Virtual hull monitoring systems for assessment of structural integrity of ships

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Synopsis

During operations, vessels will experience rough weather conditions and therefore fatigue accumulation in the ship's structure. To ensure the vessel's reliability, calculations can be executed to determine actual loads on the hull, forecast maintenance needs and allow for rational decisions on lifetime extension when this becomes relevant.
This paper presents the setup of three types of monitoring schemes and shows the feasibility of a Virtual Hull Structure Monitoring (VHSM) system, which only considers publicly available data. In his paper, Stambaugh [1] emphasized differences in terms of cost and accuracy depending on the monitoring scheme used. The VHSM uses data from the Automatic Identification System (AIS) together with wave hindcasts to estimate the fatigue consumption. This system does not require any onboard sensors. However, AIS data has limited coverage, especially for military ships. Therefore, a minimal structural monitoring scheme has been defined as well. In this setup, a dedicated GPS system is used to monitor ship operations. A motion sensor is used to estimate wave characteristics from the ship motions. The results of these approaches are compared to data from a traditional Hull Structure Monitoring system. Data from strain gauges installed onboard a USCG cutter is used to quantify the fatigue accumulation at selected details on the ship.
Regarding the use of a true VHSM system, the lack of AIS data makes it hard to make a strong conclusion on the fatigue accumulation in the ship's hull. However, this lack of data can be overcome through installation of a dedicated GPS unit. Fatigue assessments based on the combination of GPS measurements and hindcast data have shown good agreement with the fatigue accumulation obtained using the strain gauges. It has been observed that the hindcast models underestimates peak values of the significant wave height. Wave height estimates based on motion data outperform the hindcast models in such cases. A hybrid solution using hindcast data and motion measurements is therefore considered the best solution to obtain accurate wave data.
This paper shows the feasibility of structural monitoring of a ship using limited onboard instrumentation and indicates its accuracy. This allows operators to continuously assess seakeeping loads during operations for an entire class of vessels with limited instrumentation effort. The methodology can be further strengthened by including more extensive structural monitoring on a small number of vessels. This data can be used to estimate the effect of nonlinearities and other (unknown) features in the loads for the class of vessels.

Keywords: Fatigue; Structural monitoring; Virtual monitoring; hindcast;

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1. Introduction

During their operations, vessels can experience rough weather conditions and therefore damage the ship's structure. To ensure the vessel's reliability, fatigue life assessment can be executed to forecast maintenance's needs and extend ship's lifetime accordingly. Fatigue life assessment can be conducted through Hull Structural Monitoring (HSM) systems.

Several types of HSM systems have been developed. In his paper, Stambaugh [1] drew a comparison of five different HSM systems, mainly highlighting the differences especially in terms of cost and accuracy. Conventional strain gauges, used as a reference in this paper, tend to have a high accuracy in term of life cycle maintenance and real time guidance but require constant verification of the proper functioning of the sensors. Therefore, this system despite being accurate appears to have its drawbacks in terms of cost, time and efforts. Developments of sea state measurement techniques as detailed in Thornhill and Stredulinsky [2] have enabled the use of such data to predict the structural response of naval vessels [3]. When using measured sea states together with measured ship's characteristics, it can be referred to as minimal hull structural monitoring. It still requires onboard equipment, such as a wave radar of motion sensor, to calculate the fatigue damage experienced by the structure.

The development of numerical models, Automatic Identification System (AIS) and hindcast has enabled the development of a fully Virtual Hull Structure Monitoring (VHSM) system [4]. AIS, as an automatic tracking system, provides information about the course, position or speed of vessels automatically to other ships, aircraft and shore stations. In 2000, IMO adopted a new regulation which requires ships to carry AIS, therefore more and more AIS data are available for monitoring purposes [5]. Hindcast models such as WAVEWATCH III from US-based National Oceanic and Atmospheric Administration (NOAA) or ECWAM from EU-based COPERNICUS provide wave data as statistical parameters. However, distinction between different wave components can be obtained from these models and the influence of this multi-modality can be studied as well. The stresses induced by the sea state are expressed by the use of a linear Response Amplitude Operator (RAO). These RAOs are the results of hydrodynamic and structural models specific for this ship [6]. Data from AIS and hindcast models together with the RAOs enable the quantification of the fatigue consumption on the ship's hull.

Although VHSM is interesting due to its low cost and easy access of data, it requires deep analysis to understand the influence of the different errors in the estimation of the fatigue damage consumption. This paper aims at investigating the feasibility of a VHSM to assess structural integrity of ships.

The Monitoring schemes section describes the three different type of hull structural monitoring system studied. The Results section presents operational profile and environmental conditions, calculated fatigue accumulation and sensitivities regarding different parameters. A comparison is made in the Discussion section before summarizing results in the Conclusion section.

2. Monitoring schemes

The paper by Stambaugh [1] highlights the different cost and accuracy depending on the structural monitoring scheme used. In this paper, three different monitoring schemes are discussed. The first one can be qualified as a Hull Structure Monitoring (HSM) system, the second one as a Minimal Hull Structure Monitoring system and the third one as a VHSM system.

2.1. Hull Structure monitoring

A traditional HSM system comprises a multitude of sensors. Typical component are strain gauges, motion sensors, GPS and accelerometers and possibly a wave radar. Such a system provides the context of the operating and environmental conditions in order to gain better understanding of these measured responses. Speed, heading and location can easily be obtained from the GPS. Accurate monitoring of the wave conditions is challenging. For ships, a wave radar is the most feasible options to conduct wave monitoring. These measurements can be improved to yield a more accurate wave height assessment using motion measurements with methods as presented by Thornhill and Stredulinsky [2]. An example of a sensor array used for structural integrity assessment is provided by Drummen *et al.* [13] and shown in Figure 1.

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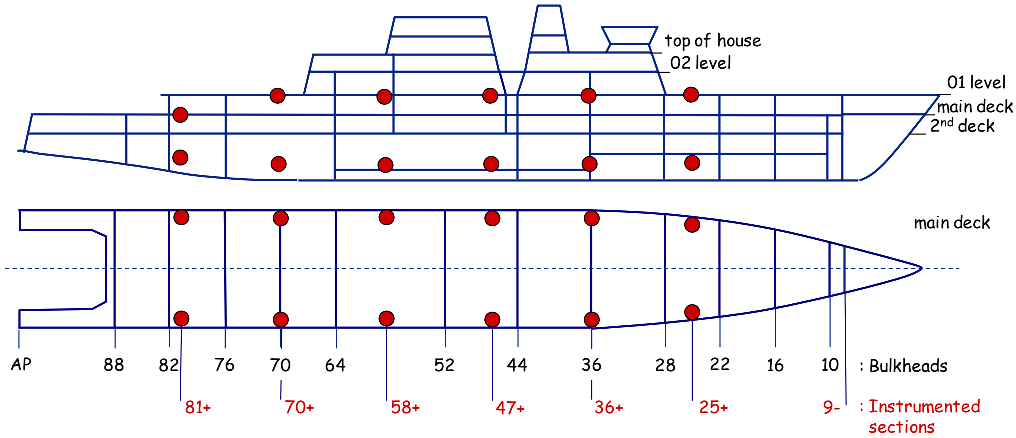

Figure 1: Array of Long Base Strain Gauges used to monitor global loads on hull during operations [13].

The traditional HSM systems provide highly accurate information on the ships operations and loads acting on the hull. This is useful for research studies, but too extensive if used for operational feedback alone. The other monitoring solutions may be more appropriate in those cases.

2.2. Minimal Monitoring system

Monitoring of a limited number of structurally critical locations may already provide the necessary operational feedback to naval architects. When doing so, the selection of sensor locations needs more careful analysis and evaluation using numerical models.

The wave radar used to determine the sea state characteristics is an expensive piece of equipment which requires frequent maintenance. An added drawback for ships with a military mission is that the radar generates radar signature which is obviously not desirable. Therefore, minimal monitoring setup alternative methods are preferred. The estimation of wave conditions from in-service measurements can use motion measurements and solved as an inverse response problem. Traditionally, such problems are solved using numerical models of the ship's response. An extensive overview of such procedures is provided by Nielsen [10]. When data from simulations or in-service measurements is available, Machine Learning methods can be applied as an alternative to solve the inverse problem [11]. The latter method has been applied in this paper.

2.3. Virtual Monitoring

To predict the fatigue consumption of the ship's hull by using public accessible data, AIS data can be used together with a hindcast database. The AIS provides the vessel's characteristics needed, ship's speed and heading, in the calculation of fatigue.

With the position of the vessel taken from AIS, the corresponding wave's characteristics from the hindcast models can be retrieved. The hindcast data can provide multiple wave systems such as windsea and multiple swell components. The primary swell is defined as the swell with the highest wave height. For each type of wave system, the period, height and direction are provided. Additional wave characteristics are provided as the mean and the peak statistical values of the wave system. In this research, data from the Copernicus data set has been used. The output is provided on a global grid with a spatial resolution of $1/12^{th}$ of a degree.

With these data retrieved from public and easily accessible sources, the calculation of fatigue damage can be performed following the same method as the minimal monitoring which is detailed and illustrated in the following section.

2.4. Data Evaluation

Information from a minimal in-service measurement campaign on a US Coast Guard cutter is available to the authors. This system and its results over a three year monitoring campaign are described in detail by Drummen *et al.* [7]. The data contains amongst others strain gauge readings at a number of fatigue sensitive locations. This data has been used to establish a reference for the fatigue accumulation during operations. The fatigue accumulation has been generated from the strain measurements using Rainflow counting [12]. The vessels flexural response has been removed prior to the fatigue assessment. This procedure allows for a fair comparison between a spectral fatigue assessment, which considers only wave induced stresses, and the measurements.

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As detailed by Mondoro [3], the stress-life (S-N) approach can assess fatigue consumption and has been implemented in this study using ABS S-N curve Class C [8]. Figure 2 illustrates the process of the estimation of the fatigue. From left to right are the hull structure monitoring which uses strain measurements, the minimal monitoring and virtual monitoring systems which have different inputs but same method for the calculation of the fatigue accumulation. It should be noted that ship's and wave's characteristics are both necessary. Depending on the monitoring strategy, environmental and operational conditions could be obtained in different ways. The procedure to estimate the wave conditions includes an estimation of the wave period which is conditional upon the wave height. The speed and heading measurement data are used to interpolate the Response Amplitude Operator (RAO) which is determined for discrete intervals of speed and heading. The interpolated RAO is used to assess the wave-induced stresses. The numerical model of this ship is described in more detail by [6]. A figure of the numerical model of the vessel is provided in Figure 3.

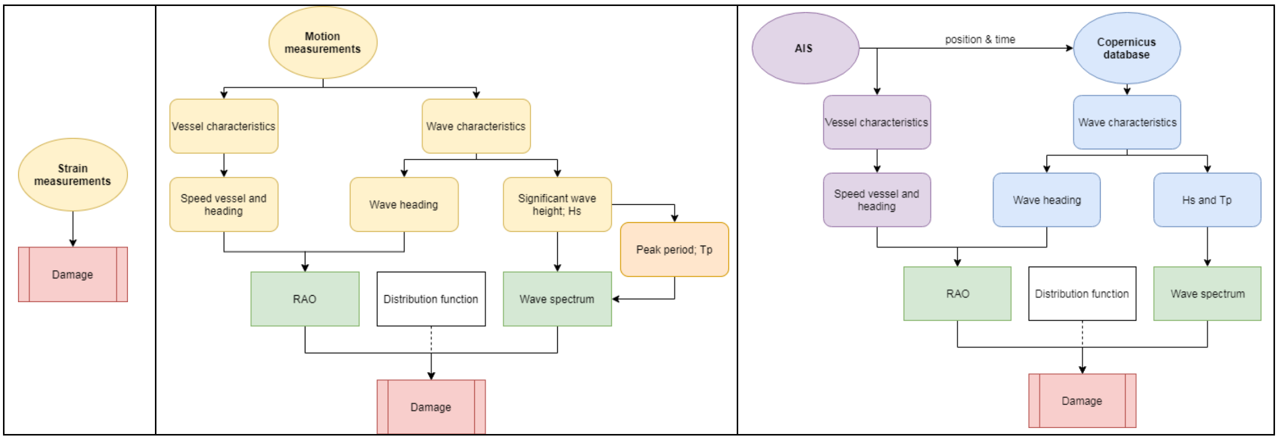

Figure 2: Flow scheme of the different methods used to assess the fatigue damage, ranging from a direct assessment in a HSM system (left), a minimal system using indirect wave measurements (middle) and a full VHSM (right)

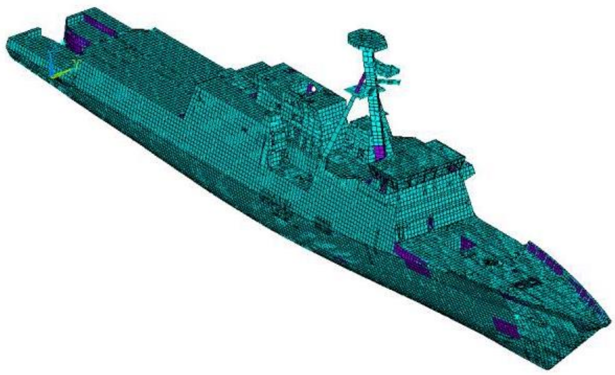

Figure 3: Numerical model of vessel [6]

3. Results

Measured data considered for this study corresponds to three different deployments combined which is equivalent to 10 months in total. For the VHSM, data from AIS were retrieved for the same periods. However, data were considered only above a speed threshold (0.15 kn) because the determination of the heading is not accurate for very low speed. It has been confirmed that the measured damage in those low-speed periods was not significant. The selection resulted in 217 days of available data from the HSM system.

In contrast to measured fatigue accumulation which is evaluated every 30 minutes, AIS data are available on irregular intervals from few minutes to several weeks. Consequently, to improve data availability, interpolation of the data has been performed while insuring consistency in the data, that is, interpolation is only executed if the missing data does not exceed three hours and the vessel is operating in open water. Despite this interpolation, the data coverage from the full VHSM system using AIS and hindcast data represents only 15% of data available

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from the onboard system. Missing data from the combination of AIS and hindcast can be explained by two factors. The first one is an operational factor, by the nature of the studied vessel, the AIS can be switched off or out of range and it therefore decreases the available data. The second explanation is that there is no hindcast data when the ship is close to the shore. This second source of missing data has a smaller impact as it occurs less frequent and the vessel tends to have a low speed close to the coast and therefore less significant resulting damage than at sea.

In this research, the three different fatigue assessment procedures as discussed in the previous sections were executed. The results are presented for a single strain gauge only, but very comparable findings have been obtained at other measurement locations on this ship.

Table 1: Availability of measured data

Monitoring scheme	Number of days of data
Hull Structure Monitoring	217
Minimal Monitoring	203
Virtual Monitoring	33

3.1. Operational Profile & Environmental condition

It is of great interest to determine the operational profile under which measurements have been performed. An operational profile denotes the distribution of time in which the ship has spent in at certain speed and with a certain relative wave angle. In the following tables, the operational profile can be found based on AIS data together with the mean statistics of the Copernicus database, and the one based on the measured data onboard.

These tables of the operational profile show that the AIS provides fewer high-speed conditions. At the same time, the measurements show a strong preference for head and bow quartering seas, which is not visible from the AIS data. Both effects can be explained from the fact that AIS data is relatively scarce when the vessel is at open sea. At open sea, the crew will generally prefer a bow quartering or head sea condition to minimize roll motions and will be operating at higher speeds more often than when the vessel is operating in more congested waters near shore.

Table 2: Operational profile AIS data

Speed Heading	0	5	15	18	21	28	
Head	0.01	0.09	0.09	0.02	0.00	0.00	0.20
Bow	0.01	0.12	0.13	0.02	0.01	0.00	0.28
beam	0.01	0.09	0.07	0.01	0.00	0.00	0.17
stern	0.01	0.09	0.06	0.01	0.01	0.01	0.19
Following	0.01	0.09	0.05	0.00	0.01	0.00	0.16
	0.04	0.47	0.38	0.06	0.04	0.01	1

Table 3: Operational profile measured data

Speed Heading	0	5	15	18	21	28	
Head	0.00	0.12	0.18	0.06	0.04	0.00	0.41
Bow	0.00	0.12	0.14	0.04	0.02	0.00	0.33
beam	0.00	0.04	0.04	0.01	0.01	0.00	0.09
stern	0.00	0.05	0.03	0.01	0.01	0.00	0.10
Following	0.00	0.04	0.02	0.01	0.01	0.00	0.06
	0.01	0.37	0.41	0.12	0.08	0.01	1

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3.2. Lifetime consumption

To assess the accuracy of the different monitoring schemes, the cumulative fatigue damage is considered and compared using the HSM system with strain gauges as the reference. In the figure and table below, a comparison of the reference and the two other calculations of the fatigue accumulation is shown. These results indicate that both approaches can capture the dominant trends with reasonable accuracy. It should be noted that the wave estimation method generally provides a somewhat conservative estimate of the sea state. The combination of AIS and hindcast model provides a strong match with the measurements except for the storm event at the end of the period resulting in a considerable nonconservative result overall. For reference, the hindcast model provides a wave height of 4.5m, while the onboard procedure provides an estimate of 6m in this developing storm event.

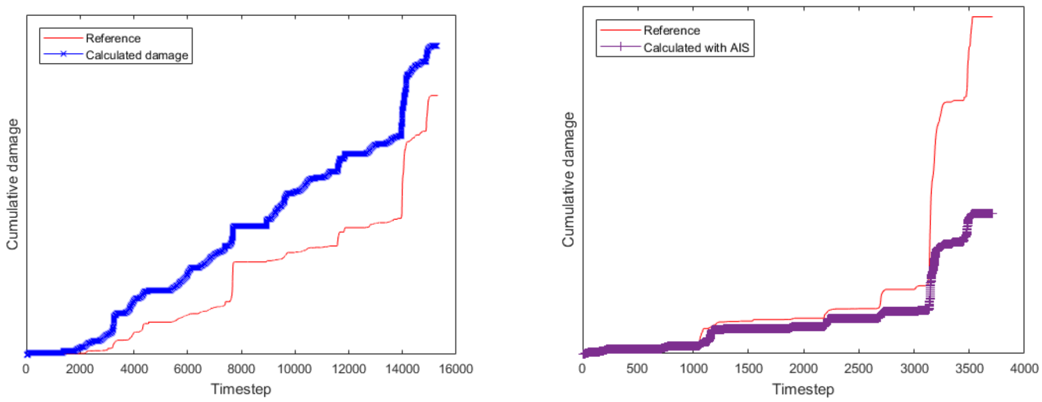

Figure 4: Comparison of the cumulative damage of the minimal (left) and virtual (right) monitoring schemes with respect to the same reference curve

Table 4: Difference in total cumulative damage using both monitoring schemes

	Minimal monitoring	Virtual monitoring
Difference with true fatigue accumulation [%]	17	-58

3.3. Sensitivities

Different parameters have been analysed to study the sensitivity on fatigue accumulation. As mentioned previously, spreading can be added to the initial calculation. The cosine-squared spreading function is included to model spreading of the wave spectra while keeping the energy spectrum the same [9]. In the previous calculations, only the main heading of the relative heading was considered. In the hindcast database, other statistics than the mean are available such as the swell and wind characteristics which were combined to calculate a new multimodal spectrum. The spectral shape which corresponds to the actual waves experienced by the ship is unknown. Therefore, the results of calculation using three different wave spectra have been compared. These are the Ochi-Hubble, JONSWAP, with γ equals 3.3, and Brettschneider spectra.

In Table 5 and Table 6, the comparison of the rate of difference between the total cumulative damage of the HSM and the different sea state descriptions are shown.

Table 5: Difference in total cumulative damage using multiple sea state descriptions.

Difference with true fatigue accumulation [%]	Minimal monitoring	Virtual monitoring Bulk statistics	Virtual monitoring swell & windsea
Without spreading	17	-58	-57
With spreading	-6	-66	-60

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Table 6: Difference in total cumulative damage using multiple wave spectral shapes.

Difference with true fatigue accumulation [%]	Minimal monitoring	Virtual monitoring
Ochi spectrum	42	-54
JONSWAP spectrum	17	-58
Brettschneider spectrum	-5	-67

A few interesting observations can be made. First of all, the use of multimodal sea state description shows relatively little change to the overall fatigue accumulation indicating that the overall wave conditions in the area of operation are dominated by a single component. Secondly, the introduction of spreading shows a reduction of fatigue accumulation resulting from the fact that spreading distributes wave energy away from the dominant wave direction (head seas). This effect has a magnitude of around 20% on fatigue life. The changes in fatigue accumulation resulting from different wave spectrum definitions is more significant at around one third of the total fatigue accumulation. The Brettschneider spectrum, which is the most broad spectrum, results in the lowest fatigue accumulation.

4. Discussion

When conducting missions, the crew will be aware of the operating conditions and will be able to indicate whether a deployment should be considered as mild or severe. However, fatigue accumulation is governed by load severity and exposure time and features nonlinear relations. This makes it not straightforward to summarize the severity of a deployment numerically which is needed if one wants to rank deployments. A minimal or virtual monitoring setup can be used to obtain such an indicator.

The authors have examined the influence of several assumptions on sea state description in the fatigue calculations. It has been noted that hindcast models produced generally good wave statistics for use in a fatigue assessment. However, the results obtained in developing storm conditions are nonconservative and may result in a significant underestimation of the fatigue accumulation. In the area of operation, multimodality of the sea state has a negligible effect and the influence of wave spreading on fatigue accumulation is also very small. When using longcrested waves overall conservative results will be found. However, the choice of an appropriate wave spectral shape has a more pronounced effect and should be carefully considered when executing virtual monitoring.

The application of this methodology has been examined for a number of different vessels. For example, Thompson [14] shows the application of this method on a 135 m naval vessel during dedicated trials. This article shows a good match between the calculated and measured stresses with an average underestimation of the calculated stresses of 10%. However, the results become more non-conservative with higher waves and can therefore show a more significant underestimation of the fatigue accumulation. Hageman *et al.* [15] shows an analysis similar to the analysis presented in this paper for a number of permanently moored offshore units in West-Africa. For these units, the fatigue accumulation rate is highly sensitive to wave spectra and spreading. The statistical wave data provided by different hindcast models provided a good match with the nearby wave buoy. However, this strong correlation was partially attributed to the overall mild conditions in this area.

In the applications above, the location of the ship is always known. However, AIS data for ships in general and navy ships in particular may be incomplete for part of the time. This paper has shown that the lack of AIS data provides a challenging when assessing lifetime consumption during normal operations. The first reason for lack of AIS data is that this data is not registered by any coastal state while the ship is traversing open ocean. The second is that AIS of military ships can be switched off on purpose. In the first case, the course of the ship might be estimated with reasonable accuracy when begin and end point of the route are known. In the second case, the environmental conditions can be estimated using an area sweep. For this method, the begin and end point of the missing interval are used in combination with an average vessel speed. With this data, an area of operation can be estimated. Over this area, a set of possible environmental conditions can be retrieved which can be used to estimate the fatigue accumulation in the period without AIS data. Both approaches are currently under investigation for future use.

A virtual approach does not include any shipboard sensors. A motion sensor is a relatively simple sensor which can be installed with limited efforts. References [10] and [11] use such a sensor to derive wave conditions using either a physics-based or data-based model. However, it can also be used to derive a correction model which can be superimposed on the hindcast data. This procedure is shown by [16] to improve motion estimates. Whereas the other procedures require continuous motion measurements to estimate the wave conditions, this last approach requires only a limited set of measurements on one ship to develop the correction model. Afterwards, this model can be used on the same ship or class of ships without further onboard measurements.

The virtual hull monitoring method does not provide a fully accurate assessment of the fatigue accumulation in the ship hull. However, given the typical level of uncertainties in a fatigue assessment, this is not to be expected. There are also significant safety margins included to cover these uncertainties [17]. The VHMS allows to generate a qualitative assessment of the fatigue accumulation during operations and allows for a comparison with the design assumptions. Application of the procedure across a fleet of similar ships allows for a fleet wise optimization of integrity procedures. This can be achieved by comparing the fatigue accumulation of the different ships and link these to their operating areas. This will allow for dedicated inspection planning or home-port rotation of the vessels.

In this article, hindcast models have been used to assess fatigue accumulation in the hull structure of ships. However, the same data can be used to perform post-event analysis of a multitude of effects during vessel operation. These include evaluation of speed-power performance and the probability of propeller ventilation. For different applications, the physics involved are different and a holistic analysis of all uncertainties is required to identify whether hindcast data can be used for that property with a reasonable accuracy. Publication of a wider range of applications can aid operators in improving their operations and allows for multi-objective optimization of operations or support a multi-objective optimization of new vessel designs.

5. Conclusions

The following conclusions summarize the findings of this work:

- Overall, the evaluation of fatigue/ accumulation using a VHMS with GPS and hindcast data provides reasonable results compared to direct in-service measurements. Of particular concern are high fatigue accumulation rates in higher sea states. The hindcast models may underestimate the actual conditions leading to a significantly lower fatigue accumulation. These periods are generally short, but they may be responsible for the majority of fatigue accumulation during a deployment.

- For military ships, applying virtual monitoring solely on AIS data will lead to a biased and nonconservative operational profile. Therefore, a dedicated GPS system is considered necessary to allow for minimal integrity monitoring during operations. Other methods of supplementing AIS data are under investigation, but have not yet proven themselves as a reliable substitute.

- The addition of a motion sensor provides valuable, though not essential, reference data to confirm the findings obtained from the virtual monitoring setup. The presence of such equipment will not have any influence on the day to day operations of the vessel.

Acknowledgement

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