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On-board trend analysis for cargo vessel hull monitoring systems

Oleg Gaidai[1], Gaute Storhaug[2], Fang Wang[1], Ping Yan[1], Arvid Naess[3], Yu Wu[1], Yihan Xing[4], Jiayao Sun[5]

[1] Shanghai Engineering Research Center of Marine Renewable Energy, College of Engineering Science and Technology, Shanghai Ocean University, Shanghai, China

[2] Det Norske Veritas, DNV Maritime, Oslo, Norway

[3] Norwegian University of Science and Technology, Norway

[4] University of Stavanger, Norway

[5] Jiangsu University of Science and Technology, Zhenjiang, China

ABSTRACT

With the increased focus on sustainability, de-carbonization and digitalization also the shipping industry is scrutinized. High steel weight implies high initial CO_2 footprint but also higher operational CO_2 footprint. With requirements to decreased emissions through IMO indices EEDI and CII, it is beneficial to lower the steel weight but without compromising safety. Utilizing sensor technology may enhance the safety and potentially allow for a more optimized structural design. For hull girder loading this is related to hull stress monitoring systems.

Container ships are becoming increasingly important in the shipping industry. As manufactured goods are increasingly containerized, the container ship fleet has expanded.

According to DNV's hull monitoring rules, it is required to provide a forecast prediction based on recent measurement data to alarm the captain of potential extreme hull girder loading. If this forecast prediction is too low then a false impression of safety is provided, and if the prediction is frequently too high the captain may lose confidence in the system. These results are not acceptable, and it is therefore necessary that this prediction is reliable. This paper highlights modern challenges and ideas, incorporating novel statistical method to serve safe navigation. Trans-Atlantic voyages along with monitored onboard hull girder response data are discussed.

Sequence of the latest data from each individual sensor shall be displayed as a trend. Current rules states that 4-hour data sequence from each individual sensor shall form the basis for a forecast trend prediction of the expected response for at least the next hour. Encountered maximum stress may overshoot predictions by 50%, which is regarded unreliable. If too high values are predicted all the time, captain lose confidence and trust in the system trend analysis. If too low values are predicted the system provides false impression of safety. Both outcomes are unacceptable.

Special focus is paid to whipping, which is defined as a transient hull girder vibration phenomenon caused by wave impacts. The vibration decays slowly because of low damping, which results in whipping being superimposed on both the wave sagging and wave hogging cycle. The challenge is that the whipping may be of more freak nature than the more conventional wave bending considered in design.

Predicted stress level obtained by extrapolation is focused on extreme value for the sake of vessel hull safe navigation. Extrapolation by ACER (averaged conditional exceedance rate) method was done, including uncertainty bands.

Main motivation for this paper is to contribute to the development of reliability assessment methods for decision support on board ships which may facilitate an improved balance between safety and structural design. Seamanship is already a factor in ship design but through digitalization it may be enhanced allowing for some steel optimization without compromising safety.

KEYWORDS

ACER, ship hull, whipping, reliability, extreme stress, container vessel.

INTRODUCTION

The latest DNV rules "Hull monitoring systems - HMON", (DNV rules for classification Ships, 2021) clearly requires early warning from the on-board software tool to warn captain about potential incoming extreme hull girder loading. Hull girder loading are of critical concern for vessel safety, as extreme loads may cause not only rapid fatigue damage but an immediate local or global collapse of the hull girder. Guidance note (DNV rules for classification Ships, 2021) DNV-RU-SHIP Pt.6 Ch.9 Sec.3 states: "It is recognized that no extrapolation method is regarded perfect for all responses at any time. Extrapolation should focus on the extreme value. Extrapolation by a Weibull fit should be done as a minimum, but other methods can be used simultaneously to improve the reliability and include uncertainty bands". With container vessels sizes are increasing, some with extreme bow designs, the concern towards whipping has increased. The experience with such large container ships is limited. The combination of large bow flare and high service speeds makes these vessels vulnerable to whipping. This has been a concern for the industry for a while, but the effect is not limited to large vessels. This will be illustrated considering measurements on board a 2800TEU container vessel operating in the North Atlantic. This is nowadays considered as a feeder design, but it is still a vessel of about 245 m of length, and due to the Panamax width of 32.25 m. The 2800TEU bow flare is moderate with a maximum local angle of 40°, which is not much compared to a modern post-Panamax vessel, and the amount of whipping will thereby also be limited. The vessel was instrumented in August 2007 and the route since then are shown in lower Fig. 1.

Fig. 1 Upper: An example of a loaded Panamax container vessel. Lower: Sample North Atlantic routes between Europe and North America.

Fig. 1 presents an example of a loaded Panamax container ship along with sample North Atlantic route. Routing to avoid the worst storms are evident from the selected paths, otherwise it would be shortest distance every time and the voyages would collapse to a couple of lines. This is already demonstrating the captain's wise decisions related to seamanship to safeguard the cargo, hull and the crew. Still the hull may be close to overloaded.

Safety of cargo ship transport is an important issue in a view of dramatic episodes like MOL Comfort (Post-Panamax container ship broke in June 2013). Ship broke due to overloaded hull girder (ClassNK, 2014) – report indicate that critical overload was partially due to whipping caused by bow flare slamming. Hull girder load is a key factor that may cause vessel damage.

ONBOARD SENSORS

The hull monitoring system onboard the container vessel will be discussed along with explanation of the background, motivation and purpose of the measurements. The 2800TEU vessel was equipped with strain sensors and supplemented by wave radar and motion measurements, and the monitoring system also utilizes other standard sensors already available onboard.

First of all, this vessel was instrumented because it operates on the North Atlantic which is considered as the design environment for ship design and the worst wave environment in the world in practice. Secondly this vessel was selected because the operator has experience with high loading on this route and damages not only on this vessel. Finally, because the operator also saw the value of enhancing the safety investing in the measurement system on this vessel. The vessel was also classed by DNV even though it was not originally approved to DNV rules.

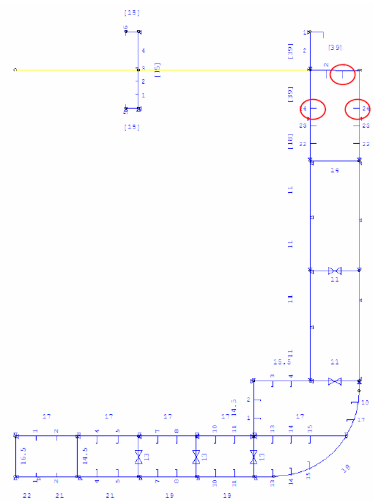

Fig. 2 Layout of mid-ship cross section with measurement position in upper deck and crack positions at the stringer level 1 marked with two red circles.

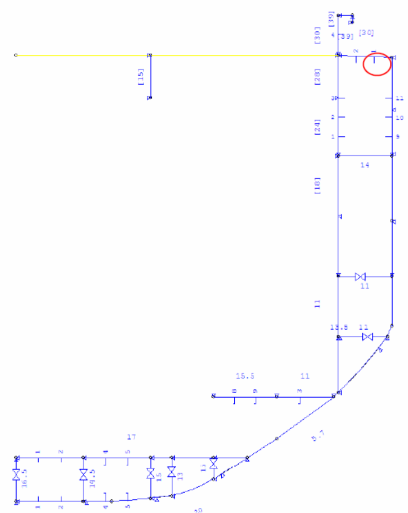

Fig. 3 Layout of cross section at frame number 67 with measurement position indicated in upper deck.

Fig. 2 and Fig. 3 present the 2800 TEU container vessel on-board strain sensors placement in upper deck at midship and at aft quarter length along with observed crack positions at midship, see (Storhaug, Moe and Lopes 2007). It is seen from the cross sections that the vessel design is slightly unconventional with a longitudinal girder in deck at quarter breadth.

DECK STRESS TREND IDENTIFICATION

This section presents new ideas regarding trend build up, preceding occurrence of deck stress global maxima of each single transatlantic voyage. This paper relies on the wide database of over 70 individual transatlantic crossings by the same 2800 TEU container vessel following similar route, see Fig. 1, in different sea conditions. Then these analyzed voyages were numbered from 1 to over 70 for convenience, therefore 1st voyage refers simply to the 1st in database. It should be noted that towards North America the vessel experiences prevailing head seas, while prevailing stern seas on the way towards Europe. This means that higher loads due to whipping is expected towards North America.
A nonscientific note is also that these strongly nonlinear whipping events may be perceived as more freak than the wave process itself, but this cannot be easily demonstrated as the measurements do not reveal the wave process even though 2-dimensional wave spectra are measured and collected. The larger whipping events are a combination of unfavorable wave profile versus the bow shape and even though whipping occur frequently from small wave impacts, the larger more dramatic whipping events may not be frequent. This freak nature of the larger whipping response may then introduce additional challenges to trend analysis.

Fig. 4 presents an example of DMP (Deck Midship Port) stress on-board recorded data (1st voyage), star indicates an outlier max stress (freak event). An arrow indicates the local trend. Later on in this paper 10 different voyages that took place between 2007-2010 will be analyzed.

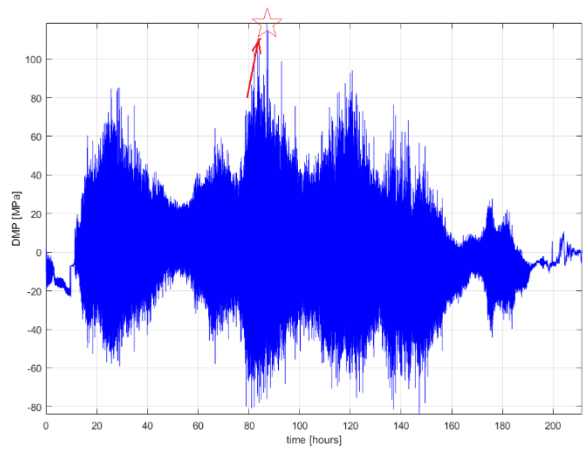

Fig. 4 An example of measured deck midship port (DMP) stress. Star indicates extreme action moments to be scrutinized. Single transatlantic crossing. Total 9 days of 1st voyage.

In this study 12 hours "observation window" was chosen for trend analysis, as it is typical for the storm to brew up within about 12 hours period of time. Since "stationary" sea state is typically lasts for 3 hours, it was natural then to split the above mentioned 12 hours "observation window" into four 3 hours storms for subsequent statistical trend analysis. The four 3-hour storms will be used for prediction of maxima within the read area of Fig. 5.
Fig. 5 upper plot presents 12 hours preceding occurrence of the 1st voyage global stress maximum (indicated by star). In red 2 hours of stress record containing the global voyage maximum; and on the lower plot 12 hours of preceding occurrence of 1st voyage global stress maximum split into four 3-hour storms with each 3-hour storm maximum plotted. Red arrow indicated maximum increase gradient between 3-hour storms maxima.
Note that Fig. 4 and Fig. 5 upper plot corresponds to the same 1st voyage and represents the same global voyage stress maximum. Fig. 5 lower highlights the maximum increase ΔΣ between neighboring four 3-hour storms stress maxima. The latter increase ΔΣ will be used as a trend correction for predicted extreme stress belonging to the red area, see further this section.
Fig. 6 is analogous to Fig. 5 with only difference is that 2nd voyage is analyzed instead of 1st.

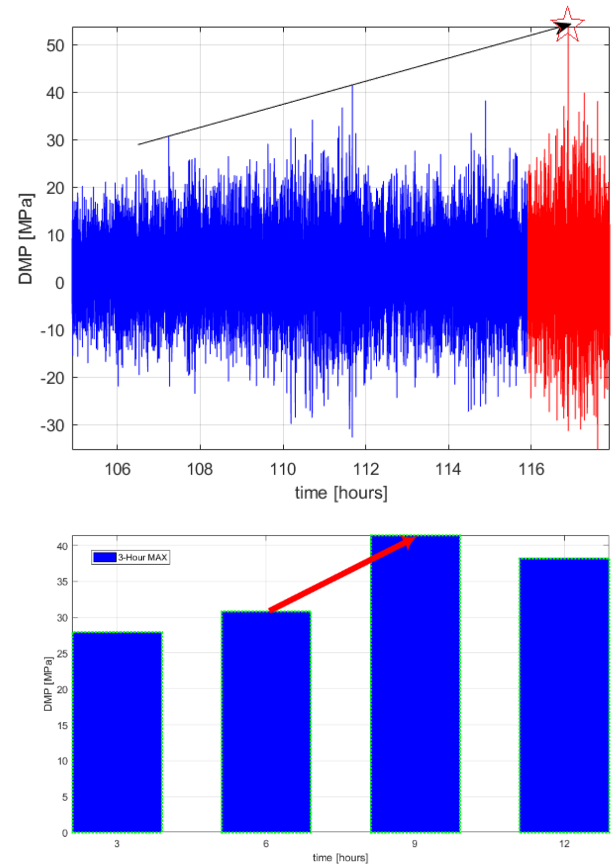

Fig. 5 Upper: In red: 12 hours preceding occurrence of 1st voyage global stress maximum (indicated by star), plus in blue: 2 hours of subsequent stress record containing the global voyage maximum.
Lower: 12 hours of preceding occurrence of 1st voyage global stress maximum split into four 3-hour storms with each 3-hour storm maximum plotted. Red arrow indicated maximum increase gradient between 3-hour storms maxima.

Note that in Fig. 5 there is no trend as such, or in other words there is no monotonous increase in 3-hour maxima, however as will be shown in the next section, the suggested approach of "trend correction" is still performing well.

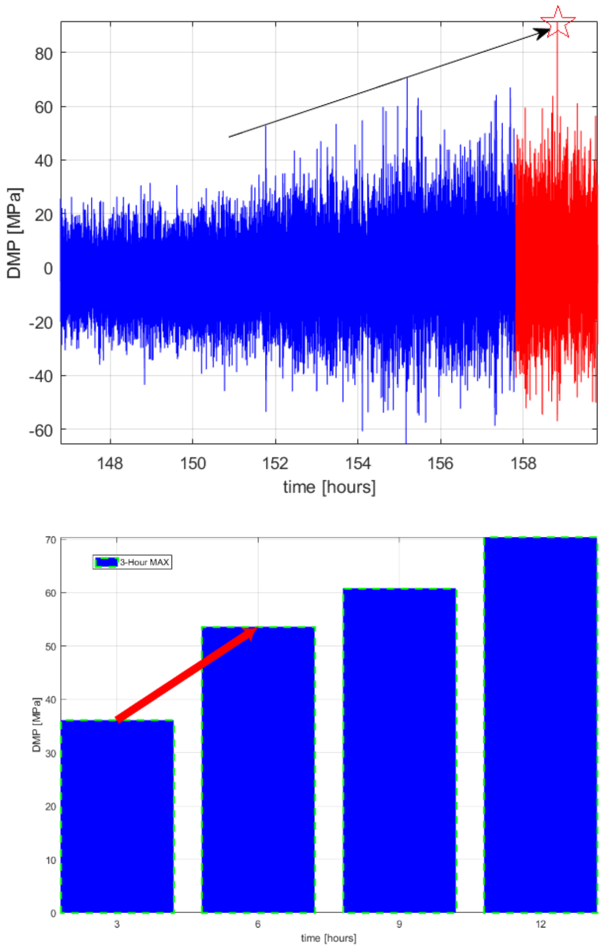

Fig. 6 Upper: In red: 12 hours preceding occurrence of 2nd voyage global stress maximum (indicated by star), plus in red: 2 hours of subsequent stress record containing the global voyage maximum. Lower: 12 hours of preceding occurrence of 2nd voyage global stress maximum split into four 3-hour storms with each 3-hour storm maximum plotted. Red arrow indicated maximum increase gradient between 3-hour storms maxima.

Voyage No	3-hours MAX_1	3-hours MAX_2	$\Delta\Sigma$
1	30.8	41.4	10.9
2	36.11	53.6	17.5
3	49.2	79.9	30.7
4	33.0	59.2	26.2
5	26.8	61.5	34.7
6	56.9	61.9	4.9
7	26.8	61.5	34.7
8	43.6	62.6	19.0
9	58.8	69.5	10.7
10	34.9	44.4	9.6

Table 1 List of $\Delta\Sigma$ stress correction in MPa per voyage.

Table 1 presents 1 List of $\Delta\Sigma$ stress correction in MPa per single transatlantic voyage. Note that $\Delta\Sigma$ = 3-hours MAX_2 −3-hours MAX_1. The main challenge is to quantify the "trend". Table 1 is based on idea that if there is no trend then all four 3-hour storms will not differ much in their stress maxima and therefore no trend correction is needed. If, however, there is significant variation between four 3-hour storms stress maxima, then $\Delta\Sigma$ correction is generated and to be applied as trend correction to statistical prediction, discussed in the next section.
The trend correction issue is of significant engineering importance for both safe operations as well as container transportation cost reduction, especially given the recent rise in container transportation expenses around the globe.

STATISTICAL ANALYSIS

This section presents ACER (Averaged Exceedance Conditional rate) method results applied to selected storms from the previous section. Note that ACER as well as other classical methods like e.g. Gumbel, Weibull, Paretto are based on assumption of stationarity (i.e. no trend) and therefore trend correction is required. As discussed in the previous section, the 12 hours "observation window" was chosen for the distribution tail extrapolation. For details on ACER method see (Gaidai et al, 2019-2020; Naess et al, 2008-2013; Xu et al; Gao et al, 2018).
To summarize, 12 hours of recorded data, preceding the freak event, were used to predict next 2 hours incoming stress maxima.

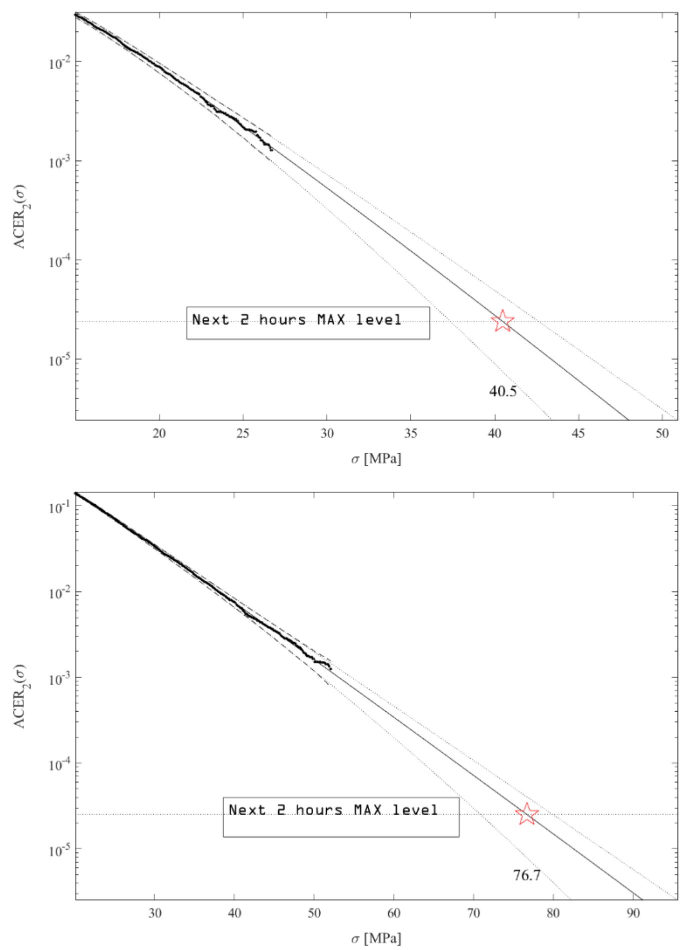

Fig. 7 Upper: ACER prediction for the 1st voyage, see Fig. 5, no trend correction applied. Star indicates next 2 hours predicted maximum stress in MPa. Lower: ACER prediction for the 2nd voyage, see Fig. 6, no trend correction applied. Star indicates next 2 hours predicted maximum stress in MPa. Dotted lines indicate 95% CI (confidence interval).

Fig. 7 on the upper side presents ACER prediction for the 1st voyage, see Fig. 5, no trend correction applied. Star indicates next 2 hours predicted maximum stress in MPa. Fig. 7 on the lower presents analogous results for the 2nd voyage. Note that further on the upper 95% predicted 2 hours CI limit will be used in Table 2 as a base for extreme value prediction.

Table 2 Comparison between corrected and actual maxima for different voyages.

Voyage No	Predicted	Corrected	Actual
1	43.6	54.5	53.9
2	80.2	97.7	91.6
3	108.8	125.3	118.7

Table 2 presents comparison between corrected and actual maxima for three first voyages, 95% CI limit was used as 'Predicted' value. 'Corrected' = 'Predicted' + $\Delta\Sigma$. It is seen from Table 2 that for selected voyages suggested trend correction worked indeed well, when using as benchmark actual recorded stress maximum, denoted as 'Actual'.

CONCLUSIONS

This paper has discussed an important issue of trend analysis and related non-stationary stochastic processes. As manufactured goods are increasingly containerized, the container ship fleet has expanded. According to the DNV ship hull monitoring rule trend analysis is required to provide the captain with decision support. The main conclusion of this paper is that indeed, trend has to be taken into account, and proper trend correction should be applied to the predicted extreme value that is based on stationarity assumption and does not account for the trend.

The on-board cargo vessel data was analyzed during numerous (over 70) transatlantic voyages. For this study 10 voyages have been initially selected, to begin with. The suggested methodology of trend estimation however raw and approximate, appears to be novel and yielding accurate predictions. It should be emphasized that in all these cases the upwards trend over 12 hours have been chosen, and it is necessary that the procedure to work also when the trend goes downwards but also of course when there is no non-stationary trend (which should be the easiest case).

The main challenge was to quantify the "trend", and further study is needed. This paper suggests simple yet robust way of accounting for the trend correction. The latter is of significant engineering importance to provide useful decision support to the captain.

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