TECHNICAL NOTE

VIRTUAL HULL MONITORING: CONTINUOUS FATIGUE ASSESSMENT WITHOUT ADDITIONAL INSTRUMENTATION

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SUMMARY

A novel technique to monitor hull stresses using data currently collected on most ships is explored. This technique, referred to herein as virtual hull monitoring, uses global position signals, measured or numerically-modelled wave data, and a database of calculated stress transfer functions. This enables monitoring of short-term stress states and corresponding fatigue damage accumulation for many structural locations, either onboard or at a central location, for an entire fleet. The components, benefits, and limitations of this proposed technique are discussed. Wave buoy and strain gauge measurements from a full-scale naval vessel trial are used in comparisons with hindcast wave data and the calculated stress spectra for one structural location. Close agreement between the wave data sources and corresponding stress spectra warrants further examination of virtual hull monitoring.

NOMENCLATURE

D_p	Primary wave direction (°)
FPSO	Floating production storage and offloading
GPS	Global positioning system
H_s	Significant wave height (m)
RAO	Response amplitude operator
RMS	Root-mean-square
S-AIS	Satellite – Automatic Identification System
S-N	Stress range – number of cycles
T_z	Zero-crossing period (s)

1. INTRODUCTION

Fatigue cracks in ship hulls initiate primarily from cyclic interactions with millions of sea waves. Unchecked, small cracks can develop into major problems or even catastrophic failures. The threat of operating with compromised structure motivates extensive inspection, repair, and hull monitoring regimes. Modern ships rationally designed to limit weight may assess fatigue life in design. However, in operation, the ship may experience conditions that vary significantly from design assumptions.

A ship's structural response can be directly measured with a hull monitoring system. Strain and acceleration are commonly measured and corresponding wave condition measurements are occasionally monitored with mounted wave radars. The measurements can be used to calculate the consumption of the fatigue damage budget through the ship's life, facilitating better through-life platform management.

Costs limit hull monitoring. There are initial expenses to acquire and install instrumentation as well as ongoing maintenance expenses. Challenges remain to store, handle, and interpret measurement data (Hess, *et al*, 2015; Kaminski, *et al*, 2006). This study is motivated by the desire to maximise the ratio of hull monitoring benefits to the total costs.

This study examines a hull monitoring technique that uses data currently collected on most ships. The global location signal, such as those from the Global Positioning System (GPS) or Satellite – Automatic Identification System (S-AIS), can identify a ship's location, speed, and heading at any given time. Wave data can be acquired from onboard wave measurements (if available), by using the global position to query online wave hindcast datasets, or using alternative sources. Combining these two types of data yields ship speed, relative heading, and wave conditions for short periods of time (in the order of an hour). The loading condition can be determined from the draught reported on the S-AIS signal or from the ship's load monitoring system. These environmental and operational conditions can be combined with methods to determine the hydrodynamic loads and corresponding stresses. In this study, a database of stress transfer functions generated using spectral fatigue analysis is used to calculate stress spectra. However, simpler or more complicated methods may be suitable, depending on the ship. This technique, referred to herein as virtual hull monitoring, enables continuous automated fatigue assessment in near real-time, either onboard or at a centralised location. Following validation, this technique may enable hull monitoring with reduced instrumentation.

No mention of the virtual hull monitoring technique described herein was found in a literature review. Similar work has been done for floating production storage and offloading (FPSO) units with the Monitas system (Aalberts, 2010). It involves measuring waves and performing spectral fatigue analysis calculations to complement measurements. FPSO assessment does not require that speed be taken into account and the relative heading is calculated for each sea state as the mean stable vessel heading. In a study by Mao *et al*. (2010), container vessel fatigue assessments with actual and alternative routes were conducted using a simplified fatigue model and wave hindcast data. The goal was to show that accounting for fatigue in ship routing could be beneficial. The required calculations are similar to those in the current study, but the focus differs significantly.

An explanation of virtual hull monitoring is provided in Section 2. Interim results from a reanalysis of a full-scale naval vessel trial are presented in Section 3 with a discussion of the results and technique benefits and limitations. Conclusions and future work are discussed in Section 4.

2. VIRTUAL HULL MONITORING

The proposed hull monitoring technique involves performing fatigue assessments for each short-term condition using readily-available sources. In this section, the components are described.

2.1 SPECTRAL FATIGUE ANALYSIS

The current application of spectral fatigue analysis is built on the notion that a ship's operational life consists of many spatiotemporal segments, each with a combination of ship speed, relative heading, loading condition, and wave conditions (Sikora, *et al*, 1983). The probability of experiencing any given combination of these factors is the product of the probabilities for each parameter. Hydrodynamic analysis is used to predict the loads, as bending moment or pressure response amplitude operators (RAOs) from wave and hull interactions for the considered conditions. Stress RAOs are calculated from load RAOs for each combination of speed, heading, and loading condition, commonly with beam analysis or finite element analysis. If finite element analysis is used with hydrodynamic pressure loads, all wave load components are included. Stress spectra for considered conditions can be calculated and combined with a stress-number of cycles (S-N) curve to estimate the time for a through-thickness fatigue crack to form. An overview of spectral fatigue analysis is provided in Guedes Soares, *et al*, 2006.

2.2 WAVE DATA

In order to get meaningful results with spectral fatigue analysis, good wave data are required. The source (or combination of sources) must be accurate and have temporal and spatial coverage that include the considered ship's operations. A review of wave data sources is provided by Vanem, 2011. Although there are other potential wave data sources such as satellite wave measurements [8], wave data fusion (Stredulinsky and Thornhill, 2011), or extensive wave buoy measurements [10], this study examines the use of wave hindcasts.

Wave hindcasts generate predictions of historical sea wave conditions. Wind wave spectral models determine the wave conditions for a calculated wind field, based on historical climate measurements. The hindcast data used in this study are from the WAVEWATCH III® 30-year Hindcast Phase 2 [11]. The hindcast has a global grid of 0.5° with local refinements in several areas. Two-dimensional spectra and wave statistics are available every three hours from 1979–2009. A related ongoing hindcast has data from February 2005 to present with monthly updates [12]. A validation study of the ongoing hindcast found the significant wave height bias varied, but was within 50 cm globally (Chawla *et al*, 2009).

2.3 SHIP'S LOCATION AND LOADING

A ship's speed, relative heading, and loading condition are required to determine accurate hydrodynamic loads. These can be obtained from the combination of an S-AIS signal or a recorded GPS signal and wave data. If S-AIS signals are used, the broadcast speed, heading, and draught values are available. If the S-AIS draught value is not sufficient to determine the loading condition, data from the ship's load management system may be used. Daily reports sent to headquarters or departure and arrival condition reports could be used to determine the loading conditions.

3. RESULTS AND DISCUSSION

3.1 INTERIM RESULTS

The interim results developed in this study use the same models, software, and wave buoy measurements as a spectral fatigue analysis validation study for a naval vessel (Thompson, 2016). That study showed good agreement between stress spectra calculated with spectral fatigue analysis and stress spectra derived from strain gauge measurements, particularly near midship. The trial was conducted in the North Atlantic on or near the Grand Banks of Newfoundland; the trial runs covered an area over 5° of latitude and 13° of longitude. It consisted of 75 legs, each with constant speed (nominally 10 or 20 knots) and heading. Divided into 15° relative heading increments, there were 7 legs near head seas and the rest were approximately evenly distributed over 360°. Significant wave heights were between 0.7 m and 6.1 m.

In this study, hindcast data are compared with trial wave buoy measurements. Stress spectra at the bottom of the keel girder near midship were calculated for the 75 trial legs using each wave dataset. The spectra are compared to one another and spectra derived from strain gauge measurements. The significant wave height (H_s), zero-crossing period (T_z), and primary wave direction (D_p) were used in a two-parameter Pierson-Moskowitz spectrum (Stansberg, *et al*, 2002) and a cosine-squared spreading function (DNV, 2014). The GPS record was used to determine the ship speed and heading, as in the previous study. The midpoint of each trial leg was used to identify the appropriate hindcast entry; 25 hindcast data points were used for the 75 trial legs. In the trial area, hindcast data are available on a 0.5° grid. As in the previous study, the hydrodynamic analyses were conducted with the PRECAL_R software (van Daalen and Sireta, 2014); spectral fatigue analyses were done within the STRUC_R software (Thompson, *et al*, 2013).

Table 1 presents a summary analysis of the hindcast data and wave buoy measurements. The direction bias was calculated as the mean of the differences ($D_{p\text{-}hindcast} - D_{p\text{-}buoy}$) when the directions were defined within ±180°. The RMS error values used the buoy measurements as the reference in the same manner. The averages of significant wave height and zero-crossing period agree quite well, but the direction agreement is poorer. The root-mean-square (RMS) error values indicate there is significant scatter. The bias and RMS error are similar to reported values for the significant wave height (Chawla, *et al*, 2009; Caires, *et al*, 2004). Notable outliers include a trial leg with a hindcast significant wave height over-prediction of 3.75 m and three trial legs with directions that differed by about 160° from buoy measurements. The direction outliers came from the same hindcast data point. The height outlier was from another hindcast data point separated from the direction outlier by several days and several hundred kilometres. The results are promising because many of the trial legs were near the edge of the Grand Banks, an area where significant local bathymetry changes would not be represented at the wave model resolution [20].

Table 1: Comparison of wave data from trial deployed buoy and hindcast for all trial legs.

	Mean H_s (m)	RMS Error (m)	Mean T_z (s)	RMS Error (s)	D_p bias (°)	RMS Error (°)
Buoy	2.96	-	6.27	-	-17.7	-
Hindcast	2.99	0.66	6.10	0.82		37.4

The RMS stresses and stress zero-crossing frequencies calculated using the wave buoy measurements and the wave hindcast data are shown in Figures 1 and 2, respectively. A summary of the analysis is shown in Table 2; note that the R^2 values are based on regression analysis through the origin (Eisenhauer, 2003). Slightly more dispersion is seen in both parameters calculated using hindcast data than with buoy data. That is, the RMS errors for the hindcast stresses and frequencies are about 20% and 10% greater, respectively. The two sets of calculated results are very similar to one another and differences in the best-fit line slopes are small. Also, 77% of the hindcast RMS stresses and 88% of the hindcast stress zero-crossing frequencies are within 25% of the corresponding values calculated using buoy data. The calculated RMS stress agrees quite well with values derived from strain measurements; the under-prediction of stress zero-crossing frequencies are consistent between the two sets of wave data. In the previous study (Thompson, 2016), the use of a 2-d wave spectrum changed the slopes of the best-fit lines for RMS stress and zero-crossing frequency to 0.98 and 0.94, respectively. This suggests the under-prediction of zero-crossing frequency in Figure 2 may be due to the approximations in the wave spectrum model.

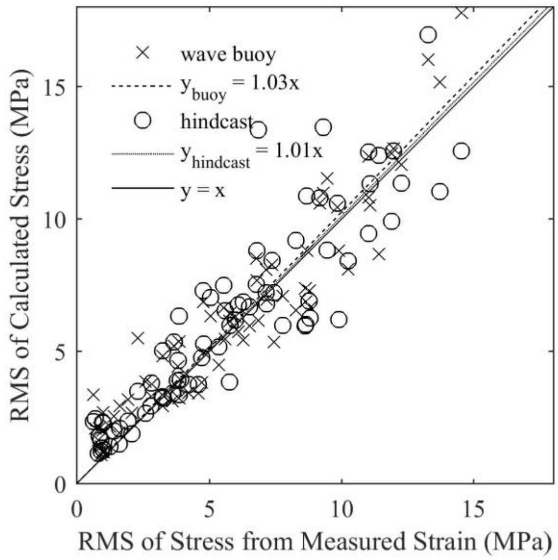

Figure 1: Comparison of RMS stresses calculated with wave buoy and hindcast data against RMS stresses derived from strain gauge measurements.

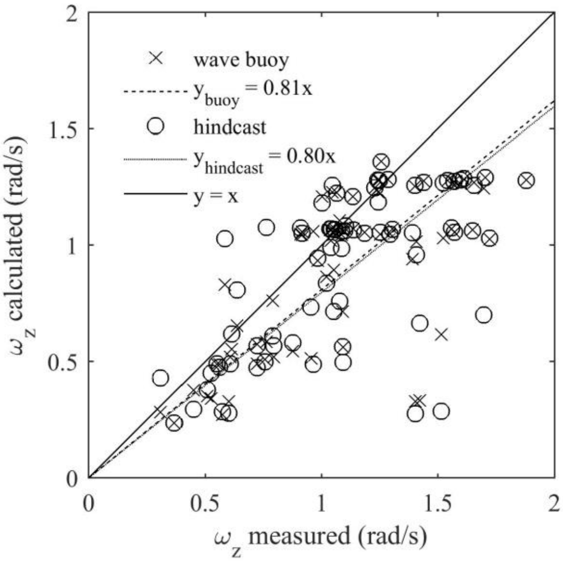

Figure 2: Comparison of stress zero-crossing frequencies calculated with wave buoy and hindcast data against zero-crossing frequencies derived from strain gauge measurements.

Table 2: Summary of stress spectra best-fit lines.

Wave data source	RMS stress		Stress zero-crossing frequency	
	slope	R^2	slope	R^2
Buoy	1.03	0.96	0.81	0.94
Hindcast	1.01	0.95	0.80	0.92

The hindcast wave data show small biases with several outliers. Although there is scatter in each of the RMS stress and zero-crossing frequency plots, the hindcast results are similar to those generated using wave buoy measurements. The similarity with wave buoy results suggests further investigation is warranted.

3.2 BENEFITS AND LIMITATIONS

Potential cost savings make virtual hull monitoring attractive. The reduction in volume and complexity of collected data enables automation of assessments. For example, over one year, four strain gauges sampling at 20 Hz generate about 2.5 billion measurements that may contain noise or drift. Conversely, recording GPS readings every minute and loading data hourly create about 500,000 and 10,000 measurements per year, respectively. Automated assessments reduce the labour required to gain the benefits of hull monitoring and bypass challenges related to data management. Once the stress transfer function database has been populated for the first ship in class, sister ships should be able to use the same database unless structural variations are significant. The limited interaction with the monitored ship results in a low marginal cost. This concept fits in well with the digital twin technology which intends to virtually replicate items based on changing data (Glaessgen and Stargel, 2012).

Centralised, automated data assessment could facilitate realising many benefits of hull monitoring. Quantifying the fatigue damage accumulation of all the ships in a class could improve platform management by informing routing, maintenance, and remaining lifetime assessments. Inspection results and repairs may be incorporated into a model-based assessment to validate and refine the approach. Proposed repairs and structural modifications could be assessed with accurate operational profiles generated through this technique.

Collecting operating information for an extended period of time can inform new designs and facilitate better assessments. The collection of large amounts of wave data in operating areas may also be useful to calculate extreme conditions.

The relationships between wave data and fatigue damage are complex. So, thorough validation of virtual hull monitoring (with the selected wave data source) by comparison with measurements is required before results can be relied upon. However, if wave hindcast data are used, a basic check is possible by comparing calculated ship motions to those measured by the ship's gyroscope, similar to the ship as a wave buoy technique (Nielsen, 2006).

The accuracy of results from virtual hull monitoring is uncertain; it will depend on the quality of the hydrodynamic and structural assessments and the wave data source. Also, non-linear loads and responses will not be captured with this approach if linear hydrodynamic analysis is used. Fortunately, correction factors can mitigate some of the non-linear aspects and others can be monitored with strain or acceleration measurements. As virtual hull monitoring components improve (e.g. wave hindcasts (Breivik, *et al*, 2017), hydrodynamic analysis (Temarel, 2016)), corresponding improvements should be observed in the accuracy of results. Operator guidance can be provided to avoid undesirable structural conditions when strain or acceleration instrumentation is monitored; this is a drawback to using wave hindcasts, but onboard wave measurements or short-term forecasts may make this feasible.

Should virtual hull monitoring be found to provide sufficiently accurate and reliable results, there are practical and business aspects that should be considered. For instance, there may be challenges with obtaining the GPS signals for some vessels. Also, this technique needs to fit into the International Maritime Organization inspection regime.

4. CONCLUSIONS

Combining measured or numerically modelled short-term wave data for spatiotemporal global locations with vessel loading conditions quantifies a ship's operating conditions. For each period of time, the short-term stress spectrum can be calculated from a database of stress transfer functions. Using this method with wave hindcasts, S-AIS or GPS signals, and spectral fatigue analysis enables hull monitoring without additional instrumentation.

Wave measurements taken with a deployed buoy during a naval vessel trial are compared with hindcast wave data and found to be in good agreement. Stress spectra at the keel girder near midship were calculated using each wave dataset. The results are very similar and both agree well with stress spectra derived from strain gauge measurements.

The potential benefits for reduction of total ownership costs motivate future work to validate this method. Further work is required to reassess the naval ship trial. Multiple wave representations and data sources should be compared to determine how their variations influence fatigue damage calculations. Of course, further validation studies with varying ship types and operational areas are required before firm conclusions can be drawn on the feasibility of virtual hull monitoring.

5. ACKNOWLEDGEMENTS

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6. COPYRIGHT

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