DESIGN AND IMPLEMENTATION OF A COMPREHENSIVE FULL-SCALE MEASUREMENT SYSTEM FOR A LARGE CONTAINER CARRIER

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SUMMARY

As modern container carriers become larger, certain parts of the existing prescriptive rules may pose increased uncertainty due to a lack of service experience. For example, questions concerning the envelope of wave-induced sag-hog moments may be raised as to whether the nonlinear effects due to the hull form or forward speed are properly reflected. The direct calculation methods are often used by ship designers to apply the ship motion and sea loads calculated from nonlinear seakeeping theory, then the finite element structural analysis is carried out to assess the structural integrity of the vessel. Although many advances have been made in the nonlinear hydrodynamic tools used for design reviews of the large container carriers, systematic validation of the wave loads and structural performance of these vessels in real operational conditions have not been reported.

A comprehensive full-scale measurement system was developed to measure the wave environment, ship motions and structural loads. The complete system consists of the hull stress monitoring system, onboard wave monitoring system and voyage optimization system. The hull stress monitoring system employs ten long base strain gauges to measure the hull girder bending moments and torsional moment. The onboard wave monitoring system, which is based on the X-band radar signal, is used to monitor and display the significant wave height, periods and direction. Data from the vessel operation and navigation are obtained from the onboard voyage optimization system.

The system was installed on an 8063 TEU container carrier in 2006, and the measurement campaign is currently underway. This paper presents the design of the onboard measurement system, installation and testing of the system. A description of the methodology to derive the torsional moment from the strain gauge signals is also included.

1. INTRODUCTION

1.1 BACKGROUND

One of the well-known full-scale measurement projects on commercial vessels was the SL-7 research project in the 1970’s. The SL-7 research project was sponsored by Sea Land Services, Inc., American Bureau of Shipping (ABS) and Ship Structures Committee (SSC) with an overall objective to “either develop or provide supporting evidence for rational design methods for ships”. The main objective of the full-scale data measurement phase
of the project was that the results of wave-induced stress measurement would be compared with model and computer analysis data. Another important objective was to develop and validate “analytical tools and technique” for ship motion, sea loads, and structural responses including finite element analysis. The “analytical tools and technique” have been further evolved since then to become the basis of the ABS SafeHull-Dynamic Loading Approach (DLA) [1].

The benefits of the full-scale measurement are once again relevant as the recent growth in size of modern container carriers has been very rapid. This has created challenges for the container shipping industry including the operators, designers, builders and classification societies. The recent trend in design and construction of large container carriers and technical approaches taken by ABS have been presented in recent publications [2] [3]. The limitations of the traditional classification rules criteria and linear seakeeping analysis were addressed, such as sag-hog wave moments, wave-induced shear force and torsional moment, and load combination. These papers also presented the way in which the nonlinear seakeeping program may be applied to overcome these limitations.

The operators of modern large container carriers are also concerned about the safety and performance of these vessels since they do not have a lot of experience with these ships. The hull stress monitoring system is gaining popularity among ship operators in order to provide assistance to the crew for better handling of difficult situations. For example, Orient Overseas Container Lines (OOCL) has equipped all vessels of Samsung Heavy Industries (SHI) built 8063 TEU class container carriers with the hull stress monitoring system (HSMS). The HSMS system has primarily been used by the ship’s crew to monitor the hull girder bending moment and bow acceleration to assure that the vessel operates within safe operational limits. ABS considers the monitoring of hull condition important and has published the ABS Guide for Hull Condition Monitoring Systems (1995, 2003) [4].

The ship designers and builders are also interested in providing more value-added features to ships in order to enhance safety and operational efficiency to make their ships more attractive to potential owners. SHI has developed the HSMS system as a valued optional feature to make their ships more attractive to potential owners. Yet another feature often used for modern container carriers is the weather routing and voyage optimization system. This system is also becoming popular since it can not only assist the crew in avoiding heavy weather conditions but can also provide additional information, such as expected ship motion or fuel consumption, etc., for the crew to operate the ship more safely and efficiently. SHI developed a system known as SORAS.

OOCL, SHI and ABS have been working together in the design, classification review, construction, and commissioning of the OOCL 8063 TEU class vessels. These three parties recognized the opportunity for carrying out full-scale measurement in actual operating conditions. The objectives of the full-scale measurement project are to validate the HSMS and WaveFinder against analytical results and available weather data and to investigate the long-term statistics of sea loads. This paper presents the installed measurement systems and results of measurements taken during the maiden voyage.

1.2 TEST VESSEL

MV OOCL Europe was one of a series of container carriers built by SHI and delivered to OOCL on 29 July 2006. The first of this series vessel was delivered in 2002, and principal particulars are given in Table 1. The vessel was recognized as the largest container carrier at the time of delivery. The vessel design was reviewed using full-ship finite element analysis using ABS Dynamic Loading Approach. The profile and plan view of the vessel is shown in Figure 1.

| Length O.A. | 323.0m |
| Length B.P. | 308.0m |
| Breadth (Mld.) | 42.8m |
| Depth (Mld.) | 24.6m |
| Draught (Scant.) | 14.5m |
| Speed (Design) | 26.0 knots |
| Container Capacity | 8063 TEU |
| Cb | 0.68 |

Table 1 Principal Particulars of OOCL Europe

2. FULL SCALE MEASUREMENT SYSTEM DESIGN AND INSTALLATION

The full-scale measurement system consists of two main component systems; the hull stress monitoring system (HSMS) and the onboard wave monitoring system (WaveFinder). The test ship is also equipped with the voyage optimization system (SORAS). It shares the processing computer with WaveFinder and the ship motion sensor is a part of SORAS, which is also used by HSMS. The testing of SORAS is not addressed in this paper. Figure 2 shows the computer systems installed on
the bridge and the X-band radar at the bow for WaveFinder.

Figure 1 Profile and plan view and of MV OOCL Europe 8063 TEU Container Carrier

Figure 2 Installation of the measurement system for OOCL container ship

2.1 HULL STRESS MONITORING SYSTEM

In general, HSMS installed on commercial ships have been used to monitor global hull girder stresses and related vertical bending moment by using long base strain gauges (LBSG) from a section near the midship. Existing guidelines for the HSMS system require monitoring of the measured stress and moments to demonstrate the soundness of hull structures. There are numerous studies indicating that the torsional moment, in addition to the vertical and horizontal bending moments, is one of the most important design parameters for a container ship having a channel-type cargo hold structure [6]. The detailed method of deriving external moments from the measured strains, therefore, is to be developed by the HSMS designers.

Kenichiro et al [7] has proposed an approach to derive external moments based on strain signals from a midship section and correlation parameters that are derived by applying FE analysis. This is quite a useful suggestion but the limitation is that the torsional component is derived from one transverse section of the ship rather than from two adjacent sections. It is believed that the derivation of the torsional moment from the strain measurements at two adjacent sections may yield more accurate results.

Choi and Kang [8] have proposed a method based on two sections which conform to the theoretical formulation. The derived bimoments using the strain decomposition method from two sections, which have four long base strain gauges at each section, are used in the formulation. Section 3 of this paper summarizes the brief theory as reference. This systematic approach is selected in this full-scale measurement project.

Figure 3 Arrangement of long base strain gauges for Hull Stress Monitoring System installed on the test vessel

Figure 3 illustrates the arrangement of long base strain gauges for the hull girder stresses at three transverse sections: at two sections in midship region (Fr. 183, Fr. 207) and at the fore part (Fr. 320). The sensors in the midship region are four long base strain gauges at each section, and two LBSG are installed at the forward part of the upper deck. All sensors have been calibrated by the strain values using calculated levels in a calm sea condition. An accelerometer is installed at the forward bosun store to monitor the bow acceleration as well as the effects of impact loads due to slamming.

A motion sensor is also installed at the accommodation area to record the roll and pitch motions. The motion sensor is part of the SORAS system and primarily used to check the calculation of ship motion performance of SORAS. The motion data is accessible to HSMS by serial connection for this ship.
All sensor signals of the HSMS are digitized at 20 samples per second. The sensor signals are processed to generate statistics for each 5-minute time history, and then are recorded on the hard disk of the processing computer. The statistics include the maximum, mean, minimum, peak-to-peak, standard deviation, root mean square (RMS) and mean crossing period. In addition to the statistics, the raw time histories of the HSMS sensors are also recorded for 5 minutes on every hour.

The HSMS provides an interactive user interface to display the bending moments, torsional moment, statistics, bottom slam occurrence, cumulative fatigue cycle count and the real-time sensor signal display. The HSMS also provides an option to replay the recorded data.

Figure 4 illustrates a sample replay screen of the HSMS, which shows the option to display the measured strain, the derived bending and torsional moments, and the navigation route from the recorded data. Hence, hull structural conditions are easily measured and analysed using this hull stress monitoring system.

2.2 ONBOARD WAVE MONITORING SYSTEM

The ship’s crew typically receive weather information through a weather services company during ocean voyages. The forecast is typically updated every 12 hours. The crew of the ship also use visually observed wave height and period in making operational decisions, such as slowing down or changing course. It is not practical, however, to observe the weather conditions in the dark or in severe weather conditions.

Wave measurement using marine X-band radar has been introduced to overcome this drawback and has been installed on some offshore structures. The radar images by near range setting have suitable wave information of direction, period, and height [9]. The wave parameters can be estimated by applying Fourier analysis with a unique filtering procedure to accommodate radar dynamics and to reduce certain undesirable signals such as those from ships. The feasibility study for the shipboard application has also been carried out by considering the speed effects of the ship. However, the validation was difficult due to the lack of true information on waves.

Recently, Park et al [9] have completed the development of the system, using marine X-band radar, named WaveFinder, and have performed several sea trial tests comparing this data with buoy data. Their results illustrate the system’s validity. Hence, the system has been included in this full-scale measurement such that the measured hull stresses may be correlated with respect to the related wave and wind conditions.
2.3 VOYAGE OPTIMIZATION SYSTEM, SORAS

It is necessary to have the navigation route, related operational conditions, and the weather service information to understand the recorded data better and to further correlate the measured data or results against analytical results. SORAS (Samsung Optimum Navigation System) [10] has been developed to support the crew in finding the optimum navigation route by considering weather condition and related seakeeping parameters such as ship’s motion and bending moments. The system can also manage the navigation route information by connecting to the Voyage Data Recorder. Hence, SORAS is added in order to have navigation data and ship motion data available for the project.

3. DERIVATION OF HULL GIRDER LOADS FROM STRAIN MEASUREMENT

A ship in a seaway is subject to irregular wave excitation that would produce the vertical, horizontal and torsional moments on the hull girder. The strains measured from the full-scale measurement are the combined effects of these external moments. Therefore, it is necessary to develop a formulation such that allows the measured strains to be directly related to the bending and torsional moments. Choi and Kang have proposed a procedure [8]. The decomposition method can derive the independent strain components due to the individual moments from the combined measured strains. Figures 7 through 11 are sketches which define the arrangement of strain gauges and the derived strain components due to different external moments [12].

\[
\epsilon_m = \hat{A} \hat{E}
\]

where,

\[
\hat{E} = [\epsilon_1 \quad \epsilon_2 \quad \epsilon_3 \quad \epsilon_4]^T
\]

\[
\hat{A} = \begin{bmatrix}
-1 & 1 & 1 & 1 \\
1 & 1 & -1 & 1 \\
0 & 0 & -1 & 1 \\
0 & 0 & -1 & 1 \\
\end{bmatrix}
\]

\[
\epsilon = [\epsilon_f \quad \epsilon_z \quad \epsilon_w \quad \epsilon_T]^T
\]
Here, the measured strain components are $\varepsilon_1, \varepsilon_2, \varepsilon_3, \varepsilon_4$ counter-clock-wise and the symbol $\bar{E}$ stands for the strain vector consisting of strain components of horizontal, vertical, warping, and pure torsion at the 1st sensor, and $U$ stands for the warping function that can be obtained by the finite element modelling: Fujitani (1990) [11] for complex geometry, Kim et al. [12] for simple geometry.

The decomposed strain component vector, therefore, is defined as the following, with respect to the strain at the 1st sensor.

- Strain due to horizontal moment: $\varepsilon_{1y} = -\varepsilon_y$
- Strain due to vertical moment: $\varepsilon_{1z} = \varepsilon_z$
- Warping strain due to torsional moment: $\varepsilon_{1w} = \varepsilon_w$
- St. Venant strain due to torsional moment: $\varepsilon_{1T} = \varepsilon_T$

Similar results can be obtained at an adjacent plane with subscript $a$ and the distance $d$ of in-between sections, and then the subtraction of the two equations can be expressed as

$$\Delta\bar{E}_m = \Delta\bar{E}$$

Here,

$$\Delta\bar{E}_m = \begin{bmatrix} \varepsilon_{1a} - \varepsilon_1 & \varepsilon_{2a} - \varepsilon_2 & \varepsilon_{3a} - \varepsilon_3 & \varepsilon_{4a} - \varepsilon_4 \end{bmatrix}^T$$

The transformation matrix $A$ will be the same because the two planes will be located at the plane having the same cross-sectional properties. Finally, the torsional component due to warping can easily be obtained by the following:

$$T_w = -\frac{1}{2} U_1 \frac{d^2 w}{dx^2} = -\frac{1}{2} \frac{\varepsilon_{av} - \varepsilon_w}{U_1 d}$$

Here, $\Gamma$ is the torsional constant and multiplication of Young’s modulus and the second moment of cross section at shear center. $w$ is the slope of twisting angle.

The warping strain $\varepsilon_{av}$ at an adjacent cross section is required to obtain the torsional moment.

4. Onboard System Testing

4.1 Maiden Voyage

The test ship MV OOCL Europe was commissioned to the trading route between the Far East and Europe, which would take about 60 days for the round trip. It was determined that the installed hull stress monitoring system and the onboard wave measurement system should be tested during the maiden voyage. The onboard system was tested during the voyage from Busan to Port Suez, as shown in Figure 12.

4.2 Hull Stress Monitoring System

Figure 13 is the selected records of the hull stress monitoring system taken during the voyage from Busan to Port Suez. Each data point in this figure represents a processed statistic, such as mean, maximum, etc., over a five-minute period. Figure 13(a) shows the vessel speed during the voyage annotated with the names of the ports at which the ship had called.

Figure 12 The route of the onboard testing of the measurement system

Figure 13(b) shows the ship’s heading with key leeway points annotated. The annotated route segments are also shown in Figure 12. The ship maintained 20 to 25 knots in the open ocean segment while reduced to lower speed in short coastal segments. Figure 13(c) shows the mean wind speed measured by the onboard anemometer. The wind direction relative to the ship and ship’s heading are also recorded. The true wind speed and direction may be determined for comparison to the weather forecast or hindcast data.

Figure 13(d) shows the average still water bending moment measured in the midship region (Fr. 183, Fr. 203) and at the forward location (Fr. 320). It is noteworthy that the mean bending moments show very little change over the long open ocean segments compared to those during the short segments. It was observed that the transfer of ballast water or fuel oil was the main reason for the changes. This ship is equipped with an automatic heel control system that maintains the ship in an upright position during the loading and unloading operation in the terminal. The system automatically transfers ballast water between port and starboard ballast tanks located in the midship region. The ship typically intakes ballast water for heel control before entering a port and discharges in open waters. The fuel oil is also transferred before entering port for bunkering. There exist many other causes that may change the mean bending moment, such as trim, speed, temperature, etc.
Figure 13(e) shows the measured wave bending moment and the standard deviation of vertical acceleration measured at bow. The vertical scales are determined to produce the two records aligned on top of each other as much as possible. This can be considered as simple ways of checking correlation. It is observed that the wave bending moment and the bow acceleration indicate consistent correlation except for the period between 8/24/06 20:00 and 8/26/06 12:00, which is annotated as the segment between leeway points A and B in Figure 12.

Figure 13(f) is the mean, maximum and minimum of the hull girder stress measured by LBSG located at Fr. 183 on the starboard side of the upper deck. The mean stress time history follows very closely with those of the mean bending moment.
Figure 14 Correlation of bow acceleration and wave bending moment

Figure 14 is a plot showing the correlation between wave bending moment and bow acceleration. The data points marked as circles are those from 8/24/06 20:00 to 8/26/06 12:00, and the data points marked as dark dots are from the rest of the test voyage. The figure suggests that the wave bending moment displays two different response characteristics for given acceleration. It is noted from Figures 11 and 12(b) that the ship entered the open waters of the Indian Ocean at about 8/24/06 20:00 and continued on a steady course until the ship changed heading near the southern tip of India at about 8/26/06 12:00. This indicates that the relative wave heading changed at the leeway point B near the southern tip of the Indian subcontinent, and shows the different wave bending responses.

Figure 15 shows typical time histories of the LBSG signals. The upper panel shows the strain from the LBSG on the deck and the lower panel shows those from the lower sensor near the inner bottom. The time histories of the strain show that the strains from these two sensors are out of phase, i.e., they are in opposite directions. The time histories of the LBSG signals can be used to validate the phase relationship between the hull girder loads, such as bending moments and torsional moment.

4.3 ONBOARD WAVE MONITORING SYSTEM

The WaveFinder system was tested during the open ocean voyage from Port Kelang to Jeddah. The measured significant wave height from WaveFinder was compared with the forecasted wave patterns from the weather service data in Figure 16. The measured significant wave height is plotted using a square symbol. The measurement results of WaveFinder are the average value of one-hour measurement. The discontinuity of the measurement is due to the rain or too low level of radar echo signal. Since the wave forecast provides the anticipated wave conditions for the following five days, the forecasted wave heights are overlapped in the plot. Hence, one can use the WaveFinder as a real-time onboard wave measurement system.

Figure 16 Wave heights during the voyage from Port Kelang (Malaysia) to Jeddah (Saudi Arabia)

5. CONCLUSIONS

A comprehensive full-scale measurement system has been successfully designed and installed on a large container carrier. The system consists of the hull stress monitoring system, the onboard wave monitoring system, and the voyage optimization system. The HSMS and WaveFinder systems were tested during the maiden voyage of the test ship MV OOCL Europe from Busan to Jeddah.

- The initial investigation of the recorded data indicates that the system was fully functional throughout the test period and all recorded data could be recovered in good quality.
- The recording of operational data, such as ship’s heading, position, speed, etc., was found very useful in understanding the recorded data.
- The onboard wave monitoring system can further provide important wave parameters that would assist in validating the analytical results of ship motion and sea loads.
- The recorded time histories of the sensors will also be valuable in validating the phase relationship between the ship motion and sea loads.
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7. REFERENCES


8. AUTHORS’ BIOGRAPHIES

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