DOI: 10.3217/978-3-99161-057-1-113

Vibration Analysis of Ship Hulls using Fiber Bragg Grating

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ABSTRACT: The paper outlines an ongoing research project, incorporating Fiber Bragg Grating (FBG) systems to measure and detect the vibration in a ship's hull. The causes of such vibration are due to the various engines and motors on board, as well as the force induced by the movement of the sea, and the vibration induced into the hull by the propellor. Five ships in all have been monitored using the FBG system, using both 3 sensor rosettes, and chains of 10 sensors. All the sensors used were glued to the ships' hulls and various sea trials carried out. The tests included gathering data with the engines switched off, the engines running at various speeds, both whilst stationary in the harbour as well as whilst sailing.
Change detection is the main application of such monitoring, and such change is evident and detected due to a broken flange on one ship, and a new engine on one ship. Data were gathered before and after such effects were changed. The induced vibration due to the propellor is also evident.

KEY WORDS: Fibre Bragg Grating, Deflection monitoring, frequency analysis, SHM.

1 INTRODUCTION

Previous work conducted by the authors has focused on using RTK GNSS [1, 2] to monitor the long-term deformations of large bridges [3] as well as measuring the short-term deflections of such structures [4, 5, 6, 7, 8, 9] and extracting the frequencies of the movements [4, 7, 10]. Such deflection measurements and resulting frequency analysis can be used to detect movement characteristics of the structure due to damage or long-term deterioration. In parallel, the use of Fiber Bragg Grating (FBG) approaches was used to measure long term deformations of infrastructure such as roads and tunnels [11, 12, 13].

Both approaches were brought together by the authors [14] to use the high data rate and very precise data of the FBG system to measure dynamic characteristics of ship structures. Ships are structures that deform and deflect. Such deflections are caused by various external forces, such as the force induced on the hull by the sea as well as vibrations in the structure of the ship caused by various engines and motors on board. Ships, like all structures, can experience damage and long-term deterioration. These can result in deflections and vibrations in the ship's structure changing in characteristics over time or even instantly. The hypothesis of our research is that sudden changes in the characteristics of the ship's structure, caused by damage, can be detected by measuring changes in the frequencies observed in the vibration and deflection of the structure. The research objective of this current work is to be able to measure changes in the frequency response of the ship in relation to any damage or changes made to the ship. This was done by carrying out measurements using a FBG system on several ships, three of which exhibited damage or changes in engines, which resulted in the frequency responses changing. We gathered data on such vessels before and after any damage was fixed or engine changes were made.

FBG sensors were installed on a passenger ship in the Faroe Islands, and data were gathered at a rate of 1kHz during normal scheduled activity in 2017 and 2018 [14] and at a rate of 5kHz during the more recent tests. The frequency responses of the data were extracted to identify the frequency characteristics of the structure i.e. ship. The movements are caused by the ships' engines, motors and external factors such as weather and sea effects. In addition, vibrations are caused by the rotation of the propellor inducing force on the ship hull and causing vibrations. Further, change detection in these characteristics is possible, therefore detecting early damage to such infrastructure.

Following the initial sea trials, a three-year research project was undertaken to further this work.

2 FBG SENSORS

Fiber Bragg Gratings (FBGs) are patterns of refractive index changes inscribed in the core of a glass fiber with a typical length of about 1cm. When a broadband light source emits light into the fiber, the FBG behaves as a wavelength dependent mirror, meaning that only that portion of light with a wavelength corresponding to the spacing of the grating is reflected whereas other wavelengths can pass the grating unaltered, Figure 1. Hence, several gratings with different wavelengths can be placed along a single fiber enabling tens of sensor locations. The FBG sensors sample strain measurements at a rate of kHz with a precision of better than 1$\mu\varepsilon$ (= 1 ppm = 1μm/m) and can be used for long term static monitoring as well as dynamic monitoring [11].

If local strain changes occur, the spacing of the patterns change and thus also the wavelength of the reflected signal peak changes. With appropriate calibration of FBG sensors [12] the recorded wavelength change can be reliably converted into a strain change. However, local temperature changes have an impact on the refractive index of the fiber and thus lead to a

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wavelength change of the backscattered signal. A common method to numerically compensate the temperature impact is to place one or more FBGs along the sensing fiber, or to use a separate FBG, which are not coupled to the measurement object and thus only sensitive to temperature changes. The recorded wavelength changes of these gratings are in the processing subtracted from the measured wavelength changes from the rigidly connected FBGs. The remaining wavelength changes are then the real strains of the object.

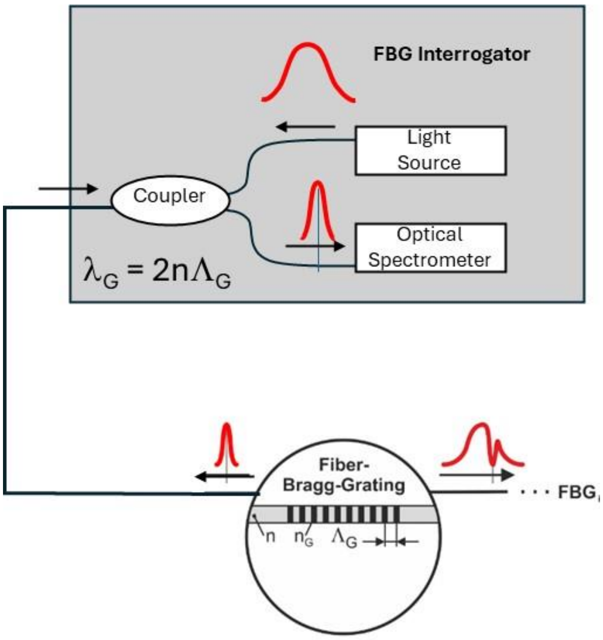

Figure 1. Principle of FBG measurements [14].

To monitor strains of the hull of the ship two different types of FBG sensor chains were used during the field tests. Firstly, a strain rosette, incorporating three FBG sensing elements, Figure 2. The rosette is an equilateral triangle, and the orientation of the three sensors of the strain rosette differs by 60°. Hence with this layout it is possible to determine the magnitude and direction of the principal strain. However, with one strain rosette these values can only be determined on one location.

In order to determine the strain distribution a secondary buffered FBG chain incorporating 13 FBG elements on the original Smyril tests conducted in 2017 and 2018, and 10 on all the more recent tests, Figure 3, were used. One of the sensors is loosely embedded in the chain and acts as temperature sensor, used for compensation measurements whilst the other 12 or 9 are rigidly embedded and capture the strain of the hull. The FBG chains were laid out in a meander shape glued on the inside of the ship's hull with sensors laid in the horizontal and vertical directions. Both the strain rosette and the secondary buffered FBG chain were installed on the inside of the hull of the ships in the engine room.

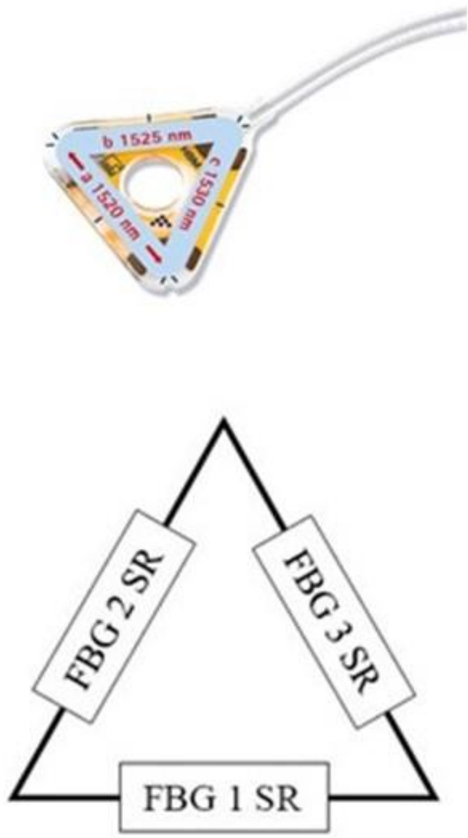

Figure 2. A strain rosette incorporating three FBG sensing elements [15].

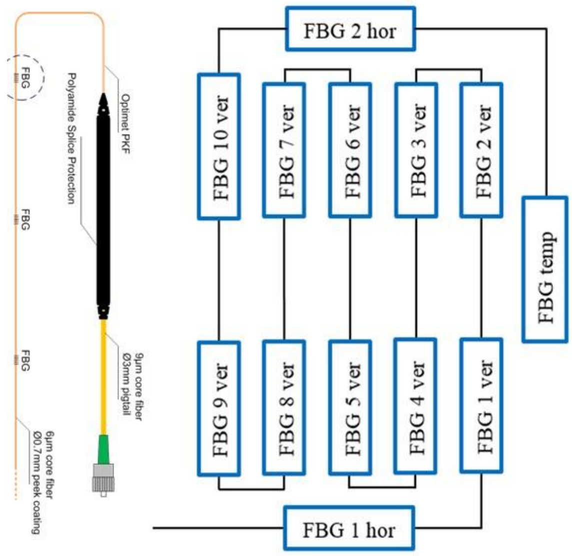

Figure 3. A secondary buffered FBG chain incorporating 1 temperature FBG sensor and 12 strain FBG element [15] positioned in both horizontal and vertical orientation.

3 FIELD TESTS

Five vessels were experimented upon, these being

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- Smyril passenger ferry, operated by SSL (A 135m long passenger and vehicle ship, data were gathered before and after repairs were made to a flange)
- Jákup Sverri research vessel, operated by Havstovan (55m long research ship)
- Krosstindur, a fish farm vessel operated by Luna (15m long service vessel, we gathered FBG data before and after a new engine was installed)
- Samson, tugboat operated by MEST
- Gadus, a large fishing trawler owned by JFK (88.1 long ship with vibrations detected at high speeds)

The tests were conducted, where possible, under different conditions i.e. main engine on/off, propellor running/stationary, low speed passage and high-speed passage. The various parameters helped to identify the sources of the various vibrations detected using the FBG system. The data from Gadus, Smyril and Jákup Sverri were gathered whilst the ships were operational at sea, whilst the other vessels were gathered in and around the harbour areas but being able to vary the speeds and when the engines were switched on and off.

The sensors come in a number of different formats. They are glued onto a very clean surface on the body of the ship, such as the inside of the hull. The surface of the hull is thoroughly cleaned of grease using alcohol-based products, and the surface is also rubbed with sandpaper in order to create a good surface for the glue to work on. We used a rosette sensor, that incorporates three sensors in an equilateral triangle shaped housing, as well as a chain of 10 sensors. Figure 4 illustrates a rosette (left) and chain (right). Both cost around 1000 euros. However, the rosette is far easier and quicker to install, and the three measurements are at 60° to each other, whereas the chain takes 10 measurements, and each individual sensor along the chain are 1m apart, so it can cover a larger area. The chain also takes longer to install as each of the 10 sensors need to be attached individually using an epoxy resin glue.

Figure 4. Rosette sensor on the Gadus (left) and chain sensor on the Jákup Sverri (right).

Figure 5 illustrates the interrogator unit (left) and the software used to gather the data, showing the real time data from 13 FBG sensors on a chain located on the Smyril (right). The interrogator costs around 30,000 Euros, and this version gathers data at a rate of 5 kHz. Up to four sensors can be attached to the interrogator unit at any one time. The approach that we have is to install a number of FBG sensors on a number of vessels, and rotate the interrogator unit between them.

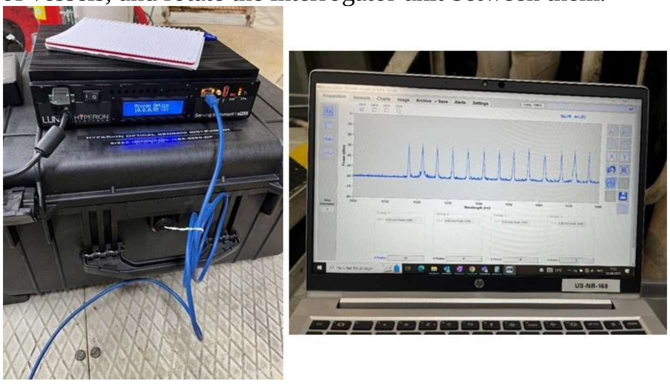

Figure 5. The interrogator unit (left) and a screenshot of the software used to gather the data (right).

A test rig was used in order to assess the precision of the system as well as the various sensor types. This is a rotating motor, with weights attached to the drive wheel in order to cause vibrations. Figure 6 illustrates the test rig used on a bench test with a rosette FBG sensor and an FBG chain attached to the table.

The chain was co-located with the FBG in order to compare results, and a couple of the chain sensors located on the chair away from the vibrating table as a baseline.

Figure 6. The vibrating test rig during a bench test, with a FBG chain and FGB rosette located on the table.

Possible applications are as follows. Once an initial installation of the sensors is carried out, subsequent data

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collection can be compared to the initial data and change detection in the frequency response of the structure can be determined. Such changes in frequency response can be down to several factors, such as damage to the ship, damage to the propellors, or gradual deterioration of the vessel.

4 RESULTS AND DISCUSSION

4.1 Smyril

The Smyril data was compared to historical data that we gathered in 2017 and 2018 using a similar system belonging to TU Graz. During the initial tests, a flange was damaged at the stern of the ship, and vibration could be felt throughout the ship. We can see this in the data from 2017 and 2018, Figures 7 and 8, and it being absent in the new data we gathered during this current project, Figure 9.

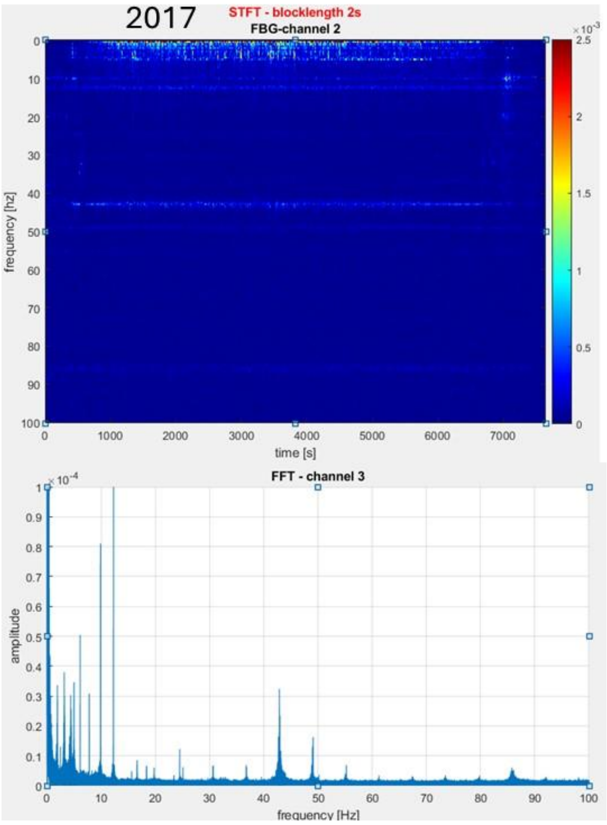

Figure 7. Waterfall and FFT plots from the tests conducted on Smyril in 2017.

The data from 2017 and 2018, Figures 7 and 8 respectively, illustrate the results showing more and noisier frequency characteristics than the more recent tests in 2023, Figure 9. This is especially true in the data in 2017 below 13Hz, Figure 7. The original setup consisted of a FBG rosette and a chain of 13 sensors glued to the inside of the ship's hull in the engine room. However, the connectors to the rosette had been cut off, for some reason sometime between the 2018 and 2023 tests, so this sensor couldn't be used in 2023. However, the FBG chain worked perfectly well. It is thought that the less frequency responses, and cleaner frequency characteristics are due to there being a broken flange at the rear of the vessel during the 2017 and 2018 tests.

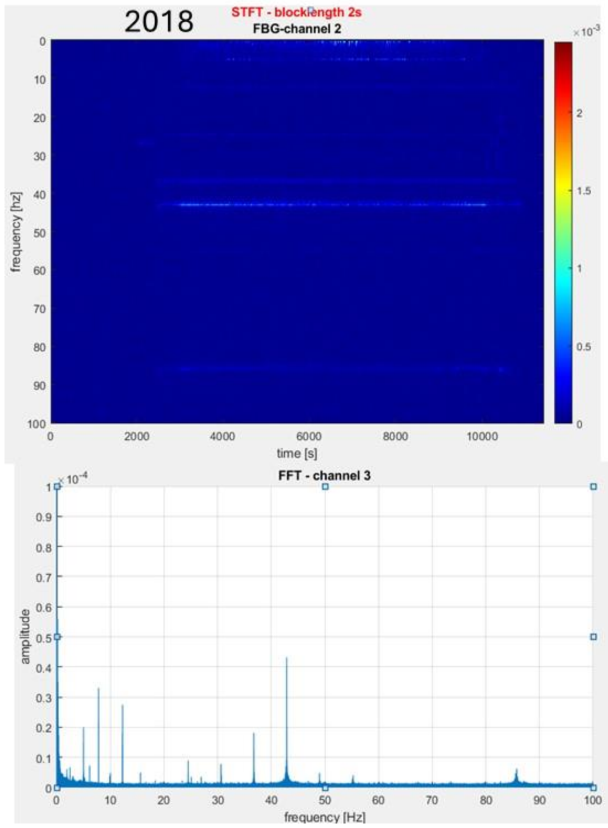

Figure 8. Waterfall and FFT plots from the tests conducted on Smyril in 2018.

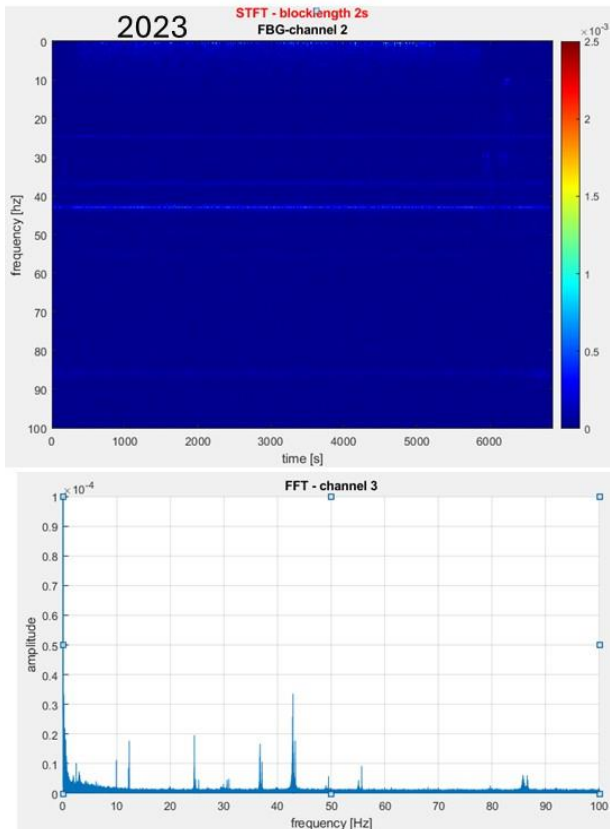

Figure 9. Waterfall and FFT plots from the tests conducted on Smyril in 2023.

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4.2 Krosstindur

Figure 10. The Krosstindur vessel.

The Krosstindur vessel, Figure 10, was suffering from vibration, and a new engine was installed with a lower vibration characteristic. Again, we gathered data before and after the engine was replaced, and we could see significant differences in the characteristics. More vibrations can be seen in Figure 11 (top) when the old engine was used, compared to the new engine, Figure 11 (bottom).

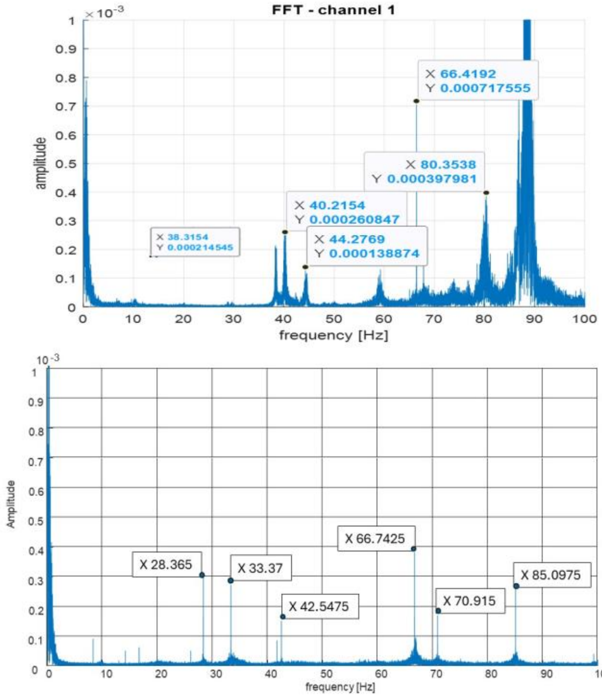

Figure 11. FFT results from the tests conducted on Krosstindur before (top) and after (bottom) the engine was replaced.

4.3 Gadus

Gadus is a relatively new fishing trawler/factory. It is owned and operated by JFK. Rosette sensors were installed next to the rudder housing, Figure 12 (bottom), as well as in the bridge, Figure 12 (top right), and FBG chains were placed in the chief engineer's cabin, Figure 12 (top left), and in the engine room, Figure 12 (middle). The data were gathered during one of the ship tours in the Baren Sea. The interrogator spent periods of time attached to the various sensors during sailing and trawling, and notes were recorded of the ship speed, engine speed etc.

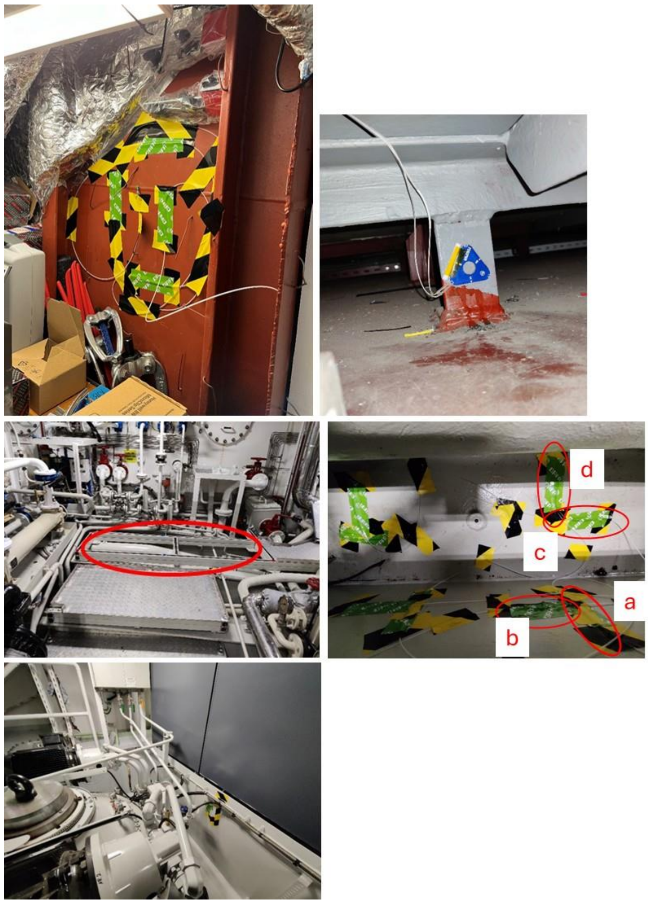

Figure 12. Sensor locations on the Gadus. FBG chain attached to a structural girder in the Chief Engineer's cabin (top left), Rosette attached to the structure in the bridge (top right), Engine room location of FBG chain (middle left) and the chain (middle right), Rosette located adjacent to the rudder (bottom).

Figure 13 illustrates a selection of FFT plots resulting from the FBG chain sensor in the engine room. All the results correspond to the same time series. The graphs show the FFT for the four locations, marked a-d in Figure 12 (middle right). It can be seen that there are different frequency response characteristics for the four locations, even though they are relatively close to each other. It is seen that the two horizontal results on the horizontal girder, a and b, show that there is a stronger vibration response in the bow to stern direction, and that the vertical girder results show that the vertical direction response has least vibration. All such responses have been shown to the chief engineer to help understand the vibration characteristics of the ship. These results illustrate that it is important to understand that the orientation of the sensor is important in order to measure specific frequencies.

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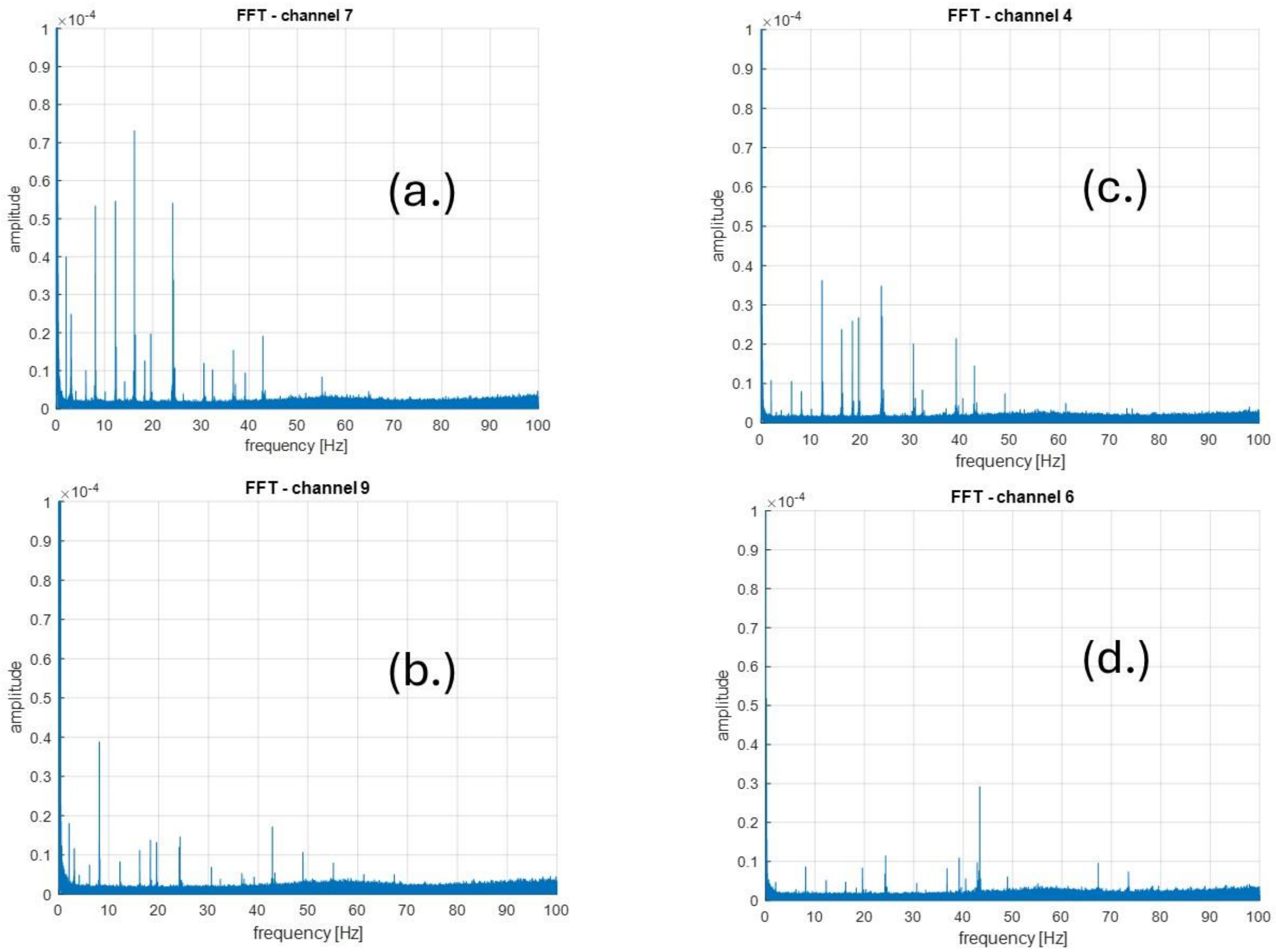

Figure 13. FFT results from the tests conducted on Gadus in the engine room. The graphs show the FFT response in the horizontal direction (stern to bow direction) on the horizontal girder (a.), the horizontal direction (port to starboard direction) on the horizontal girder (b.), the horizontal direction (port to starboard direction) on the vertical girder (c.), and the vertical direction on the vertical girder (left). Figure 12 (d.) a, b, c, d respectively.

Figure 13 (b.) illustrates the details of the FFT response at location b, Figure 12. The engine at this instance was operating at 735 RPM, and the propellor rotating at a speed of 122 RPM. The corresponding frequencies to these values are 12.25 Hz and 2.03 Hz respectively. These correspond well to the values of 12.24 Hz and 2.03 Hz in Figure 13 (b.). Further to this, the propellor has four blades, and 4x 2.03 Hz is equal to 8.1 Hz, again corresponding to the value of 8.1 Hz in Figure 13.

5 CONCLUSIONS

The paper outlines the field tests conducted using the FBG sensors to measure the frequency characteristics of ships. Two types of sensors are used, these being a FBG rosette and a FBG chain of 10 sensors. We can clearly detect changes in characteristics, as well as detecting the vibrations induced into the ship by various elements of the ship such as the engine and propellor.

The FBG sensors are relatively inexpensive, and can be installed on many vessels, then using a single interrogator to

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gather data periodically, or when changes are thought to have occurred, in order to investigate any changes.

Gathering such data on a vessel can then be used as a blueprint to compare future data.

The measurements can be carried out at sea, so the vessel doesn't need to return to harbour, resulting in minimal down time in the vessel's activities.

Sudden changes due to damage or gradual changes due to deterioration can be detected.

ACKNOWLEDGMENTS

The project was funded by the Research Council of the Faroe Islands, through the project (04589) HARMONISE - HeAlth and EnviRonmental MONItoring of Ships and PropEllers.

The authors are also very grateful to the help of the staff at MEST, JFK, Luna, SSL and Havstovan for their help and assistance in obtaining access to the vessels and invaluable input to the project.

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