Onshore use of hull monitoring data retrieved from ultra large container ships

Gaute Storhaug[1] and Ole Jacob Hareide[1]

[1] DNV GL, Maritime advisory, Oslo, Norway
Gaute.Storhaug@dnvgl.com

Abstract. Digitalization is associated with the fourth industrial revolution. It covers many aspects, e.g. sensors. Sensor data can be displayed on board for decision support. Class approved hull monitoring systems do exactly that. This is not new, and it is not about digitalization. There is however a need to use sensor data in decision support onshore. This can be related to an alternative survey arrangement, which can give benefits compared to a rigid inspection regime. The aim is to reduce risk of damages, repairs and inspection costs. To do this, data needs to be collected, quality assured and assessed, and results needs to be displayed to decision makers. This process involves digitalization, and this is new for hull structures of merchant ships.

Four container ships are instrumented. They are sister vessels and operates on the same Asia to Europe trade. The hull monitoring supplier has retrieved data from the vessels and converted the data to a supplier independent format stored on a data platform. A quality dashboard and a result dashboard are developed. These dashboards are available through a secure web access for the owner.

The experience with the hull response for such large ships is limited. Results for fatigue and extreme loading including the effect of vibration are shown and related to seamanship, inspection and future expectation. Damping is estimated for main vibration modes, which can be useful for numerical analysis. Overall, the structural performance on this trade is good building confidence to the design.

Keywords: Sensors, Digitalization, Condition monitoring, fatigue, container ships, vibration.

1 Introduction

1.1 Hull monitoring systems

Many of the class societies have rules for hull monitoring systems, but IACS (International Association of Classification Societies) has no harmonized hull monitoring rules. DNV GL rules, established in the early 90ies, was latest revised in 2017 [1]. This is associated with the class notation **HMON(…)**, where the content in parenthesis includes qualifiers which described the number and types of sensors included in the system. The rules are flexible and can extend beyond hull monitoring to any sensor purpose, but herein the focus is on hull response measured by strain sensors.

There are two qualifiers that are related to digitalization. The first is the qualifier D, **HMON(D)**, which implies that the system has an online data link to shore, so system maintenance can be carried out without costly trip on board. This is highly relevant if there are quality issues, which should be expected. Secondly, there is a qualifier B, **HMON(B,D)**, which implies that the data (raw data and statistics) should be sent annually to the class society. This makes sure that the data is stored and can be used from shore. This is facilitated with the data platform Veracity, www.veracity.com. The rules require that statistical data is stored for five years and time series for one year on the system on board. These are elements that facilitate digitalization but is frequently lacking.

All ships are instrumented with sensors systems, but it is only about 1% of the world fleet that is instrumented with hull monitoring systems focusing on hull response. Very few of these installed systems are facilitating digitalization, and only the leading supplier is focusing on this.

1.2 Data management versus use of sensors data

Assuming that data has a value for the operator, data management can become important. The value of data is dependent on the need, and it can be related to focus on saving operational costs, ensuring safety or use it in a competitive advantage towards other stakeholders. It can also simply be required or optional in rules and regulations. This is already the case within certain rules such as fleet in service rules for ships related to especially machinery [2] but also for offshore units related to hull [3]. In these cases, an alternative survey arrangement is offered. The rules say: “Any type of application shall be approved, and any sensor data used shall be quality assured according to the rules and applicable standards”. This implies new requirements to the supplier and user of data related to condition monitoring. The data assessment shall be performed according to ISO 8000-8 standard [4] (International Organization for Standardization). It also states that “data quality assessment shall be followed up by a continuous process during operation”. This is also handled in a new recommended practice related to data quality assessment framework [5]. The owner of the ship, operator of the ship and/or supplier of the hull monitoring system (in this paper all these are referred to as “owner”) retrieving and using data as part of the classification systematics must also be certified with respect to organizational maturity [6] containing five levels, and where it can be necessary to obtain level three. The five levels are referred to as: Initial, repeatable, defined, managed and optimized, and depends on differentiation in governance, organization and people, processes, process efficiency, requirement definition, metrics and dimensions, architecture, tools and technologies and finally data standards. Training of relevant personnel is necessary to improve the organizational maturity, which becomes essential when the data has value. A data quality service level agreement (data SLA) is regarded necessary for data sharing. All these issues may appear as new but being an owner can actually handle all this can give significant competitive advantage. This paper presents a preliminary solution for how to handle data quality. It is however, far from a complete solution.

1.3 Inspection regime for hull

As a ticket to trade, a vessel must be in class to get insurance. This means that the vessel design is approved by a classification society before delivery, and after delivery the classification societies follows up the vessel with inspection surveys during operation. The main objective of inspection is to reveal damages and enforce necessary repairs to maintain safety. Class inspections are done annually, each 2.5 years (intermediate) and every 5 years, where the last inspection survey is related to substantial efforts and costs, e.g. the vessel is taken off-hire and is docked to inspect everything including below bottom. This is regarded as a rigid inspection regime and it does not matter who you are and how good you have been to maintain your vessel. As mentioned, an alternative survey regime for the hull is already offered for offshore units [3]. It is also offered for FSRUs (Floating Storage Regasification Unit) in DNV GL. Why is this not offered for merchant ships in maritime?

It is regarded as a matter of time, before this becomes applicable also for maritime ships, but for the time being, it is IMO (International Maritime Organization) that regulate the inspection regime, which is further interpreted by IACS in unified requirements, UR Z7 [8]. This basically states that every 5th year special survey (renewal survey or main survey) is required for “all spaces” (tanks & holds). In IMO, on the other hand, only “selected tanks” is specified. There is thereby a difference here. Without clearly being stated, IMO opens for some flexibility, while IACS does not. There is also a stricter inspection regime referred to as Enhanced Survey Programme, but this is not applicable to container ships, but CSR (common structural rules) ships as bulk carriers and oil tankers. Vetting is yet another inspection regime (also not applicable to container ships), which is beyond the scope of classification societies but enforced by oil majors. There are reasons behind the different inspection regimes, but in principle a ship is a ship, and the inspection regime could in principle be the same with changes in extent to reflect different risk. It could be questioned if today’s inspection regime should be improved based on collected data that provides a better insight of the condition of a ship. Sensor data from hull monitoring systems could be used for this purpose.

1.4 Objective of the paper

The main purpose of this paper is to address three main concerns:

- The use of sensor data to confirm the safety margin in operation
- The use of sensor data in condition monitoring for input to maintenance planning and inspection
- The condition monitoring of the data itself to build trust in the data for use in decision support

The first point is relevant in relation to the recent concern related to a few container ship accidents. It has been questioned if whipping, as an excitation source, has contributed to break vessels in two. Based on this, IACS has reacted and issued a new unified requirement, UR S11A [9], where whipping is required to be assessed in design for new post panamax container ships. It is not stated how this should be done, or how important it is, but DNV GL has a guideline to handle this. Instrumentation of the vessel is then related to safety and used to establish confidence in the design for the owner and the crew on board. It can also be used on board, to see the effect of change of course and speed on the hull girder response, and to confirm that operation is continued within safe limits.

The second point is related to operational costs related to damages associated with extreme and fatigue loads, such as local buckling damages and fatigue cracks. Since there are more strict requirements to coating and the coating is improved, corrosion in the future is expected to be relatively less important, and then the other type of damages becoming more visible. Fatigue damage is not an extensive problem in the industry, but it has been confirmed that wave induced vibration can contribute significantly to accelerated fatigue damage accumulation, so this may be a concern on certain trades, especially in harsh wave environment. On board, the fatigue rates based on strain sensor in deck covering hull girder wave induced bending can be monitored on a display on the bridge to give the officer on watch and captain an understanding on how much fatigue damage is accumulated compared to design. The effect of changes to speed and course can also be observed.

The third point is firstly related to checking if all the sensors is working as intended, and can give useful information on board, but also for the purpose of using the data on shore, in relation to e.g. class systematics or maintenance planning and inspection, or for any other purpose. The value of data can be a bit undefined today, e.g. today the class may not utilize the data, so the full value of the sensor data is for sure not exploited today. However, if this should be exploited in the future, it is necessary to make sure that the quality is satisfactory also today from day one until it will be used.

Based on the objective, sample results will be shown from the vessels in relation fatigue and extreme loading, but also for other perspectives. A separate section is focusing on data quality through a web-based dash board solution including also a result dash board. Finally, conclusions and further work will be summarized.

2 Candidate vessels and monitoring system

The vessels that has been investigated are four container vessels with a capacity of about 20 000 TEU (twenty feet equivalent unit). They are sister vessels, and about 400 m overall length, and with a beam of slightly less than 60 m, and a draught of about 16 m, but in practice less. These are considered as relatively standard design without any extreme bow flare shape.

The ships are equipped with a hull monitoring system from one of the three leading hull monitoring suppliers [7]. The instrumentation is not quite standard, and it is not extensive, but include the following main sensors:

- Two strain sensors in longitudinal direction 100 mm on longitudinal stiffener below upper deck at midship frame 265; one on port side and one on starboard side (referred to as GMP/GMS)
- One strain sensor in longitudinal direction 50 mm above bottom at longitudinal girder 1465 mm off center line at midship at frame 239 (referred to as BMC)
- One strain sensor in longitudinal direction 100 mm on longitudinal stiffener below upper deck in aft ship at frame 120 on port side (referred to as GAP)
- Bow accelerometer at center line close for forward perpendicular in Bosun store for vertical acceleration (referred to as AFV)
- GPS for position, speed over ground and course over ground
- RPM of the propeller
- Anemometer for wind speed and direction (this is not corrected for vessel heading and forward speed)

A wave radar is not included on board, due to the cost of such a system, but there are some requirements in [1] related to this. They are normally type approved sensor systems with Wavex from Miros and Wamos from OceanWaves as leading suppliers. However, an alternative is to match GPS data with wave hind cast data, which can be retrieved from different wave hind cast suppliers.

The system is not approved to DNV GL's class notation HMON, but it includes statistical processing that is similar as required in the rules, which results in stored files with statistical time series sampled every half hour. Fatigue damage calculations are included, but not exactly according to the rules. The wave induced vibrations are included, but the total fatigue damage includes it implicitly. It is therefore not easy to evaluate the contribution from the wave induced vibrations. For extreme stress levels, this is however possible.

The configuration of the system suggest that the target fatigue life is set to 40 years. This affects the fatigue rates on the display on board and indicated a desire to possibly use the vessel beyond a normal life time of 25 years for ships. The stress concentration factor is set to 1.33 and combined with a S-N curve for welded joints protected from corrosive environment (by coating) [10]. This is equivalent to a stress concentration factor of about 1.16 at the hatch coaming top plate. These stress concentration factors cover basically many different deck outfitting details and structural details including butt welds with thickness effects. The mean stress effect is set to zero, which is a good assumption in the deck area for a hogging ship (still water bending in hogging) but also when residual stresses are still acting. The measurements give thereby a good indication of the risk of fatigue cracks, where a fatigue damage of 1 or average fatigue rate of 1 after 40 years, suggest a fatigue crack after 40 years with a probability of 2-3%.

All strain sensors include fatigue calculations, and all strain sensors and accelerometer have a sampling rate of at least 20 Hz to include frequency ranges that include wave induced vibrations if this occur. This can occur at higher frequencies in the range of 0.5 to 5 Hz and can contribute to fatigue and extreme loading.

The measurement data is provided as backup on USB memory sticks, so no automatic transfer of data to the clouds or to shore is set up. This makes the assessment of data to be a bit more manual.

For comparison on quality (later in the paper), an additional vessel is included from the same supplier. This is referring to a gas carrier with approved hull monitoring system according to HMON.

3 Sample results

3.1 GPS data

The first sensor data, which is normally considered, is GPS (global positioning system) data. Where is the vessel, where has the vessel been operating and how much time has it spent in port and at sea, and how does the speed profile look like? The speed by GPS is speed over ground and not speed through water. Ships are built to be at sea, but different ship segments and trades show different time in port. A speed profile may suggest that engine should be tuned possibly differently. Going back a decade many of the container ships were designed with higher design speeds than today, and some vessels are still unnecessary powerful. Is voluntary speed reduction used when the vessel enters a storm, is the captain trying to avoid the storm. Already here, the standard GPS sensor may give input of value for hull strength and seamanship, but also for fuel, emission and navigation issues.

An illustration of the trade for the four container ships is illustrated in Fig. 1. The measurement period for all ships is varying slightly because of delivery time of the vessels, but for the vessel used as an example in the following, the measurements starts in June 2017. The trade is a typical Asia to Europe trade, which is one of the main container ship trades. 292 days of measurements were collected, and the fraction of time of the system is collecting data was estimated to 98.5% of the time. While this is regarded as good, 1.5% missing records is still a quality issue. Then the positions may also be wrong, which is for instance indicated with GPS showing some zero positions west of Africa. This is not uncommon and may be related to the GPS being turned off, so no signal is retrieved.

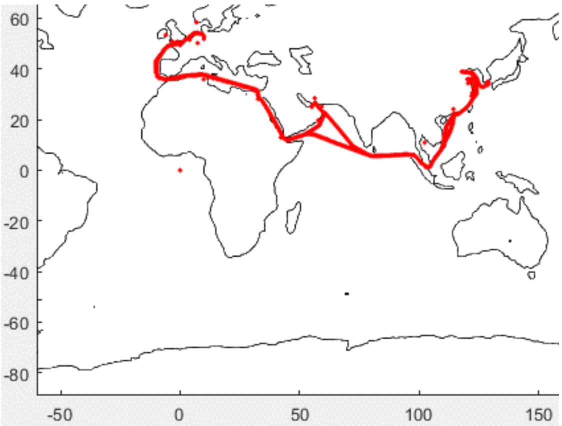

Fig. 1. Illustration of the trade.

The speed profile is defined with a resolution of 0.25 knots, and the probability of the different speeds are shown in Fig. 2. Speed less than 3 knots are considered as port time, or drifting. From this, the time in port and at sea can be estimated. The time at sea is 62.0% and the time in port is 38%. The average speed at sea is 16.7 knots, but the most probable is 19.25 knots. The maximum speed was recorded early and was 26.1 knots, which may be related to the sea trial. There is a small secondary peak at about 17 knots. On the other vessels this secondary peak is observed at above 15 knots and may be associated with channel operations.

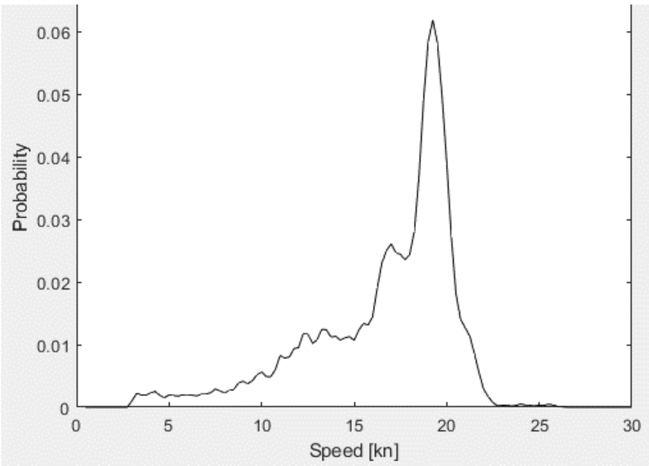

Fig. 2. Illustration of the speed profile (speed over ground including current).

3.2 Strain sensors

The strain sensors are used to assess the fatigue and extreme loading including wave induced vibrations. If the sensor is properly “zero set” (the sensor reading is adjusted to measure the stress defined by the hull girder still water bending moment from the loading computer in calm water at a given point in time) and temperature effects are sufficiently removed, it can also be useful to measure the mean stress level caused by the static loading condition. This means that also the yielding and buckling risk can potentially be assessed. The latter however requires exact warning values of this, which is not common, but the **HMON** class notation would require such zero setting.

The fatigue rates are calculated every half hour as the fatigue damage divided by the budget damage for that half hour. The budget damage is based on a constant fatigue loading that after the target life gives a fatigue damage of 1.0, suggesting a crack with 2-3% probability. The fatigue rates are then easy to relate to for the crew, because if you have stayed at a fatigue rate of 90 for one day, then you have spent 3 months of fatigue damage in one day. The fatigue rates for the midship deck sensors are illustrated in Fig. 3. Four storms can be observed, but these are not really storms, because the fatigue rates are really low. It is also observed that starboard has higher fatigue rates than port side, which can occur in off head sea directions. These fatigue rates can also be accumulated into fatigue damage and compared to the design curve. This is shown for the aft deck sensor and the midship bottom sensor in Fig. 4. The ratio between the fatigue damage measured and the design curve, is referred to as the fatigue utilization. It is thereby three fatigue terms being used; fatigue rates, fatigue damage and fatigue utilization. Fig. 4 confirms that there are four “storms” which make both the fatigue damage and the fatigue utilization jump four times. The storms are therefore important fatigue, while the statistical interpretation that fatigue is more related to average and daily or hourly distributed response level is false or misleading, e.g. associated with 10^{-2} probability level of exceedance, mentioned in CSR [11]. Taking this a step further in a damage and repair perspective, one may say that it is the storms that cost money, and it is here where the seamanship is essential. The time where this is essential is however limited on this trade, as we see the time between “storms” are well spread and each storm has limited duration, often less than a day.

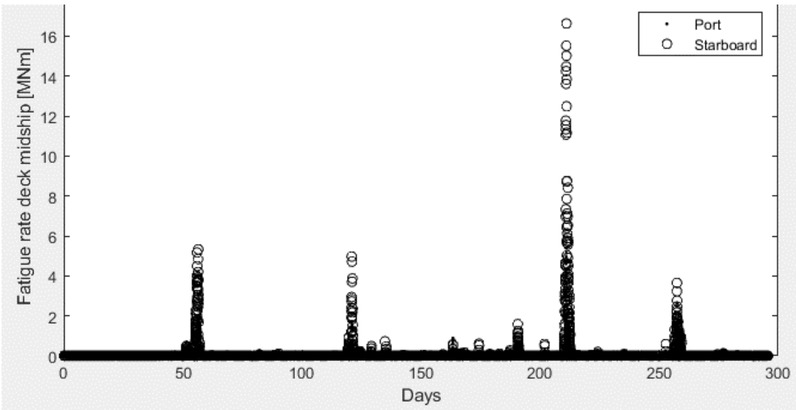

Fig. 3. Illustration of the fatigue rates for deck sensors at midship (GMP/GMS).

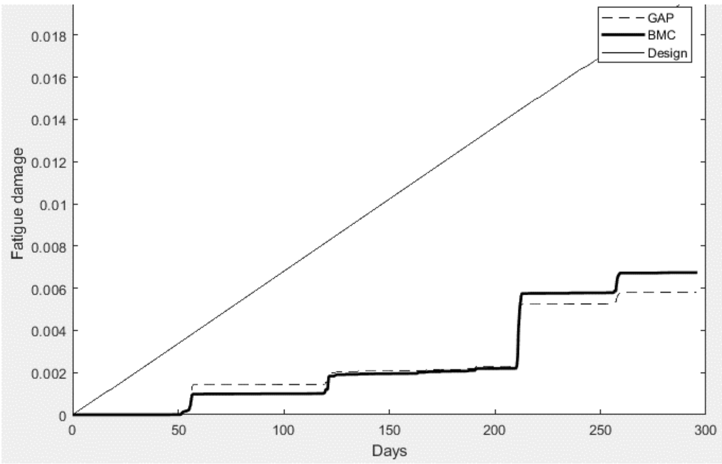

Fig. 4. Illustration of the fatigue damage for deck sensor aft (GAP) and bottom sensor midship (BMC).

The results for maximum fatigue rates, fatigue damage and fatigue utilization for the four strain sensors are listed in Table 1. Based on these results, there is no concern for neither fatigue damage, fatigue utilization, nor fatigue rates. The trade is comfortable, and the seamanship has been good.

Table 1. Fatigue results for the example vessel delivered June 2017 after 292 days

Sensor name	Fatigue damage	Fatigue utilization	Max. Fatigue rate
GAP	0.01	0.29	60
BMC	0.01	0.34	65
GMP	0.00	0.02	6
GMS	0.00	0.07	17

When it comes to extreme strain levels, it turns out that the strain sensors, e.g. in deck, has a mean stress level, which is unexpected versus the permissible stress level in maximum and minimum still water hogging. It can quickly be concluded that the strain sensors have not been properly zero set (calibrated) against the loading computer. For this reason, the opportunity to compare mean stress with the loading computer in operation is lost. This is however considered as important, because this opens for the opportunity to compare the hull monitoring system with the loading computer to confirm if the loading computer data is reasonable. A deviation suggests uncertainties to the cargo weights and filling level of ballast tanks, i.e. input to the loading computer. The loading computer is often slightly misleading, as confirmed on another container vessel based on laser measurements [12], and occasionally actions should be taken. Therefore, it is recommended to have zero setting of the main strain sensors done properly against a known loading condition with limited uncertainties.

Disregarding the mean stress level, the dynamic strain levels can be compared to permissible dynamic limits given by the design rules. The rule limit does not include whipping (and should not), but the measurements do. This is shown for the aft deck sensor (GAP) in Fig. 5. The hogging stress has been almost 100% utilized, but the limit in hogging is also lower than in sagging, but still hogging is larger than sagging.

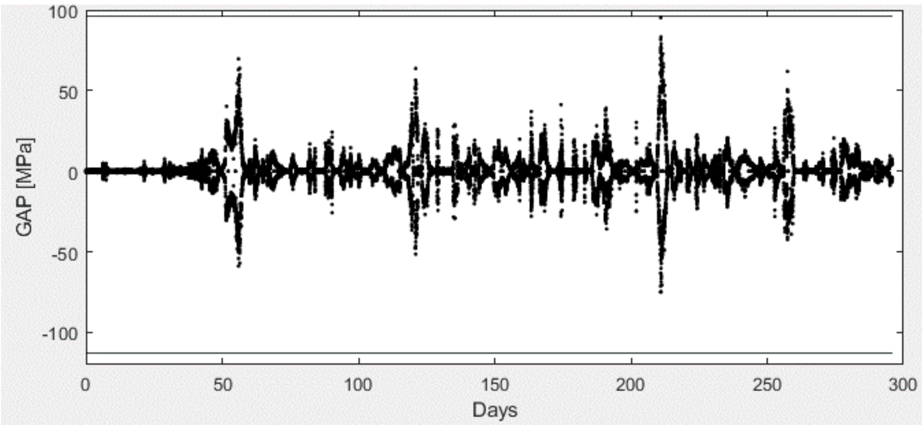

Fig. 5. Illustration of the extreme stress for deck sensor aft (GAP) in hogging (positive) and sagging (negative) versus permissible stress limits.

In Fig. 5 the four "storms" are recognized. While it may be regarded as a severe storm for one date in hogging for this aft deck sensor, this may not be the case for the other sensors, and we should remember that also whipping is included. The utilization in sagging and hogging and with and without wave induced vibration are given in Table 2. The vibration contribution is also estimated. It is observed that the utilization is much lower at midships, but that the vibration contribution may be larger there. Large amplification due to whipping (and possibly springing) is expected also in lower storms at higher speeds in head seas.

Table 2. Extreme stress results for the example vessel delivered June 2017 after 292 days

Sensor name	Utilization hog. with whipping	Utilization hog. without whipping	Vibration contribution	Utilization sag. with whipping	Utilization hog. without whipping	Vibration contribution
GAP	0.99	0.86	1.15	0.66	0.56	1.18
BMC	0.95	0.81	1.25	0.76	0.56	1.35
GMP	0.35	0.26	1.35	0.32	0.22	1.45
GMS	0.47	0.34	1.38	0.45	0.39	1.15

As seen from Table 2, vibrations are contributing. For crew, this is regarded as well known, but for shore people it can be difficult to understand that a 400 m vessel can vibrates just because of some relatively small waves. This can however be easily seen from the one-minute time series of the aft deck sensors in Fig. 6. In general, all ships vibrate now and then due to wave induced vibrations and this contributes to extreme loading and fatigue damage. In this case the vibration is significant, but not exactly coinciding with the peak of the wave frequency loading, dominated by the vertical wave bending moment. That explains also why the amplification in Table 2 appears a bit random. In another storm, suddenly another sensor shows more dramatic amplification because of unfavorable phasing.

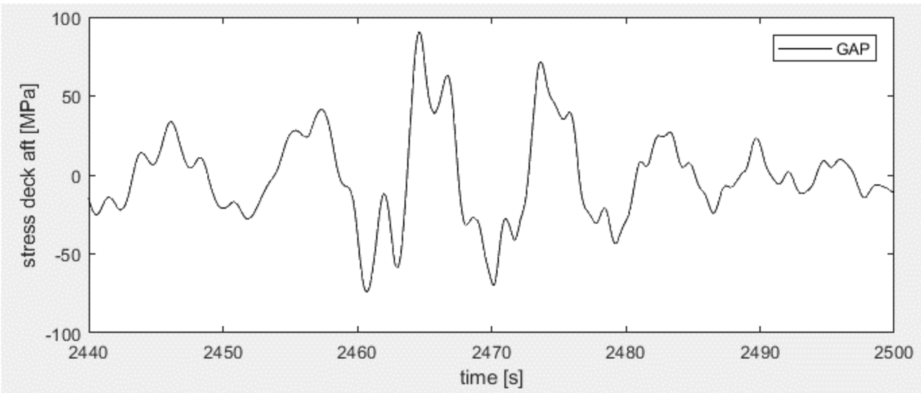

Fig. 6. Illustration of one-minute time series from the deck sensor aft (GAP) between 00:00 and 01:30 UTC on 13th of January 2018.

The time series can also be assessed with Fast Fourier Transformation to establish the spectrum to identify natural frequencies and damping. The natural frequencies between 00:00 and 01:30 on the 13th of January 2018 is shown in the energy spectrum from the aft deck sensor (GAP) in Fig. 7. The figure includes frequency in ω in rad/s and this can be converted to Hz by dividing by $2 \cdot \pi$ (=6.28). There is a frequency at 0.11 Hz (0.69 rad/s) corresponding to wave encounter response at 9.4 seconds. Then there is a vertical 2-node vibration mode at 0.42 Hz (2.64 rad/s or 2.35 s) and a vertical 3-node mode at 0.81 Hz (5.09 rad/s or 1.23 s). Torsional vibration is not seen here, but head seas may not cause significant torsional vibrations, so this cannot be excluded on this vessel. The y-axis is in log scale, so the 3-node is not regarded important, but the 2-node is.

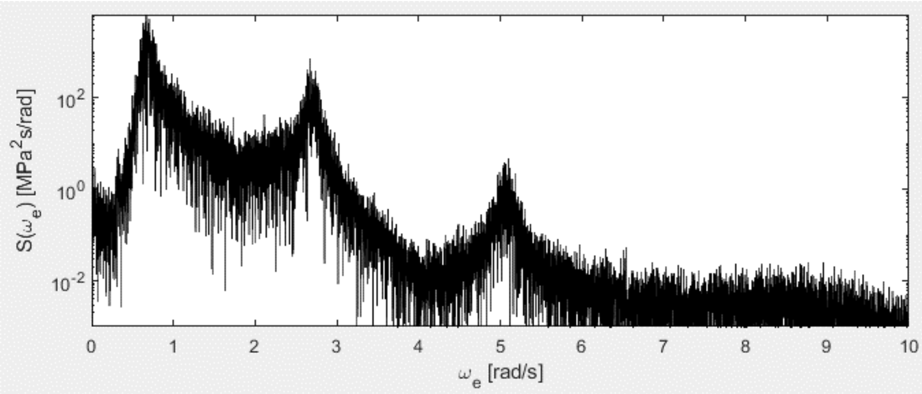

Fig. 7. Illustration of wave energy spectrum from the deck sensor aft (GAP) between 00:00 and 01:30 UTC on 13th of January 2018.

From the spectrum it is possible to derive the damping of the vibrational models. This is essential input in case numerical analysis including wave induced vibrations is carried out. This is typically done in design, but design data in literature is basically lacking for such large container vessels. For this vessel a spectral method has been used to estimate the damping ratio (percent of critical damping), and this spectral method is considered as the most robust method [13]. The results for the vertical 2-node was a damping ratio estimated to 1.9% and for the vertical 3-node 1.3%. The estimate is made based on a fit from a single degree of freedom system to the resonance peak in the spectrum as illustrated for the vertical 3-node in Fig. 8. A low and wide peak suggest higher damping than for a narrow and tall peak. This damping is slightly larger than found from some similar vessels in [13]. Some scatter and uncertainties in damping data is however expected. High damping is however regarded as good for fatigue but does not help much for extreme loading.

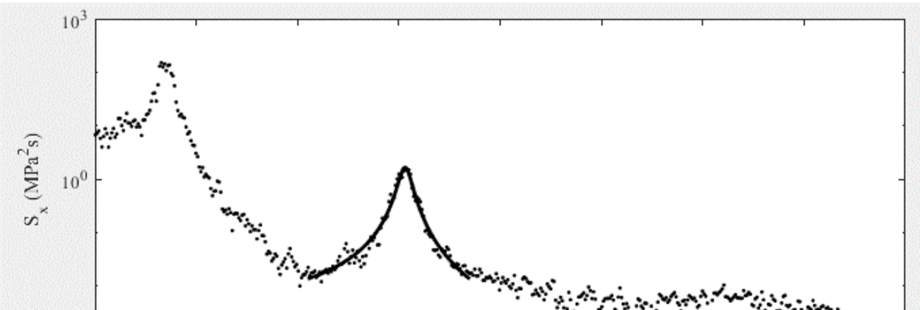

Fig. 8. Illustration of spectral method to estimate damping based on a fit for a single degree of freedom system to the resonance peak in the stress spectrum from the deck sensor aft (GAP) between 00:00 and 01:30 UTC on 13th of January 2018.

3.3 RPM

The propeller/shaft rpm is related very much to the speed, e.g. speed profile in **Fig. 2**. There are several subjects related to rpm, one being propeller racing, which can cause tear and wear of the engine. This can especially occur in stern seas and is relevant for high powered ships as container ship but is less probable for this large ship on this moderate trade. Secondly, it is relevant in extreme loading situations, because the added resistance in waves is reducing the speed in head seas, so it is easier to see the voluntary speed reduction through changes in rpm, related to seamanship. This also depends on the controlling mechanism which is assumed to be constant rpm for this vessel. The third application is towards propeller and hull cleaning, i.e. correlating rpm with speed in calm water (calm response) can suggest a drop in the performance with time used to determine correct time for hull/propeller cleaning. In this context it would be good with a speed log for speed through water to remove the current. The speed log is however often associated with uncertainties in the order of the current speed on ocean crossings for a container ship at full speed, but still speed log is considered useful. In any case, hull monitoring is regarded to provide the best data compared to noon reports for this purpose with less sampling and less accurate readings. The fourth application is to look at the probability of the rpm compared to barred speed (resonance of shafting system) and versus potential resonance frequencies of the rudder, which should be avoided, e.g. to avoid fatigue damages. Barred speed is not relevant for this vessel, and the rpm probability distribution is illustrated in Fig. 9 based on 5 minutes statistics and resolution of 0.5 rpm. The average rpm is 58.9, the maximum rpm is 84.7 and the most probable is 65.75. It is observed that the rpm distribution is spikier than the speed with a clearer secondary peak for slow steaming around 57 rpm. This is because the speed is measured as speed over ground and the current brings randomness to the speed distribution in **Fig. 2**, and the speed profile therefore does look somewhat smoothed compared to the rpm distribution.

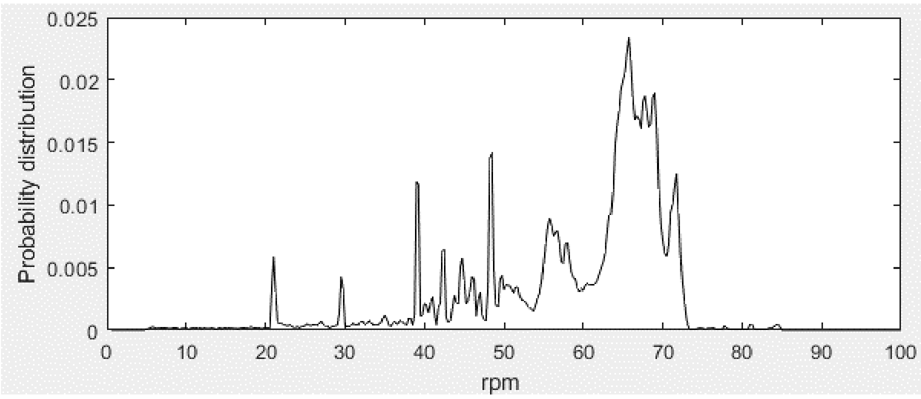

Fig. 9. Illustration of rpm probability distribution.

3.4 Bow accelerometer

The bow accelerometer captures wave frequencies and wave induced vibrations very well, but it can potentially capture higher frequencies as well, which may not be desirable. These higher frequencies may be physical but may be related to pumps and thrusters and local vibration rather than wave induced response, hence these higher frequencies are to be removed by appropriate filtering. The intention is to use it for slamming counting on board, which is related to seamanship, but in it is shown versus design limits. High whipping events measured in the bow part immediately cause additional inertia of the container stacks in the stern part from the 2-node vertical vibration. Higher vibration modes may contribute. The contribution to the inertia can be significant, and many containers have been lost from the stern part of container ships for different reasons, and whipping may have contributed in many cases. It has caused collapse of container stacks without any roll motion being reported. The peak accelerations per half hour are shown in Fig. 10. There appear to be some instabilities. Some apparent spikes may be related to wave induced vibrations, but this is a typical appearance for an accelerometer where the time series has not been processed with the correct filtering removing higher frequencies above e.g. 5 Hz, which may be associated with pumps, thrusters and other equipment close to the accelerometer. The main acceleration is not much more than 20% of the gravity, suggesting that no severe storms have been encountered. 20% of gravity horizontally, is however a border line for passenger comfort, associated also with 12 degrees heel, which is regarded as a panic angle, and elderly people may have problems standing even when grabbing onto something at these acceleration levels. This is more important for passenger vessels.

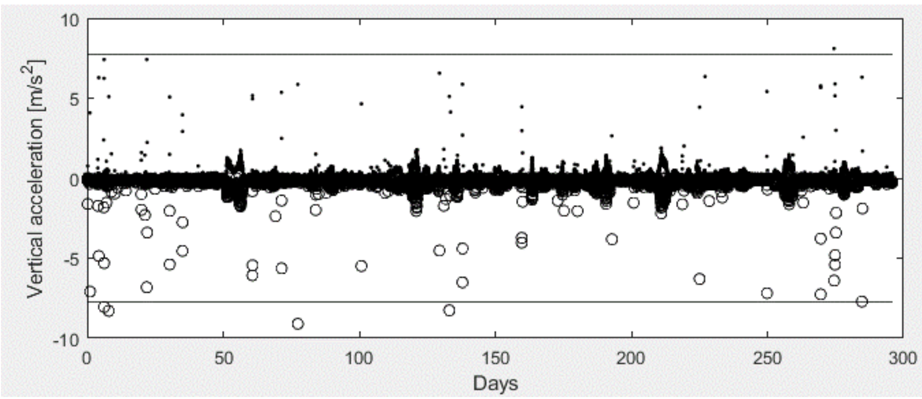

Fig. 10. Illustration of dynamic vertical acceleration.

The wind speed and wind heading are the last main sensor, but the results is not shown. As often forgotten, and common on large ships, the wind speed and heading are not corrected automatically for forward vessel speed and heading. It should also be corrected down from the sensor height to the reference height for the Beaufort scale. That would also be a better reference on board for noon reports. This sensor is most relevant when environmental conditions is combined with for instance the strain sensors. E.g. in [14] it was shown that the dominating heading to fatigue damage was not head seas on this trade, but bow quartering, because of the typical waves encountered versus the size of the vessel.

4 Data quality

Some data quality issues have already been pointed out for these installations, but in the following the concept of data profiling, i.e. finding quality issues in data is explained in simple terms. The basis in this case is the half hour statistical data. It could also be time series, but the analysis time and data amount "explode" with such data. The ratio of data amount between time series files and statistical files for one day is about 500 for this installation. The supplier has converted their binary files to .csv files on a format which is very similar to what is recommended in a new ISO standard [15]. The data is uploaded to Veracity, an open data platform, www.veracity.com. It is not open in terms of data being available to everyone, but a platform that can be used by in principle any user. A platform is basically a meeting place, where apps can be considered as shops and the platform is the mall. The .csv files are then uploaded to a sql server, and thereafter to web-based dashboards.

4.1 Data profiling

Data profiling is about establishing data quality rules for each sensor. In each file the supplier, the vessel, the time, the channel, the sensor names and 9 types of statistics for each sensor are included. Some examples of quality rule checks are:

- Does the supplier name exist on a supplier list?
- Does the IMO number exist in the database of the entire world fleet?
- Is the time stamp, in seconds from 1st of February 1970, reasonable?
- Are there duplicate records (same time)?
- Are there missing records?

Then there are more advanced rule checks for each sensor like

- Is the mean value within a reasonable range?
- Is the channel numbering constant with time?
- Are the sensor names reasonable and as expected? (these are related to the qualifiers in the HMON notation and the filtering required)
- Is the maximum and minimum value within a reasonable range?
- Is the peak to peak value correlated with the maximum and minimum?
- Is the number of observations (samples) during half an hour reasonable?
- Is the mean plus/minus the maximum/minimum within a reasonable range?
- Are correlated sensors correlated, e.g. if one goes up the other should go up? Etc.

Such rules need to be defined for each sensor, and then quality checks can be run. Considering 20 statistical points of one sensor and a specific statistical method and having 2 errors for that check, the failure rate is considered as 0.1. Having many rules for a sensor, the average failure rate can be estimated for that sensors. Then the average failure rate can also be estimated for all the sensors on one ship. This is a measure of quality, but some quality rules may be more important than others, so it should be possible to reveal also which quality rules that fail at any time.

4.2 Data quality dashboard

Based on the data quality rules for each sensor a web-based dashboard has been developed using a Power BI solution. In principle it is only the owner of the data who would have access to this, but the owner may share access also to others. In this case, the owner, operators, supplier and DNV GL advisory have all access. The overview dashboard of the fleet of ships with all sensors are shown in Fig. 11. To the left all the ships in the fleet are included. Ship no. 3 is a reference ship, a gas carrier, while the other four ships are the sister container ships. The ship with the worst quality is automatically ranked on top. The red part shows the average fraction of poor quality for each ship, and sensor. If there are many ships, it is possible to scroll down on all the ships. If no ships are marked, then the right column shows all the sensors for the whole fleet. It is then easy to detect sensors with poor quality in the entire fleet. When a vessel is marked, as is the case in Fig. 11 for ship one, then only the sensors belonging to that ship is marked. There are many sensors and channels for that, and the worst one is the wind speed, and the second one is the accelerometer. We still do not know what is for instance the problem with the accelerometer, but we have an indication that there are issues for the accelerometer from Fig. 10. There is also a bar with dates on top of the figure. The dates go from 9th of April 2007 to 28th of June 2018. These dates can be changed, by sliding the bar or changing the dates. This is essential, because once discovering quality issues, the supplier may do maintenance by going on board, or by connecting to the system from shore on more modern systems. After maintenance of the system, this dashboard can then be used to verify that the quality has improved after maintenance just by adjusting the dates. This takes a few second for the operator, and the dashboard is then representing condition monitoring of the data itself, which may be necessary during the entire operational life if the data is essential. Example of that is sloshing monitoring on FSRUs to avoid costly gas tank inspections.

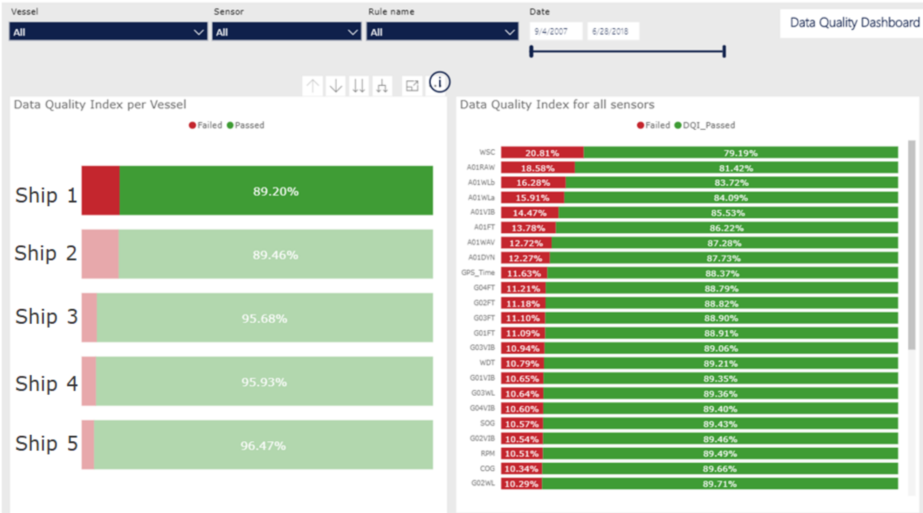

Fig. 11. Illustration of quality dashboard with overview for statistical sensor data.

In the dashboard in Fig. 11 it is possible to mark the sensor of concern and drill down into that one for more details. This is illustrated in Fig. 12 for the accelerometer based on the raw (unfiltered signal). The details are not so readable, but the color coding on the time line in the bottom suggest that there are many missing records, basically in the order of 60%. Secondly the statistical data for peak values are outside the expected range. The expected range and warning values are specified in a separate .csv file for that installation which contain metadata and configurational information of the system, for instance which stress concentrations and S-N curves and target design life that are used in fatigue calculations. To the upper left the dates and data rules that fails on a single date is shown with numbers and color coding. To the upper right the different quality rules are listed with aggregated results which explains the average quality number for that sensor. It is basically two problems with this sensor and that was the missing data and surprisingly high peak values that point to the wrong filtering. The severe issue in this case is missing data, which is basically lost data. The supplier has based on this feedback acted and identified and corrected the issue, which in this case was related to problematic GPS connection forcing the system to frequently reboot. Such an underlaying problem is regarded difficult to find directly, but this also confirms the necessity of looking at data early.

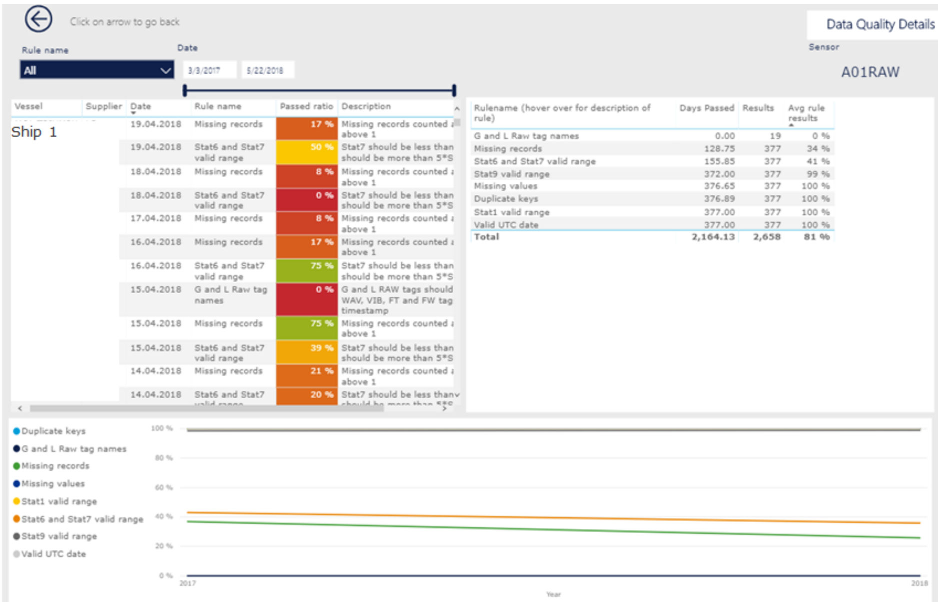

Fig. 12. Illustration of quality dashboard with detailed information on data quality rule checks for a single sensor and filtering (channel).

5 Result dashboard

Results dashboard is also made for the statistical data, similar to the sample results. The first result is a map solution similar to **Fig. 1**, and with time at sea and time in port, and speed time series. The strain sensor can be selected, and the high fatigue loading areas are visualized for experience feedback. In this case, a few spikes on the speed has been observed, due to GPS issues as shown in Fig. 13. Due to limitation of Power BI solution, only daily maximum value for fatigue is shown, and in this case the vessel has not been highly loaded (everything green).

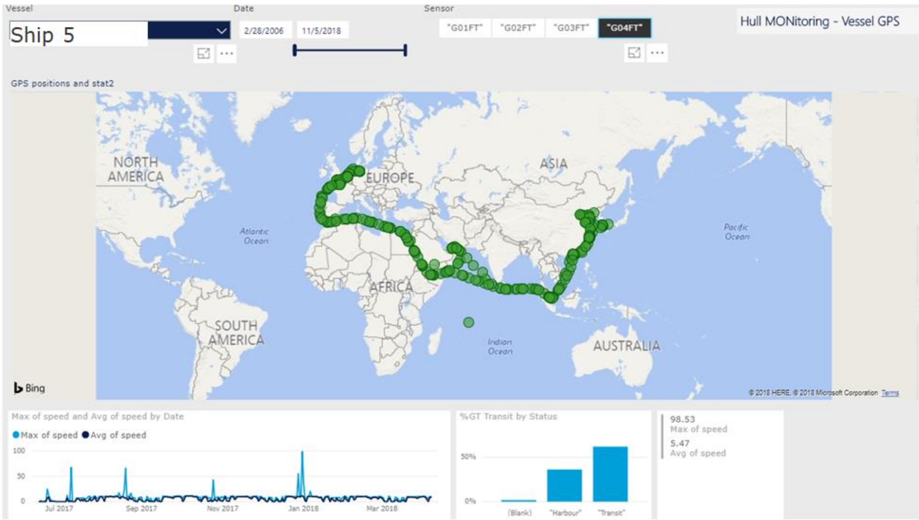

Fig. 13. Illustration of map solution with sensor information on high load areas.

The second page shows the fatigue damage, fatigue utilization and fatigue rates for selected strain sensors as time series. All sensors are also ranked with the most important sensors on top. This is illustrated in Fig. 14. In this case the worst fatigue damage is 0.01 which suggests that it is not necessary to inspect for fatigue. The maximum fatigue utilization is 0.33 which suggest that it is better than design, so the expectation is good indicating that fatigue is not expected to become an issue in the future. Finally, the maximum fatigue rate is 60, suggesting that significant fatigue loading has been encountered one day, but this is not extreme. Poor seamanship is thereby not yet any concern from a loading perspective. In addition to seamanship, this is primarily for maintenance planning and inspection. If the number of sensors becomes large, so it is not easy to know where they are located, the configuration file contains locations, so these measurement points can be shown on the design model in Sesam Insight [16], which is also web-based for owner access.

The last page is a sensor inspector, Fig. 15. In principle any sensor and any statistics can be inspected as a time series. The first shows daily peak values, but marking a day, it is possible to drill down to see values for each half hour. In that way it is easy to inspect behavior of statistical data for instance if there are quality issues. This is however less frequently used.

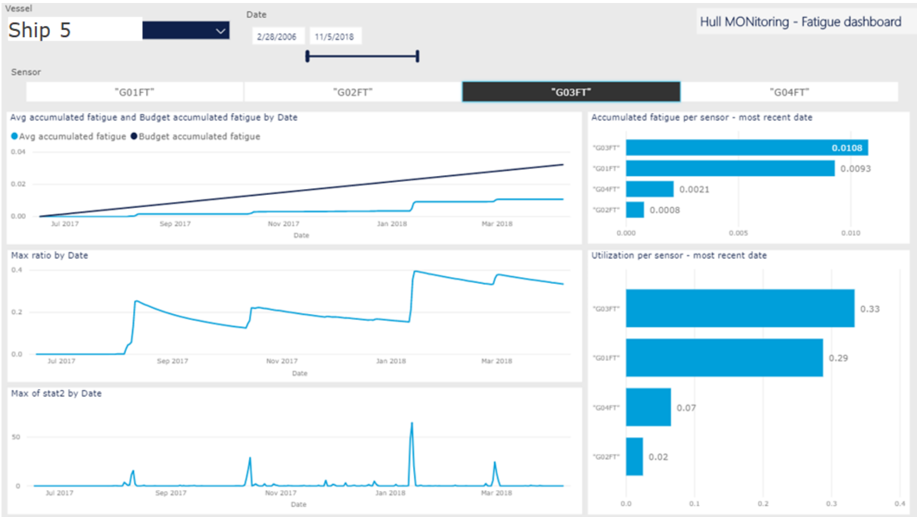

Fig. 14. Illustration of fatigue time series for selected sensor and fatigue damage and utilization for all strain sensors.

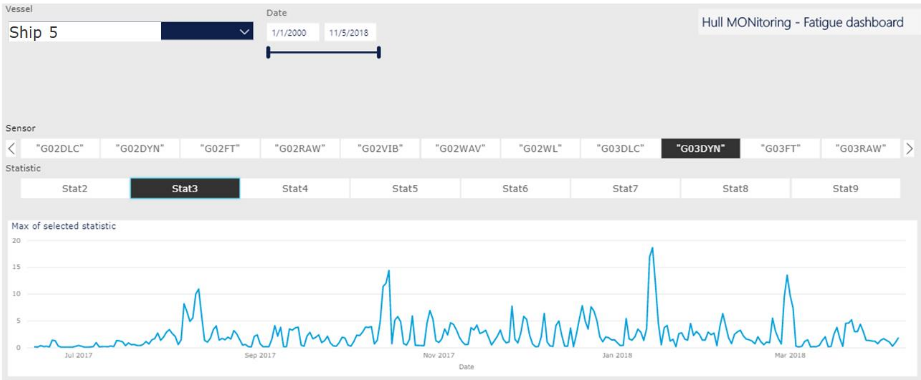

Fig. 15. Illustration of statistical sensor inspector where any sensor and statistics.

6 Conclusions

This paper represents steps towards digitalization and is related to condition monitoring using sensors. Data from four container ships have been considered, and sample results have been shown for different sensors with different purposes and potential quality issues. A web-based data quality dashboard has been demonstrated and is considered as an essential necessity to build trust in the data before it is being used.

Potential use of sensor results is also illustrated through a result dashboard related to maintenance and inspection planning, inspection and seamanship, based on fatigue monitoring. There are also other sensors included in the system which can be used for many purposes within the organization of the owner. Further work is to understand the value and use of data, which is very much dependent on the owner. It can be related to control, awareness, operational excellence, branding, and in more technical terms related to damage risk mitigation, propeller racing, fuel studies, engine tuning, cargo safety, rudder and shaft resonance issues, loading computer verification, seamanship, comfort and hull girder safety. The latter is because the hull monitoring system complements the loading computer as a dynamic loading computer closing the gap between design and operation.

Even more technical, it is observed that the fatigue and extreme loading, so far, has been comfortably low for the four sister vessels on this Asia to Europe trade. The whipping is contributing significantly to extreme loading, but no exceedance of rule limitations has been observed. No extreme storms have been encountered. No torsional vibrations have been observed, but the vertical 2-node vibration and vertical 3-node vibrations are observed contributing to the fatigue damage especially for deck details. The damping of these vibrations has been higher than on blunt ships with 1.9% being useful input to design calculations of similar designs.

7 Acknowledgement

The authors would like to thank the owner, operators, supplier and DNV GL for support and funding in this JDP and for facilitating access to data for assessment.

References

1. DNV GL rules for classification: Ships, DNVGL-RU-SHIP Pt.6 Ch.9 Sec.4 Hull monitoring systems – HMON, edition July (2018).
2. DNV GL rules for classifications: Ships, DNVGL-RU-SHIP Pt.7 Ch.1 Sec.7 [4] Data management, edition July (2018).
3. DNV GL rules for classification: Offshore units, DNVGL-RU-OU-0300 Ch.2 Sec.5 Application of data. Edition July (2018)
4. International Organization for Standardization, ISO 8000-8, Data quality – Part 8: Information and data quality: Concepts and measuring, edition 1, November (2015).
5. DNV GL recommended practices (RP), DNVGL-RP-0497, Data quality assessment framework, edition January (2017).
6. DNV GL class programmes (CP), DNVGL-CP-0484, DNV GL approval of service supplier scheme, edition March (2018).
7. Storhaug, G, Kahl, A., Hull monitoring closing the gap between the design and operation. Proceedings Design for Safety conference, Hamburg, 28-30 November (2016)
8. IACS, Unified requirements UR Z7, Hull classification Surveys, 1990, revision 26 (2018).
9. IACS, Unified requirements UR S11A, Longitudinal strength standard for container ships, June (2015).
10. DNV GL, Fatigue assessment of ship structures, DNVGL-CG-0129, class guideline, edition January (2018).
11. IACS, Common Structural Rules for Bulk Carriers and Oil Tankers, 1st January (2018)
12. Storhaug, G., Fredriksen, O., Greening, D. & Robinson, I., Practical verification of loading computer by laser measurements, MARSTRUCT, 6th International conference on Marine Structures, Lisbon, Portugal, 8-10 May (2017).

13. Storhaug, G., Laanemets, K., Edin, I. & Ringsberg J.W., Estimation of damping from wave induced vibrations in ships, MARSTRUCT, 6th International conference on Marine Structures, Lisbon, Portugal, 8-10 May (2017).
14. Barhoumi, M., Storhaug, G., Assessment of whipping and springing on a large container vessel, International Journal of Naval Architects and Ocean Engineering, Volume 6, Issue 2, pp. 442-458, (2014).
15. ISO, Ships and marine technology, Standard data for shipboard machinery and equipment, International Organization for Standardization, ISO 19848:2018, October (2018).
16. Sesam Insight home page, https://structure.dnvgl.com/