Long-term Fatigue Monitoring For LNG Carrier

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Abstract
Fatigue strength of ship structures is one of the most important items involved in the maintenance of ships. It is well known that fatigue strength very much depends on actual wave conditions which the ship encounters. The difference between design and actual wave conditions is important for assessing a ship's fatigue strength after a long period of service. Against this background, a fatigue-monitoring program is being carried out on a 135,000m³ MOSS-type LNG carrier which trades between Oman and Japan. The monitoring system covers a wide range of measurement items, including stress in local hull structure and the cargo tank system. Three years of data has already been analyzed and reviewed. Measurement is being continued in order to collect data for lifetime maintenance and longevity study. This paper presents, 1) Introduction of the monitoring system and assessment scheme, 2) Comparative study of actual stress with ship’s design condition, 3) Proposal of lifetime maintenance of LNG carrier based on long-term fatigue monitoring system.
1. Introduction

Improvements to the Life Cycle Value (LCV) is one of the most important topics for LNG carriers. For new buildings, a requirement for high-grade fatigue analysis is becoming common. Application of the latest technology is also being discussed in the longevity study for existing vessels.

Mitsubishi Heavy Industries (MHI) is a pioneer in LNG carriers, holding the top market share in LNG carrier with experience of both MOSS and membrane-type LNG carrier. For the long-term-use requirement of LNG carrier, MHI boasts advanced technology and experience in applications as follows:

- High-grade fatigue analysis and improved structural details for new constructions.
- Research on long-term fatigue monitoring for in-service LNG carrier through collaboration with owners and charterers.
- "Home-doctor" service for long-term maintenance.

In this paper, we will introduce the most up-to-date technology from MHI for the long-term use of LNG carriers – mainly research of the "Fatigue Monitoring System" – a joint study which is being carried out with Osaka Gas Co., Ltd. and NYK Line.

2. MHI’s technology for increasing life-cycle values for LNG carriers

2.1. General

Since 1983, MHI has constructed twenty-three (23) MOSS spherical tank LNG carriers, and three (3) membrane-type LNG carriers. MHI introduced the so-called "second generation LNG carrier concept," characterized by a lower boil-off rate (BOR) with a forcing vaporizer system, applying it in the Australian North West Shelf project in 1989. This concept has since become the world standard because of its economical merits and operational flexibility.

MHI has continuously been developing designs of LNG carriers, including the world's first application of a re-liquefaction plant, improvement of structural reliability by updated fatigue analysis, and development of a design with larger capacity for more economical advantage. MHI has experience in both MOSS spherical tank and membrane-type, and the abovementioned basic technology can be applied to both systems.

Furthermore, MHI has superior experience in repairing LNG carriers, including vessels built by other shipyards, and it also offers services to extend the life of carriers. Since 1973, MHI has been involved with maintenance work for certain projects including in Brunei, Malaysia, Indonesia and Australia. Currently MHI is engaged in 17 membrane vessels (GT and Technigaz) in the Yokohama Dockyard & Machinery Works and 12 Moss-type vessels in the Nagasaki Shipyards & Machinery Works.
2.2 Updated fatigue analysis technology

Recently, following the demand for longer operation periods for LNG carriers, the application of fatigue analysis is becoming more extensive with updated calculation techniques and improved computer resources. In addition, global demand for LNG transportation increases new trading routes over and above the traditional ones. For example, trading routes in the Pacific Ocean have been increased as well as the traditional Far East - Middle East route. Against this background, it is becoming more common for spectral fatigue analysis to be requested to facilitate the consideration of wave data for specific sea routes.

MHI has been continuously developing the technology for fatigue analysis as well as many applications of spectral fatigue analysis for both the building of new ships and already commissioned ships. Examples for MOSS spherical-type and membrane-type are as follows:

a) MOSS spherical-type LNG carrier

A large-scale full-spectral analysis has been carried out for MHI’s standard 145,000m³ Moss-Type LNG carrier as shown on Figure 1, with the following steps.

- [Step1] Wave load analysis based on North Atlantic wave data
- [Step2] Stress analysis using whole ship model in regular waves
- [Step3] Hot spot stress evaluation using detailed model
- [Step4] Calculation of fatigue life

Figure 1 shows the Finite Element (F. E.) Model for hopper knuckle and tank cover connection being typical evaluation points for a MOSS-type LNG carrier. From the more than 5000 check points, including other primary members and longitudinal stiffener connections in the cargo hold, a fatigue life in the North Atlantic of 40 years has been confirmed.

With regard to sphere tanks, MHI has developed a dedicated program, in which fatigue assessment in accordance with IMO gas code type-B requirement can be carried out in a short time with accuracy.

b) Membrane-type LNG carrier

Due to the limitations of hull-girder bending stress in the containment system, longitudinal stiffeners in membrane-type LNG carriers have been designed with some margin of fatigue strength. Therefore, fatigue strength of the primary members is of more concern. Special attention should be especially paid to knuckle points on the inner hull, which form the boundary between insulation layer and ballast tank. It is common for some representative locations from the knuckles to be selected as fatigue check points.

Figure 2 shows an example of the F. E. Model for fatigue analysis. Wave load analysis has been carried out by a statistical approach on a specified sea route. Detailed design can accommodate various specifications (for trading route and design fatigue life), by changing local scantlings.
STEP1: Wave load analysis
Pressure distribution with wave crest at Midship

STEP2: Whole ship F.E.Analysis (Deformation non-scaled)

STEP3: Fine mesh Analysis for Hotspot stress evaluation

Figure 1 Example of fatigue analysis for MHI’s new standard MOSS-type LNG carrier

Figure 2 Example of fatigue analysis for MHI Standard GT membrane LNG carrier
3. Long-term fatigue monitoring for LNG JAMAL

3.1 Background

Stress monitoring on a vessel in service is considered one of the effective methods for increasing the vessel’s Life Cycle Value.

The need for long-term use of vessels is becoming greater, especially for LNG carriers, where building costs are relatively high. In general, fatigue design assessment is carried out under wave conditions that are severer than the actual trading route. In such cases where there is margin in design conditions with actual load, fatigue monitoring by full-scale measurement can be an effective tool in increasing the accuracy of the overall evaluation of design fatigue life.

Against this background, the Fatigue Monitoring System has been applied to LNG JAMAL, which is owned by Osaka Gas International Transport and NYK Line. Principle specifications and general arrangement of LNG JAMAL are shown on Table 1 and Figure 3.

| Table 1  Principle dimensions of LNG JAMAL |
|--------|-----------------|----------------------|
| Length | 276 m           | Date of delivery     | 2000/10/31          |
| Breadth| 46 m            | Tank system          | Moss spherical 5 tanks |
| Depth  | 25.5 m          | Class                | NK                  |

3.2 Outline of Fatigue Monitoring System

a) Outline Specifications

MHI has been continuously developing stress-monitoring systems for vessels in service through Joint Industry Studies. In The Shipbuilding Research Association of Japan No.245 (SR245), MHI carried out full-scale measurement for fatigue strength monitoring for a VLCC. Further to the above technical development, special care has been paid as follows, considering structural characteristic of LNG carriers and long-term use of the system itself.

- To maintain the good adhesive conditions of the strain gauge, it is preferred that gauges be fitted in dry spaces. Consequently, the hopper knuckle, skirt of the cargo tank and passage deck were selected as locations of strain gauges.
- In addition, acceleration at midship and bow are measured to get information on ship motion.
- Measured data is automatically analyzed and stored into Magnetic Optical (MO) disks in the form of histogram tables. In principle, no maintenance or other action is needed for accumulating the stress histograms.
- Row data (time-series of measured data) can be collected by exchanging MO disks once every four months.
- Fatigue assessment is carried out based on measured data (stress/acceleration) and the result of F.E. Analysis.

Figure 3 shows location of sensors. Table2 shows outline specification of the system.
Table 2 Outline specification of the monitoring system

a) Measured data (Channels)
   - CH-1  Vertical acceleration in bow
   - CH-2 to 5  Stress on tank skirt (port/starboard/fore/aft)
   - CH-6 to 7  Stress on hopper knuckle (port/starboard)
   - CH-8  Stress on passage deck (port)
   - CH-9  Stress on passage deck (starboard)
   - CH-10 to 12  Acceleration at midship (vertical/transverse/longitudinal)

b) CPU & O/S  Pentium II (400MHz) / Windows NT 4.0 Workstation

c) Sampling cycle  200msec

d) Stored data
   - Row data (time-series of signal)
   - Average value, maximum value, minimum value, maximum deviation (every 10 minute cycle)
   - Peak to peak value, Zero crossing cycle (every 10 minute cycle).
   - Cumulative histogram every 30 minutes

e) Storage device  Two sets of 1.3GB Magnetic Optical Disk drive
b) Strain gauges

**Figure 4** shows examples of strain gauges. Considering that the Fatigue Monitoring System should be used for the long-term, strain gauges are fitted in dry spaces to optimize the good conditions of the bonding surface. For hull girder bending stress, a long-based strain meter is fitted on the longitudinal stiffener in the passage deck. By fitting in an enclosed dry space, any thermal effect is considerably reduced compared to fitting directly to upper deck. Measured stress can be converted to stress on the upper deck by considering the distance from the neutral axis of the hull girder section modulus.

![Strain gauge on hopper knuckle](image1)

![Long-base strain meter below upper deck](image2)

**Figure 4**  Fitting of sensors during construction

c) Computer system

**Figure 5** shows the system diagram. The system is made from the following components:

- Strain gauge/Accelometor
- Barrier
- Amplifier
- UPS
- Personal Computer
- Magnetic Optical disk drive

Data analysis is carried out by purpose built software. As shown in **Figure 6**, measured data can be seen online.
Figure 5  System diagram

Figure 6  Example of monitoring view
3.3. Measured data

a) Period and trading route

Measurements have been carried out since October 2000, under a joint study by MHI, Osaka Gas Ltd. and NYK Line.

To date, data for three years has been assessed. The vessel’s main trading route for the three years has been the Oman-Japan route as shown in Figure 7. The system is still operating without any damage to sensors thanks to the well considered selection of sensor locations.

Figure 7 Trading route during measurement

b) Row data

The signals formed by sensors are recorded in the form of a time series plot, which we have called "row data" in this paper. An example is shown in Figure 8. The "row data" is then automatically analyzed by the onboard computer and data, like that listed in d) on Table 2, is obtained.

Figure 9 shows a comparison between the maximum value on one day and the reported sea conditions of the same day. Trends of measured stress and sea state are clearly consistent.

Figure 8 Example of time series plot ("Row data") of stress on upper deck

Figure 9 Relationship between observed sea state and measured data
c) Long-term distribution of stress range

Estimations of fatigue life are based on the "long-term distribution" of stress, which is a function of the value of the stress range and the probability of occurrence. The transformation from "row data" to "long-term distribution of stress range" is carried out as shown on the schematic figure, Figure 10. The time series of stress signals are decomposed into each cyclic stress and then, the relation between stress range and number of cycles can be obtained. In this paper, this information is called the "histogram table". This is carried out using the "Rain flow method", which is a well known algorithm for this purpose.

\[ \Delta \sigma : \text{Stress range} \]
\[ Q : \text{Cumulative exceedance probability, } Q = 1/N \]
\[ N : \text{Number of cycles of stress range over } \Delta \sigma \]

In Figure 11, the dotted line shows the measurement results. For comparison, calculations by ship motion analysis and F. E. Analysis (shown in Figure 12) have been carried out and the results are shown on the solid lines. Wave data for the North Atlantic area and the Japan-Persian Gulf sea route are applied based on "Global Wave Statistics" by British Maritime Technology.

From Figure 11, the following can be concluded.

- Actual measured stress is clearly consistent with the results of the calculations based on the wave data of the Japan-Persian Gulf sea route.
- The working stress of the vessel in service was about 70% of the estimated value using North Atlantic wave data.
Figure 11  Long-term distribution of stress range (measured and calculated)

Figure 12  F. E. Model for fatigue assessment
3.4 Fatigue assessment based on results of measurement

Usually, fatigue assessment is carried out at the design stage using F. E. Analysis. One of the most effective ways to use the measured data is to adjust the estimated fatigue life calculated at the design stage by considering the actual load the vessel has encountered. Provided that there is agreement between measured stress and calculated stress by FEM with the re-assessed wave load, such re-assessment can also be applied to other fatigue checkpoints.

It is common that fatigue assessment is based on a "damage factor" which is calculated from the "S-N curve" and "Miner rule". Estimated fatigue life is inversely proportional to "fatigue damage". It is also known that fatigue damage is about proportional to the cubic of working stress. Based on this assumption, estimated fatigue damage can be corrected as follows:

\[ D_{\text{measurement}} = D_{\text{design}} \times \frac{T_{\text{measurement}}}{T_{\text{design}}} \times \left( \frac{\Delta \sigma_{\text{design}}}{\Delta \sigma_{\text{measurement}}} \right)^3 \]

- \( D_{\text{design}} \): Cumulative fatigue damage in \( T_{\text{design}} \) with design wave condition
- \( T_{\text{design}} \): Design period in fatigue assessment
- \( \Delta \sigma_{\text{design}} \): Stress range by FEM at design stage with design wave condition
- \( T_{\text{measurement}} \): Actual service period of the vessel
- \( \Delta \sigma_{\text{measurement}} \): Stress range by FEM with corrected wave load by measurement

In Figure 11, it has been confirmed that measured stress and stress by FEM with wave data for the Japan-P.G sea route agree well at the locations of the strain gauges. Therefore, FEM with the corrected load can be applied to assessment for the other fatigue checkpoints.

Table 4 shows an example of such re-assessment of fatigue damage. Point-A is the location of strain gauge. On the other hand, point B is not directly measured by strain gauge, but assessed by F. E. Analysis and a correction of applied wave load.

<table>
<thead>
<tr>
<th>Table 4</th>
<th>Example of re-assessment of fatigue damage factor</th>
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</thead>
<tbody>
<tr>
<td>Point A</td>
<td>Knuckle part of hopper</td>
</tr>
<tr>
<td>Point B</td>
<td>Knuckle part of inn. bottom</td>
</tr>
<tr>
<td>25 years in design wave condition</td>
<td></td>
</tr>
<tr>
<td>3 years in Japan-PG</td>
<td></td>
</tr>
<tr>
<td>25 years in Japan-PG</td>
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Assessment of independent cargo tank can be done in the same manner as hull structure with measured acceleration. Effect of interaction force between cargo tank and hull structure can be evaluated by strain gauge on the skirt.

It should be noted that, as well as fatigue analysis, inspection is very important for the Condition Assessment Program (CAP), since some factors that effect fatigue (for example, excessive corrosion) are not taken into account in the analysis.
3.5. Maintenance planning using Fatigue Monitoring System

The above consideration is based on the results of measurements for up to about three years from initial delivery of the vessel.

One of the main objects of this project is to continue such measurement for longer periods, say 10 years or more, in order to obtain reliable data to support the longevity study of the vessel.

As explained in the previous sections, it can be confirmed that wave condition for the fatigue analysis at design stage is conservative by long-term fatigue monitoring. Based on fatigue analysis/monitoring with wave data of actual trading route, the vessel's maintenance scheme can be optimized, for example;

1) Screening of inspected area with high importance
   To optimize the vessel's maintenance scheme, it is important to pick up inspected locations during dry docking or in service with priority. By specifying the location of detailed visual inspection or NDT, serious damage can be avoided. Fatigue analysis is normally considered sufficient for this purpose and Fatigue Monitoring System can supply supporting data to minimize inspected locations considering the actual wave condition.

2) Planning of reinforcement or repair in preparation of dry docking
   More reliable fatigue life estimation helps for preparing an optimized maintenance plan. For example, a well-organized plan can minimize scaffolding or gas free operations which can cause considerable cost, and also the risk of unexpected repair work can be reduced.

3) Feedback for other vessels
   The findings from the measurements can contribute to improving the procedures of fatigue assessment not only for the measured vessel, but also for other vessels. Especially, feedback on vessels of similar type and similar trading routes may be useful.

4) Study on effect of trading route
   Fatigue Monitoring System can estimate fatigue damage on a specific trading route. The possible effect of changing the trading route on the capacity of fatigue strength can be estimated using the system.
4. Conclusion

This paper has presented MHI’s updated technology for the long-term use of LNG Carriers and has been implemented as a joint study with Osaka Gas Ltd. and NYK Line on the Fatigue Monitoring System.

First, the latest examples of fatigue analysis by MHI were introduced, both for MOSS spherical-type LNG carriers and for GT-type membrane LNG carriers. Using the spectral approach, details of structural design can incorporate various specifications of fatigue strength (i.e. trading route and design fatigue life).

This paper highlights the joint study of the Fatigue Monitoring System by MHI, Osaka Gas Ltd. and NYK Line. Full-scale measurement of actual stress and hull acceleration has been carried out since delivery.

For an example of the application of the system, assessment of fatigue damage has been shown, based on measured data for three years. It has been concluded that the proposed Fatigue Monitoring System is an effective tool for maintenance-planning and for assessing the life-time value.