A STERN SLAMMING ANALYSIS USING THREE-DIMENSIONAL CFD SIMULATION

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ABSTRACT

A stern slamming analysis based on three-dimensional computational fluid dynamics (CFD) simulation is presented with an application to a liquified natural gas (LNG) carrier with twin skegs. This study includes: seakeeping analysis, statistical analysis for relative motions and velocities, three-dimensional slamming simulation by a CFD software, and structural assessment for plates and stiffeners.

The stern areas are divided into panels in which relative velocity/motion and pressure coefficients are to be calculated.

Seakeeping calculations are carried out in full load and ballast loading conditions at ship speeds of 0 and 5 knots. A series of equivalent 20-year return sea states in a wave scatter diagram are selected for environmental conditions. Extreme velocities are then evaluated from the loading conditions and the speeds considered with reference to the probability of slamming occurrence.

Slamming simulations are carried out in a three-dimensional domain with a CFD software to calculate pressure coefficients. Two-phase flow with water and air is to be adopted in conjunction with free surface capturing method. Viscous laminar flow is assumed in simulation.

Slamming design pressure is calculated by the pressure coefficients and the extreme velocities. Based on computed design pressure, an ultimate strength analysis is performed for the determination of required plate thickness. Also, required stiffener dimensions are determined by analytic formulas.

As mentioned above, this approach has been applied to an LNG carrier with twin skegs. In the application, two-phase flow with water and air was adopted in conjunction with the volume-of-fluid method for free surface capturing. Mixed hexahedral and tetrahedral grids were employed. The computational case was determined from simulations of global ship motion.

Maximum slamming pressure was found near the end of a skeg. Large pressure also can be observed in the stern overhang area. Generally slamming pressure decreases away from the stern.

NOMENCLATURE

\( p \) = slamming pressure
\( \rho \) = density of water (1025 kg/m\(^3\) in the present study)
\( k \) = local pressure coefficient from the calculation
\( V_{R} \) = relative vertical velocity between water and hull
\( V_{R_{ext}} \) = extreme relative vertical velocity
\( \rho_{s} \) = extreme slamming pressure
\( v_{0} \) = threshold slamming velocity (\( v_{0} = 0.29\sqrt{L} \))
\[ \text{Ref. 9} \]
\( L \) = ship length [Ref. 9]
\( \eta_{k} \) = relative motion between water and hull
\( d \) = vertical distance from the still water surface to the location, if the location is above the water surface, then it becomes zero.
\( \sigma_{v} \) = standard deviation of relative velocity
\( \sigma_{r} \) = standard deviation of relative motion
\( t \) = total duration time (3 hours in the present study)

\[ T_{z} = \frac{2\pi m_{a}}{m_{2}} \left( \frac{2 \sqrt{1 - e^{2}}}{1 + \sqrt{1 - e^{2}}} \right) \], mean period of \( V_{R} \)
\[ m_0, m_2 = \text{zeroth and second moments of} \ V_R \ \text{spectrum} \]
\[ \varepsilon = \text{broadness parameter defined as} \]
\[ \varepsilon = \sqrt{1 - \frac{m_2^2}{m_0 m_4}} \]

**INTRODUCTION**

Slamming is a significant issue as it can cause local damages to a vessel during its operation in heavy waves. Especially, due to its flatter bottom, a vessel with twin skegs is exposed to larger slamming pressure compared to that with single skeg. For this reason, twin skeg vessels therefore need additional attention in stern slamming analysis in spite of numerous advantages with twin skegs, such as improved fuel efficiency, maneuverability, etc.

Researchers [Ref. 1, 2] have utilized potential-based computer tools to estimate slamming pressure in two-dimensional sections. However, it is difficult or not applicable to handle complex geometries such as twin skegs using such potential codes. Therefore, in order to evaluate the slamming pressure in complex geometries including twin skegs of stern structure, a computational fluid dynamic (CFD) calculation is necessary. Recently, several studies [Ref. 3, 4] have been reported which employed CFD tools in the determination of design slamming loads in two dimensional calculations.

In the present study, an approach for stern slamming analysis has been presented with an application to an LNG carrier with twin skegs. The approach includes a design pressure calculation using a CFD software in the three-dimensional domain, and structural assessment based on the design pressure for a given design. In the application, the commercial CFD tool, FLUENT®, has been employed for the determination of slamming design loads. The approach includes the following:

- Seakeeping analysis
- Statistical analysis for relative motions and velocities
- Slamming analysis with FLUENT
- Strength evaluation for plates and stiffeners in stern area

Ship speeds are assumed to be 0 knot and 5 knots for the worst stern slamming. The seakeeping analysis is performed at these speeds with the selected full load and ballast conditions by a three-dimensional panel code, PRECAL v.6.3 [Ref. 5]. The code generates ship motion response amplitude operators (RAOs), which are used to calculate extreme values for relative motion and velocity.

In the next section, a description of analysis procedure will be presented, which is followed by an application of the approach to a twin-skeg LNG carrier. Conclusions are given in the last section.

**ANALYSIS PROCEDURE**

The slamming pressure calculation follows the methodology by Ochi and Motter [Ref. 6]. A brief description is presented below.

Slamming pressure is assumed to be proportional to the square of relative vertical velocity and is defined as follows:

\[ p = \frac{1}{2} \rho k V_R^2 \]  

(1)

The local pressure coefficient, \( k \), is assumed to be only geometry dependent, and can be estimated using either an analytical or computational method. In principle, the pressure coefficient is a function of ship speed, but it is known to be independent of ship speed up to the Froude number of 0.2 [Ref. 6]. Since Froude number for 5 knots is usually less than 0.1 for most of the large vessels, this assumption appears to be valid. With this assumption, the pressure coefficient can be obtained separately with a predefined magnitude of impact velocity.

Slamming occurs when certain conditions are met, i.e., the location should be out of water and the relative velocity is to be above a certain threshold. The out-of-water condition is related to relative motion and the threshold velocity is related to relative velocity of the point of interest. If it is assumed that these two incidents are independent of each other, then the probability of slamming is a joint-probability as follows:

\[ \text{Prob(impact pressure} > p) = \text{Prob}(V_R > v_0) * \text{Prob}(\eta_R > d) \]

(2)

The two terms in the right-hand side can be written as follows:

\[ \text{Prob}(V_R > v_0) = \exp \left[ - \left( \frac{v_0^2}{2 \sigma_v^2} \right) \right] \]

(3)

\[ \text{Prob}(\eta_R > d) = \exp \left[ - \left( \frac{d^2}{2 \sigma_d^2} \right) \right] \]

(4)

Considering the most probable extreme pressure in short-term approach, the left-hand side of Eq (2) can be written as follows;

\[ \text{Prob(} \text{most probable slamming pressure}) = \frac{T_2}{I} \]

(5)

Using Eqs (3) – (5), Eq (2) becomes

\[ \frac{T_2}{I} = \exp \left[ - \left( \frac{V_{R\text{exp}}^2}{2 \sigma_v^2} + \frac{d^2}{2 \sigma_d^2} \right) \right] \]

(6)

where extreme relative velocity \( V_{R\text{exp}} \) is applied. When solving for the extreme relative velocity, we obtain

\[ V_{R\text{exp}} = \sqrt{2 \sigma_v^2 \left( \ln \frac{I}{T_2} - \frac{d^2}{2 \sigma_d^2} \right)} \]

(7)

Using the relation between pressure and velocity in Eq (1), extreme pressure, \( p_* \), can be written as
This extreme pressure is to be used as design pressure for the structural assessment using an ultimate strength approach [Ref. 7]. Summarized in Figure 1 is the slamming analysis procedure based on the proposed study. In the following, the individual analysis procedure is briefly explained.

**Slamming Analysis Procedure**

![Figure 1: Analysis procedure of stern slamming using CFD tool](image)

2.1 Location for Analysis

Only stern area is considered in the analysis model, which usually ranges from aft end to 0.2 of the length between perpendiculars.

The selected stern area is divided into multiple panels for analysis. Pressures are to be computed on these panels. Figure 2 shows a typical configuration of panels with their identification numbers. The identification has two numbers: first one is the frame number and the second number is a serial number starting from the centerline. Panel dimensions are typically 3 m x 3 m in ship scale. This size is the basis for structural assessment, which gives consideration to all structural members such as shell plating, shell stiffeners and floors.

As shown in Figure 2, up to the end of skeg, most of bottom hull part is included in the analysis, while further away from the aft end, only center parts between the skegs are considered. This configuration is because overhang area is known to be more prone to high slamming pressure.

2.2 Seakeeping Analysis

The main output in seakeeping analysis is the motion responses, or RAOs of relative velocity and relative motion in the stern area. These RAOs are used in the calculation of extreme values.

![Figure 2: Typical paneling in the stern area](image)

Three-dimensional linear seakeeping code, PRECAL version 6.3 [Ref. 5] is used for seakeeping analysis. Hydrodynamic meshes are generated on the ship surface and linearized boundary conditions are applied on the free surface. Figure 3 shows a typical hydrodynamic mesh in PRECAL.

The RAOs of relative motions and velocities are calculated at the center of the panels determined in the previous step.

2.3 Statistical Analysis

In this section, a method for statistical analysis for relative motion and velocity will be presented.

2.3.1 Environmental Conditions

Unless otherwise specified, a vessel is assumed to be designed under unrestricted service conditions, which corresponds to 20 years of service life in the North Atlantic. The wave scatter diagram from IACS Recommendation 34 is employed for the unrestricted service condition. In order to consider 20-year service life, a series of 20-year return sea states are selected from the scatter diagram. The selection of sea states is based on occurrence of the sea states.

Table 1 shows 20-year return sea states from the IACS wave scatter diagram. The same data is presented graphically in Figure 4. Among these 20-year return sea states, only those 16 sea states with wave heights higher than 12.0 m significant are considered in the analysis (shaded cells in Table 1, or hollow squares in Figure 4).
2.3.2 Extreme Value Calculation
A short term spectral analysis is performed for the selected sea states using ABS SPECTRO software. The final relative velocities for pressure calculation are taken from the maximum relative velocities out of four cases considered; full loading condition at zero speed and 5 knots, ballast loading condition at zero and 5 knots.

Table 1: 20 year return sea states from IACS Rec 34 wave diagram

<table>
<thead>
<tr>
<th>Tz (sec)</th>
<th>Hs (m)</th>
<th>Tz (sec)</th>
<th>Hs (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.0</td>
<td>1.65</td>
<td>10.5</td>
<td>14.64</td>
</tr>
<tr>
<td>4.5</td>
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<td>11.0</td>
<td>14.90</td>
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</tr>
<tr>
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<td>15.11</td>
</tr>
<tr>
<td>6.5</td>
<td>8.24</td>
<td>13.0</td>
<td>15.00</td>
</tr>
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<td>7.0</td>
<td>9.49</td>
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<tr>
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<td>10.62</td>
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</tr>
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<td>12.47</td>
<td>15.0</td>
<td>13.56</td>
</tr>
<tr>
<td>9.0</td>
<td>13.19</td>
<td>15.5</td>
<td>12.89</td>
</tr>
<tr>
<td>9.5</td>
<td>13.79</td>
<td>16.0</td>
<td>12.04</td>
</tr>
<tr>
<td>10.0</td>
<td>14.27</td>
<td>16.5</td>
<td>10.88</td>
</tr>
</tbody>
</table>

Figure 4: 20 year return sea states from IACS Rec 34 wave diagram

These statistical results are utilized to obtain the final slamming pressure along with pressure coefficients, which is explained in the next section.

2.4 Slamming Simulation
The objective of slamming simulation is to calculate the pressure coefficients for those areas of interest. Three-dimensional slamming simulations are performed using CFD software FLUENT.

Because of symmetry, only half of the ship hull is modeled for the simulations. The typical computational domain is shown in Figure 5 with the boundary conditions specified.

The domain size is to be determined such that the boundary effect is minimal. The length and width of the domain may be about three times of the body length and width, respectively. The depth of the domain should be larger than three times of the body depth.

The front face of the domain is assigned as a symmetry boundary condition, while the back face and the side face of the domain are assigned as wall boundary conditions. Since the simulation time will be relatively short, the wall effect due to wave reflection, if any, will be insignificant. In fact, it was observed that there were no reflections from the walls during simulations.

Simulation time is normally short, yet long enough to compute impact pressure over the hull. Typically it is only several seconds or so, depending on the drop speed. Although it is believed that pressure coefficients are somewhat independent of the drop speed, it is recommended to have 5 m/s and higher drop speed. The inlet boundary condition is set to the selected drop speed and also the entire domain is initialized as the same speed. Initial draft is determined based on expected emergence of ship hull from global ship motion analysis.

In the simulation, the pre-selected panels are monitored for slamming pressure. The pressure is to be averaged over each panel. The design pressure for each panel is determined by taking the maximum pressure during the total simulation period.
2.5 Structural Assessment

An ultimate strength approach [Ref. 7] is employed to estimate plate thickness to the corresponding design slamming pressure. In short, the required plate thickness is implicitly calculated by equating a load parameter for the given pressure load to a load parameter for a specific plate thickness. The calculated plate thicknesses are then compared to offered plate thicknesses.

Stiffener section modulus will be calculated and compared to the required section modulus by a set of formulas [Ref. 8] under given slamming pressures. Based on the results, strengthening of plates and stiffeners are recommended if necessary.

EXAMPLE CALCULATION

In this study the procedure has been applied to an LNG carrier with twin skegs.

The body and near body areas were meshed in tetrahedral grids (unstructured grid) due to its geometrical complexity. The other volumes were meshed in cube grids (structured grid), which is a better fit for the free surface. The grid has about 140,000 cells and about 100,000 nodes.

Grid generation was started from the offset of the subject vessel. A surface grid was generated using a finite element software. The surface points were then imported to a grid generator where the surface mesh was constructed as shown in Figure 6.

A two-phase flow model has been employed for water and air and the volume of fluid method has been selected for the free surface capturing. Table 2 shows the options selected for the simulation. The bottom domain was set to have inlet velocity of 6 m/s as a velocity inlet boundary condition. Also the entire domain was initialized as the same velocity. As an initial condition, the free surface is located 0.5m above the baseline.

The initial time step was 0.01sec then varied by FLUENT during the simulation. The total calculation time for 3 sec simulation is about 30 hours in a dual 3.0GHz CPU computer.

For the evaluation of plate thicknesses, an in-house code has been developed. The calculated plate thicknesses were compared to offered plate thicknesses for possible recommendation.

The stiffener library in SafeHull V12.0 has been utilized to calculate section modulus of the stiffeners with offered scantlings. This offered section modulus was then compared with those required by a set of formulas from [Ref. 8] under the given slamming pressures.

Table 2: Options selected in CFD calculation

<table>
<thead>
<tr>
<th>Item</th>
<th>Options</th>
</tr>
</thead>
<tbody>
<tr>
<td>free surface capturing</td>
<td>Volume of Fluid</td>
</tr>
<tr>
<td>water</td>
<td>Incompressible</td>
</tr>
<tr>
<td>Air</td>
<td>Compressible</td>
</tr>
<tr>
<td>pressure-velocity decoupling</td>
<td>Coupled</td>
</tr>
<tr>
<td>viscous model</td>
<td>Laminar</td>
</tr>
</tbody>
</table>

RESULTS AND DISCUSSION

Design slamming pressures have been calculated based on the computed pressure coefficients and the relative velocities as explained in the previous section. Figure 7 shows the contour plot of the design slamming pressures normalized by the maximum dynamic wave pressure from ABS LNG Guide [Ref. 9]. Each pressure represents the maximum pressure during the total simulation period of 3.0 seconds.

As shown, large pressure values are observed near the skeg at Frames 9 and 13. It is believed that disturbed flow by abrupt geometrical change near the skeg contributes to this large pressure. Another area of large pressure is observed in the overhang area near the centerline. In general, slamming pressure decreases as away from the stern and away from the centerline.

The correlation between pressure coefficient and extreme relative velocity is shown in Figure 8 for the panels shown in Figure 7. Extreme velocity is normalized by a threshold velocity for slamming from [Ref. 9]. It is observed that the variation of extreme velocity is considerably less than that of pressure coefficient. This observation indicates that the variation of slamming pressure in location is attributed more to that of pressure coefficient than that of extreme velocity.

Based on the design slamming pressure, required plate thicknesses and stiffener dimensions were calculated following the methods in the previous section. As expected from the design pressure, thick plates are expected near the center line area, and also in the area near the outside of skeg.
to compute pressure coefficients. Slamming design pressures on the selected panels are calculated by the pressure coefficients and extreme relative velocities.

Based on the design pressure, structural assessment of shell plates and stiffeners are performed for recommendations.

In the application of the approach to an LNG carrier with twin skegs, a two-phase flow with water and air was adopted in conjunction with the volume-of-fluid method for free surface capturing. Viscous laminar flow was assumed in the simulation. Mixed hexahedral and tetrahedral grids were employed. The computational case was determined from simulations of global ship motion.

Calculations were made with the pressure coefficients and extreme relative velocities to achieve the slamming design pressure. Maximum slamming pressure was found near the end of a skeg. Large pressure also can be observed in the stern overhang area. Generally slamming pressure decreases away from the stern.

**DISCLAIMER**

The views expressed in this paper are of the authors and do not necessarily represent those of the American Bureau of Shipping.

**REFERENCES**


