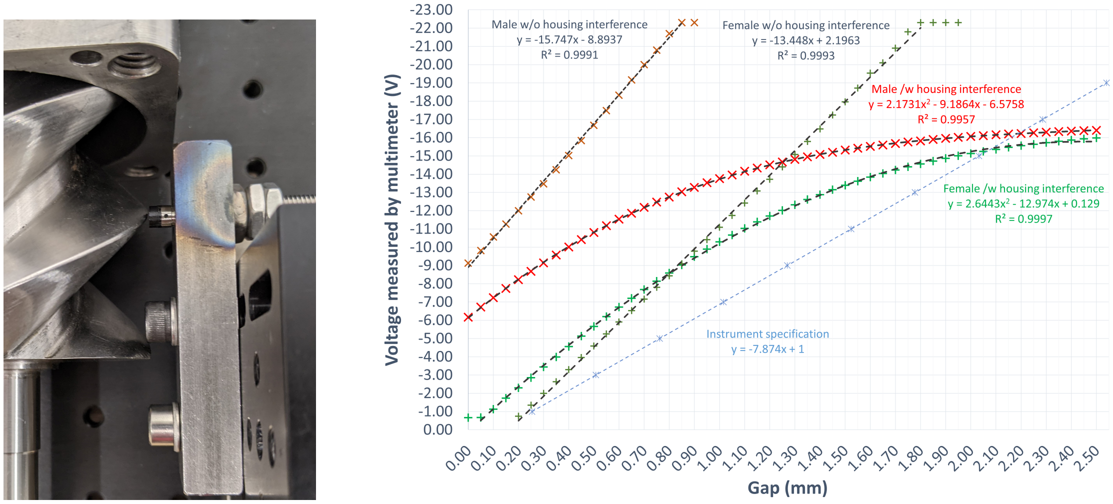
3.2 Static Measurements Using a Eddy-Current Probe

The objective of the tests presented in this subsection was to understand the influence of the target material, shape (and size) and the interference that a casing surrounding the probe would cause. An Eddy-current probe was mounted to an interface block, which was fixed to a right-angle plate and subsequently to a linear stage. The casing interference could be simulated, as the probe could be mounted with its tip proud or flush with the block's external face. Figure 3a shows the sensor mounted proud and in contact against the male screw rotor.

Three different targets were used: a carbon steel flat plate, a stainless steel female screw rotor and a stainless steel male screw rotor. The results from the flat plate are not reported here to retain clarity in the illustrated result. Measurements with each target were performed in both configurations of the mounting block. The probe was orientated such that it was normal to the target, and positioned in contact with the target as a starting position. The distance was then adjusted on the stage at 50 µm increments, and the voltage reading was recorded by a multimeter for the full range of the instrument.

Figure 3b shows the calibrated response by the manufacturer, and the measured responses to the female and male rotors (with and without the simulated housing interference). When the probe is mounted proud of the block, both the responses to the female and male rotors can be approximated linearly. While the slope is different to that of the manufacturer's calibration, the trends are nearly parallel to each other. The response to the male rotor registers change and saturates sooner than when compared to the female rotor.

When the probe is flush to the block and the housing interference is simulated, the response is no longer linear. The response to the male rotor exhibits an amplitude higher at smaller gaps compared to the response to the female rotor, as shown in the previous paragraph.



(a) Top view showing probe mounted proud and sensing the male rotor tip

(b) Measurements using an Eddy-current probe, with and without simulated housing intereference

Figure 3: Static gap measurements using an Eddy-current probe

The first observation is that the target material appears to change the sensitivity of the response. While the response sensitivities to both stainless steel targets are similar, they are nearly double that of the manufacturer's calibration which is performed on an AISI 4140 target.

The shape and size of the target seem to affect the measurable range of the instrument. The female rotor tip is nearly flat, while the male rotor possesses a steep slope from the edge of its tip. Since the probe relies on electro-magnetic fields, its measurement spot is large. If the material in the measurement spot is not at a uniform distance, as is the case of the male rotor tip, then the response reflects the gradient on the target. Although the range of the instrument is specified to begin at 0.25 mm, this explains why the male rotor tip can register a response of −9 V at 0.00 mm when this corresponds to the response at 0.85 mm on the female rotor tip. Moreover when combined with the steeper slope of the response, the maximum range is also much more restricted. For instance, the response to the male rotor tip starts saturating at 0.80 mm.

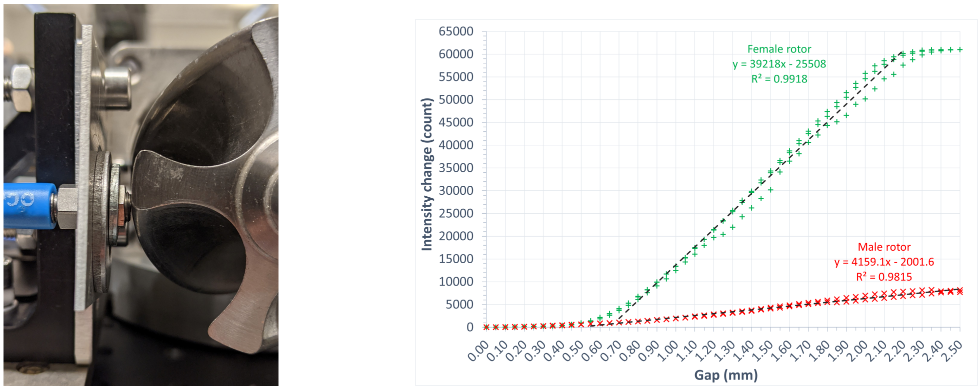
Finally, the interference caused by the housing appears to change the linearity of the response and restrict the full scale voltage output that can be achieved. Without repeated measurements and a better understanding of the accuracy in this condition, it is difficult to comment on the suitability of this behaviour for the measurement of screw compressor clearances. It is possible however to prevent such interferences if a housing is designed with a non-magnetic and non-conductive material, as Cardwell et al. have done (2008).

3.3 Static measurements using a fibre optic bundle

After testing two different fibre bundle constructions on a flat mild steel plate and using a white light source, the bundle which was more sensitive to the measurand was tested on the same rotors are described in the previous sub-section. The results from the latter tests are presented in the next paragraphs.

A dual-core fibre bundle was fixed to a right-angle plate, as shown in Figure 4a. With the bundle mounted to a linear stage, the distance to the target was manually varied. The stainless steel female and male rotors were the two different targets used during these tests. The assembly was set-up such that the stage displaced the instrument in a direction normal to the rotor tips, and from a starting position of 0.00 mm. In increments of 0.50 µm and up to 2.50 mm, 100 measurements were averaged at each gap and the test was repeated three times per target[3].

A spectrometer was used to measure the intensity of the reflected light across the spectrum of the white light source. By extracting that data, the change in intensity could be plotted at a particular wavelength against static gaps. The results obtained, using light at a wavelength of 650 nm are presented in Figure 4b, as using red light is typically associated with cost-effective components.



(a) Front view showing the optic fibre bundle pressed against the female rotor tip

(b) Measurements of distance between a fibre optic bundle and static targets (male and female screw rotors)

Figure 4: Static gap measurements using a fibre optic bundle

The figure shows how the intensity of the reflected light changes from 0.00 mm. Both responses reveal a linear trend at a portion of the measurement range of this test. It appears to be from 0.70 – 2.00 mm when sensing the female rotor tip, while a linear approximation was plotted from 0.55 mm when sensing the male rotor. The reading of the bundle when sensing the female rotor is clearly saturated due to the limitation of the spectrometer used. The trend from the male rotor tip however climbs steadily throughout the entire measurement range at this selected wavelength.

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[3] The results on the male rotor omit the measurements of the first test iteration, because the orientation of the target was corrected hence resulting in a different measured gap compared the two subsequent iterations.

The results show that a fibre bundle using red light would be the basis of an effective system that is sensitive to the distance to the rotor tip. It is clearly more sensitive to the female rotor tip, but factors such as the incident angle of the light beam to the target and the way that the reflected light is dispersed relative to the receiving fibre's aperture have not been considered. Additional factors which are also believed to influence the measurements are differences in surface features and reflectivity between the two targets. A dynamic test would offer more comparable data as the probe could capture every point as the rotor tip passed it.

By contrast to measuring with an Eddy-current probe, the measurement spot of the bundle on the rotor tip can clearly be seen in this test. This offers a convenient appreciation of the coverage of the measurement spot relative to the target, even if it consists of a sharp metal edge. However as mentioned in the previous paragraph, a sharp edge may cause less light to be reflected back to the bundle and lead to a lower sensitivity.

Finally, the data exhibits some spread along the linear regression. After some preliminary investigation the light source demonstrated some instability over time, perhaps due to temperature rise of the device. This error could be eliminated by measuring the light source, or by temperature compensation.

4. EXPERIMENTAL INVESTIGATION OF FIBRE BRAGG GRATING SENSORS

4.1 Why Fibre Bragg Grating Sensors were Considered

By locally and periodically modulating the refractive index of a fibre core, light at the Bragg wavelength will be reflected while the remaining wavelengths of the spectrum will continue to pass through the fibre. Othonos and Kalli give a detailed account of how fibre Bragg gratings (FBG) are sensitive to temperature and strain, and estimate that they are intrinsically more sensitive to temperature (by an order magnitude (1999)). If the strain is small relative to the temperature change, it can be difficult to differentiate the response of the two measurands, although techniques for temperature compensation are well established for many applications.

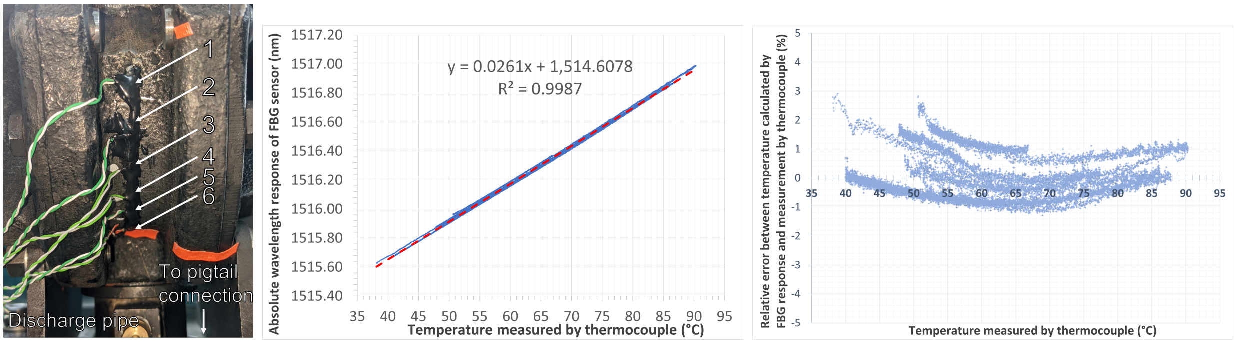
Rao (1997) and Campanella et al. (2018) comprehensively reviewed how FBGs are used for sensing. A particular interest has been shown to FBG sensors given their ability to be multiplexed, and for their potential to offer insight into other machine parameters by analysing strain measurements. A novel example of this technology's potential is presented by Fabian et al. (2018), where a permanent magnet AC motor is instrumented with FBG sensors to monitor all the parameters of interest. By routing four optical fibres, each written with 12 FBGs, Fabian et al. were able to measure vibrations, speed, torque, and the temperatures of individual permanent magnets.

4.2 Surface Temperature Measurement of a Roots Blower

As a first approach to considering whether FBGs were an effective solution for the condition monitoring of screw compressors, the response of the sensors when bonded to a curved metal surface was investigated. This would give an indication of how sensitive the sensor could be when interacting with both a metal substrate and a bonding agent such as epoxy. To achieve this conveniently, a Roots blower in an operational test rig (Patel et al., 2021) was retrofitted with a fibre optic and it was considered sufficient at this point to associate the FBG's response to the substrate's temperature only. By operating the machine with an induced pressure rise in the discharge line, the temperature of the machine could be varied over several cycles.

After the external surface of the Roots blower was roughened and cleaned, a single optical fibre with six FBGs written into it was epoxied along the casing circumference. Thermocouples were then placed as closely as possible to each FBG, to give a corresponding temperature measurement and confidence in the fibre optic-based measurement. Figure 5a shows the locations of the epoxied sensors. Their responses were acquired over four and a half temperature load cycles, four temperature rises and five temperature falls. The measurements of the third FBG sensor are presented here as representative of that investigation.

Figure 5b shows the shift of the Bragg wavelength as the temperature of the Roots blower is varied. It can be seen that the Bragg wavelength shifts from approximately 1515.60 nm to 1517.00 nm for a temperature span of about 52.0 °C. A linear regression through all the measurement points suggest a sensitivity of $26.1\,\mathrm{pm\,^\circ C^{-1}}$, and a Bragg wavelength of 1514.61 nm at 0.0 °C. By using this linear regression model, the temperature at each wavelength response was calculated and compared to the temperature measured by the thermocouple. The difference between the two was then normalised as the relative error of the measured thermocouple temperature, and plotted in figure 5c. The relative error lies between -1.2 and 3.0 %, but 81 % of points lie within ±1 %.



(a) Side view of the Roots blower casing, indicating the positions of each sensor combination **(b)** Bragg wavelength shift as the casing's external temperature varies **(c)** Relative error between the calculated and measured temperatures, using the linear regression

Figure 5: Casing surface temperature measurements of FBG 3, as the Roots blower is operating at 1,500 rpm with an induced pressure ratio of 1.4

The results presented demonstrate a clear linear relationship between the temperature experienced by the FBG on the external casing of the FBG and the shift of its Bragg wavelength. It is not possible to distinguish the contribution of strain to the instrument response shown in Figure 5b, although it is certainly present and believed to be linearly proportional to the material's coefficient of thermal expansion. The higher relative errors seen in figure 5c, especially at the extremities of a cycle, could be an indication of mechanical hysteresis[4] or simply a difference between the FBG and thermocouple's response speeds.

Of the six FBG sensors tested, the three in the middle (sensors 3, 4 and 5) returned satisfactory responses despite a very crude integration of the sensor and epoxy at this early stage of the work. The remaining three presented large deviations from the linear model, and this was attributed to the difficulty of correctly co-locating the thermocouples because of the restricted space and curvature of the casing. With additional consideration for how the instrument should be embedded into its environment, its performance characteristics could be even better exposed and that is the subject of on-going work.

Subsequent tests will seek to integrate two optical fibres on the internal and external faces of the Roots blower. They will be positioned side by side in a dedicated groove, and one will be strain relieved for temperature compensation. Before operating the machine, and once fully instrumented with the FBG sensors, it will be placed into a climate chamber and calibrated at stabilised temperatures.

Finally, FBG-based sensors offer the opportunity for a multiplex sensor system to be installed. However, care needs to be taken in the positioning of the sensors and in optimising the environment that each grating experiences so that an accurate measurement process can be ensured. Additionally, each successive sensor along the fibre will inevitably decrease in reliability. If the structure of a series system (Bentley, 2005) is considered as the basis for estimating the reliability of a single element in a multiplex system, the probability that any one sensor survives is the product of the probabilities of each preceding sensors (since they are also required to survive).

5. CONCLUSION

The measurement of clearances in an oil-free screw compressor could provide experimental data of their variations during operation. This could be a key parameter in understanding the role that leakage flows play in the energy transfers inside the machine, and inevitably the impact on performance. While this data could be used to validate modelling tools, measurement techniques which are developed in this research could be employed as condition monitoring and control systems in industrial packages.

The scale at which a screw compressor is instrumented depends on the severity of the consequences should a failure

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[4] Perhaps a lag between the thermal expansion causing the deformation and the surface temperature change, where the sensor is interacting with the measurands.

occur. In practice, standards such as API 619 reflect the monitoring requirements and safeguards with typical packages outputting over a hundred measurement points. Data of the failure rates of instruments on such assets demonstrate the need to integrate robust components that can operate in harsh environments.

Three different measurement technologies were experimentally investigated so far. While the Eddy-current probe and optical fibre bundle can measure the variation of a distance directly, FBG sensors could potentially be used to measure strain and temperature as a way to determine changes in clearances. The limitation of the gap measurements presented are the static and desktop nature of the tests. Satish et al. illustrate well the uncertainties and errors that arise in dynamic conditions, for example because of the deformation the turbine casing in which the instrument is embedded (2014). Moreover the temperature measurements using the FBG sensor did not quantify the contribution of strain to the response, and an additional strain-relieved optical fibre may be able to offer temperature compensation to extract both measurands from the data. Therefore it is suggested that future experiments should embed the two probes into the casing of a rotating machine such as the Roots blower for dynamic measurements. In parallel the FBG sensors should be fixed to pre-cut grooves on the internal and external casing surfaces, and employ two fibres of which one is strain-relieved.

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