for measuring properties of a drive shaft to operate a propeller. According to the prior art, the sensors are preferably mounted in or on a (hollow) drive shaft to reduce space outside of the shaft. However, it can be difficult to measure small deformations of the drive shaft. According to the prior art, an optic fibre is wrapped around a shaft in such way that it defines three sections: a first section longitudinal to the shaft, a second section wherein two parts of the fibre are orthogonal to one another and a twist wherein a section is radial to the shaft. However, the known system may be complex to install and prone to installation errors that would lead to erroneous measurements. Furthermore, the known system may have difficulty distinguishing different types of deformation, e.g. separating torsion, bend, and axial deformations.

Accordingly, it is desired to provide an improved sensor system and method for monitoring a powertrain having a drive shaft wherein one or more problems associated with the prior art are alleviated while maintaining at least some of the advantages.

SUMMARY

An example of the present disclosure provides a sensor system for monitoring a powertrain having a drive shaft. The sensor system comprises an optical fibre comprising a strain sensitive element configured to change at least one of its optical properties as a function of strain on the sensor. The sensor system further comprises a connection structure configured to connect the optical fibre to the drive shaft wherein a strain on the drive shaft is passed by the connection structure to cause a strain on the strain sensitive element. The sensor system further comprises or couples to a light source connected to the optical fibre and configured to emit an input light signal to the optical fibre for optical interaction with the strain sensitive element. The sensor system further comprises or couples to a light detector configured to receive an output light signal from the optical fibre

The light source and detector can be integrated e.g. in an interrogator module connected to the optical fibre. By integrating the interrogator module in the connection structure, or otherwise attaching the light source and/or light detector to the drive shaft, it can be avoided that optical signals are transferred between the rotating strain sensitive elements and the fixed world. Power and other signals can be provided e.g. via an electrical slip ring. Alternatively, by integrating a power source in the connection structure, the slip rings can be avoided and the system can be fully self-contained. For example, sensor signals can be transmitted wirelessly to a control room. Alternative to an integrated interrogator module, optical signals can also be transferred to the rotating structure, e.g. via a fibre optic rotary joint. In this way the interrogator module can be kept in a separate location and is not affected by the harsh environments that can potentially surround the shaft, e.g. high temperature, vibration, motion etc. By using an off-axis fibre optic rotary joint, e.g. slip ring, the optical fibre can be passed between the rotating and stationary frame without needing to go to a central axis of the drive shaft.

By pre-stressing the optical fibre comprising the strain sensitive element while connecting, the said sensor element may change its optical properties in both directions, i.e. both for further elongation of the optical fibre and also for shortening of the fibre. In this way, changes in the length of the fibre caused by strain on the drive shaft can be measured both in the shortening and elongating of the shaft.

Another example of the present disclosure provides a sensor system for monitoring a powertrain having a drive shaft. The sensor system comprises one or more optical fibres comprising at least three strain sensitive elements arranged along at least three respective lengths of the one or more optical fibres wherein each strain sensitive element is configured to change at least one of its optical properties as a function of

elements can also be combined, e.g. by constructive interference to enhance the signal amplitude. In one example, FBGs are placed in locations of stretching and serve as the strain sensing elements. Here, the FBG reflection wavelengths will be different, to make sure they are individually monitored. As such, the reflections will not be interfered but e.g. interpreted together to gain more detailed mapping of the shaft and/or increase accuracy. In this case for example, two or even more FBGs can be used on one fiber. In another example, the FBGs are used as partial reflectors with overlapping reflection wavelengths and Fabry-Perot interferometry is performed whereby the constructive or destructive interference from the two reflections on measured section forms an amplitude signal indicative of the length change between the two reflectors.

By using an optional temperature sensor, the system may compensate for temperature offset and/or drift, e.g. temperature induced changes of the optical properties of the strain sensitive elements. Advantageously, an optical temperature sensor can be arranged along a length of the one or more optical fibres. For example, the optical temperature sensor may comprise another FBG. By tightly wrapping the fibre with optical temperature sensor around the structure of the drive shaft or connection structure (e.g. along a looped or helical path), a temperature change may cause expansion or contraction of the structure leading to a wavelength shift of the optical temperature sensor. Advantageously, the wavelength shift caused by the expansion or contraction of the shaft/connection structure may be the same direction as the wavelength shift caused by the direct effect of the temperature on the sensor. For example, the sensitivity of the optical temperature sensor can be enhanced by a factor of two, or more.

Yet another example of the present disclosure provides a method for monitoring a powertrain having a drive shaft. The method comprises

providing the sensor system according to any of the preceding claims, wherein one or more optical fibres of the sensor system are connected to the drive shaft. The method comprises emitting an input light signal to one or more optical fibres for optical interaction with one or more strain sensitive elements. The method comprises measuring an output light signal from the optical fibre resulting from the optical interaction of the input light signal with the one or more strain sensitive elements for measuring the respective strain on the one or more strain sensitive elements. The method comprises based on the measured respective strain, calculating one or more of a torque on the drive shaft, bending strain of the drive shaft, or thrust strain on the drive shaft.

The method may e.g. be used in combination with the system features according to the first and/or second examples. For example, the method may be used for adjusting operation of an engine driving the powertrain based on the calculated torque, bending, and/or thrust. The method may also comprise distinguishing between a torque induced deformation of the drive shaft and a bending deformation of the drive shaft by comparing respective signs of wavelength shifts in the optical properties of the at least three strain sensitive elements.

In view of the above, according to a first aspect of the present disclosure, there is provided a sensor system for monitoring a powertrain. The sensor system comprises an optical fibre comprising a strain sensitive element configured to change its optical properties as a function of strain on the sensor; a connection structure configured to hold a length of the optical fibre with the strain sensitive element at a radial distance remote from a drive shaft of the powertrain, wherein the connection structure is configured to connect the optical fibre to the drive shaft wherein a strain on the drive shaft is passed by the connection structure to the optical fibre for causing a strain on the strain sensitive element to be amplified with respect to the strain on the drive shaft by the radial distance, wherein the optical fibre

comprising the strain sensitive element is held pre-stressed at the radial distance by the connection structure in absence of strain on the drive shaft; a light source connected to the optical fibre and configured to emit an input light signal to the optical fibre for optical interaction with the strain sensitive element; and a light detector configured to receive an output light signal from the optical fibre resulting from the optical interaction of the input light signal with the strain sensitive element for measuring the strain on the strain sensitive element to monitor the powertrain.

According to a second aspect of the present disclosure, there is provided a method for monitoring a powertrain having a drive shaft. The method comprises: providing the sensor system according to any of the preceding claims, wherein one or more optical fibres of the sensor system are connected to the drive shaft; emitting an input light signal to one or more optical fibres for optical interaction with at least three strain sensitive elements arranged along at least three respective lengths of the one or more optical fibres, wherein the respective lengths of the one or more optical fibres follow parallel paths with respect to each other wherein the parallel paths extend at least in a direction along a length of the drive shaft; measuring an output light signal from the optical fibre resulting from the optical interaction of the input light signal with the at least three strain sensitive elements for measuring the respective strain on the at least three strain sensitive elements; and based on the measured respective strain, calculating one or more of a torque on the drive shaft, bending of strain on the drive shaft, or thrust strain on the drive shaft, wherein a torque induced deformation of the drive shaft is distinguished from a bending deformation of the drive shaft by comparing respective signs of wavelength shifts in the optical properties of the at least three strain sensitive elements.

BRIEF DESCRIPTION OF DRAWINGS

These and other features, aspects, and advantages of the apparatus, systems and methods of the present disclosure will become better understood from the following description, appended claims, and accompanying drawing wherein:

FIG 1A schematically illustrates a first embodiment of a sensor system wherein optical signals are coupled between an interrogator and strain sensor by an off axis fibre optic rotary joint;

CLAIMS

1. A sensor system (10) for monitoring a powertrain (20), the sensor system (10) comprising

- an optical fibre (2) comprising a strain sensitive element (3) configured to change its optical properties as a function of strain (S2) on the sensor;
- a connection structure (4) configured to hold a length of the optical fibre with the strain sensitive element at a radial distance remote from a drive shaft of the powertrain, wherein the connection structure is configured to connect the optical fibre (2) to the drive shaft (1) wherein a strain (S1) on the drive shaft (1) is passed by the connection structure (4) to the optical fibre for causing a strain (S2) on the strain sensitive element (3) to be amplified with respect to the strain on the drive shaft by the radial distance, wherein the optical fibre comprising the strain sensitive element is held pre-stressed at the radial distance by the connection structure in absence of strain on the drive shaft;
- a light source (5) connected to the optical fibre (2) and configured to emit an input light signal (Li) to the optical fibre (2) for optical interaction with the strain sensitive element (3); and
- a light detector (6) configured to receive an output light signal (Lo) from the optical fibre (2) resulting from the optical interaction of the input light signal (Li) with the strain sensitive element (3) for measuring the strain (S2) on the strain sensitive element (3) to monitor the powertrain.

2. The sensor system (10) according to claim 1, wherein the drive shaft has a shaft radius (R1) and the strain sensitive element (3) is held by the connection structure (4) at a distant radius (R2) from a centre of the drive shaft (1), wherein the distant radius (R2) is at least a factor one and a half times the shaft radius (R1).

3. The sensor system (10) according to any of the preceding claims, wherein the connection structure (4) comprises at least two rigid rings

(4a,4b) of high rigidity composite configured to clamp around an outer surface of the drive shaft (1).

4. The sensor system (10) according to any of the preceding claims, wherein the connection structure (4) comprises at least two rigid rings (4a,4b) disposed at an axial distance from each other configured to hold the length of the optical fibre with the strain sensitive element (3) there between, wherein the strain on the drive shaft is passed by the rigid rings of the connection structure to the optical fibre held there between for causing the strain on the strain sensitive element to be amplified with respect to the strain on the drive shaft by the radial distance, wherein the optical fibre comprising the strain sensitive element is held pre-stressed between the rigid rings at the radial distance in absence of strain on the drive shaft.

5. The sensor system (10) according to claim 4, wherein the connection structure (4) comprises a cylindrical intermediate part disposed along an axis of the drive shaft between the at least two rigid rings, wherein a rigidity of the intermediate part is lower than respective rigidities of the rigid rings.

6. The sensor system (10) according to any of the preceding claims, comprising at least three strain sensitive elements (3a,3b,3c) arranged along at least three respective lengths (2a,2b,2c) of one or more optical fibres (2a,2b,2c) at the radial distance remote from the driving shaft, wherein the connection structure (4) is configured to hold the respective lengths (2a,2b,2c) along parallel paths with respect to each other, wherein the parallel paths extend at least in a direction along a length of the drive shaft (1).

7. The sensor system (10) according to any of the preceding claims, wherein the system comprises a fibre optic rotary joint (7) with an off-axis fibre optic slip ring.

8. The sensor system (10) according to any of the preceding claims, wherein the light source (5) and/or light detector (6) are comprised in the connection structure (4) rotating with the drive shaft (1).

9. The sensor system (10) according to any of the preceding claims, comprising a memory for recording the measured strain on the strain sensitive elements as a function of time; and a processor configured to calculate vibrational components in the drive shaft (1) based on the measured strain as a function of time.

10. The sensor system (10) according to any of the preceding claims, comprising an interferometer configured to receive two or more output light signals from the optical fibre (2) resulting from the optical interaction of the input light signal with two or more partially reflective elements (3e,3f) for interferometrically combining two or more output light signals from the elements (3e,3f) for measuring the strain by the interferometric combining.

11. The sensor system (10) according to any of the preceding claims, comprising

- one or more optical fibres comprising at least three strain sensitive elements (3a,3b,3c) arranged along at least three respective lengths (2a,2b,2c) of the one or more optical fibres, wherein the respective lengths of the one or more optical fibres follow parallel paths around a drive shaft of the powertrain, wherein the parallel paths are equidistant with respect to each other along a circumference of the drive shaft, wherein each strain sensitive element is configured to change at least one of its optical properties as a function of strain (S2) on the respective length of the optical fibre comprising the strain sensitive element; wherein the respective lengths (2a,2b,2c) of the one or more optical fibres are connected to the drive shaft (1) wherein the connection is configured to pass a strain (S1) on the drive shaft (1) to cause as a respective strain (S2a,S2b,S2c) on the strain sensitive elements (3a,3b,3c);
- one or more light sources (5) connected to the one or more optical fibres and configured to emit input light signals (Li) to the one or more optical fibres for optical interaction with the strain sensitive elements (3a,3b,3c); and

– one or more light detectors (6) configured to receive output light signals (Lo) from the one or more optical fibres (2a,2b,2c) resulting from the optical interaction of the input light signals (Li) with the strain sensitive elements (3a,3b,3c) for measuring the respective strain (S2a,S2b,S2c) on the strain sensitive elements (3a,3b,3c) to monitor the powertrain by comparing respective signs of wavelength shifts in the optical properties of the at least three strain sensitive elements for distinguishing at least between a torque induced deformation of the drive shaft and a bending deformation of the drive shaft.

12. The sensor system (10) according to claim 11, wherein the respective lengths (2a,2b,2c) of the one or more optical fibres comprising the strain sensitive elements (3a,3b,3c) follow parallel helical paths extending around the drive shaft (1).

13. The sensor system (10) according to claim 11 or 12, comprising a first length (2a) of the one or more optical fibres comprising a first strain sensitive element (3a), and a second length (2d) of the one or more optical fibres comprising second strain sensitive element (3d), wherein the first and second lengths (2a,2d) follow opposite helical paths around the drive shaft (1).

14. The sensor system (10) according to any of claims 11 – 13, wherein an optical temperature sensor (3T) is comprised in a length (2d) of the one or more optical fibres that is tightly wound around the drive shaft (1) and/or connection structure (4)..

15. The sensor system (10) according to any of claims 11 – 14, wherein the respective lengths (2a,2b,2c) of the one or more optical fibres are equidistantly distributed along a circumference around the drive shaft (1).

16. The sensor system (10) according to any of claims 11 – 15, wherein the respective lengths (2a,2b,2c) of the one or more optical fibres are connected to the drive shaft (1) by a connection structure (4) configured to hold the respective lengths (2a,2b,2c) at a radial distance remote from the

drive shaft (1) for amplifying the strain (S2) on the respective lengths (2a,2b,2c) of the one or more optical fibres comprising the strain sensitive elements (3a,3b,3c) with respect to the strain (S1) on the drive shaft (1).

17. A method for monitoring a powertrain (20) having a drive shaft (1), the method comprising

– providing the sensor system (10) according to any of the preceding claims, wherein one or more optical fibres (2) of the sensor system (10) are connected to the drive shaft (1);

– emitting an input light signal (Li) to one or more optical fibres (2) for optical interaction with at least three strain sensitive elements (3) arranged along at least three respective lengths of the one or more optical fibres, wherein the respective lengths of the one or more optical fibres follow parallel paths with respect to each other wherein the parallel paths extend at least in a direction along a length of the drive shaft;

– measuring an output light signal (Lo) from the optical fibre (2) resulting from the optical interaction of the input light signal (Li) with the at least three strain sensitive elements (3) for measuring the respective strain (S2) on the at least three strain sensitive elements (3); and

– based on the measured respective strain (S2), calculating one or more of a torque on the drive shaft (1), bending of strain (S1) on the drive shaft (1), or thrust strain (S1) on the drive shaft (1), wherein a torque induced deformation of the drive shaft is distinguished from a bending deformation of the drive shaft by comparing respective signs of wavelength shifts in the optical properties of the at least three strain sensitive elements.

18. The method according to claim 18, comprising

– adjusting operation of an engine (21) driving the powertrain (20) based on the calculated torque, bending, and/or thrust.

19. The method according to claim 18 or 19, wherein a first length of the one or more optical fibres comprises a first strain sensitive element, and a second length of the one or more optical fibres comprises a second strain sensitive element, wherein the first and second lengths follow opposite helical paths around the drive shaft, wherein the method comprises distinguishing between a torque induced deformation (α) of the drive shaft (1) and a thrust induced deformation (ß) of the drive shaft (1) by comparing respective signs of wavelength shifts in the optical properties of the first and second strain sensitive elements.

20. The sensor system according to any of the preceding claims 1 to 16, wherein each strain sensitive element (3; 3a,3b,3c) is formed by a Fiber Bragg Gratings (FBG).

21. The sensor system according to any of the preceding claims 1 to 16 and 20, wherein the powertrain is a powertrain of a boat or ship.

22. The method according to any of the preceding claims 17 to 19, wherein each strain sensitive element (3; 3a,3b,3c) is formed by a Fiber Bragg Gratings (FBG).

23. The method according to any of the preceding claims 17 to 19 and 22, wherein the powertrain is a powertrain of a boat or ship.