Global strength assessment in oblique waves of a large gas carrier ship, based on a non-linear iterative method

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Abstract. At the ship's design, the first step of the hull structural assessment is based on the longitudinal strength analysis, with head wave equivalent loads by the ships' classification societies' rules. This paper presents an enhancement of the longitudinal strength analysis, considering the general case of the oblique quasi-static equivalent waves, based on the own non-linear iterative procedure and in-house program. The numerical approach is developed for the mono-hull ships, without restrictions on 3D-hull offset lines non-linearities, and involves three interlinked iterative cycles on floating, pitch and roll trim equilibrium conditions. Besides the ship-wave equilibrium parameters, the ship's girder wave induced loads are obtained. As numerical study case we have considered a large LPG liquefied petroleum gas carrier. The numerical results of the large LPG are compared with the statistical design values from several ships' classification societies' rules. This study makes possible to obtain the oblique wave conditions that are inducing the maximum loads into the large LPG ship's girder. The numerical results of this study are pointing out that the non-linear iterative approach is necessary for the computation of the extreme loads induced by the oblique waves, ensuring better accuracy of the large LPG ship's longitudinal strength assessment.

Keywords: longitudinal strength, non-linear iterative method, oblique waves, gas carrier ship.

1. Introduction

The modern ship design process requires increasing the accuracy of the computational methods starting from the initial design concept [1].

As the first step for the ship's structural assessment, the longitudinal strength analysis is carried out with design statistical still water and head wave loads according to the hull ships' classification societies' rules [2,3,4,5]. The rules design wave loads are statistically based and do not take into account the exact mass distributions and geometric non-linearities of the ship's hull shape, having as reference only the main dimensions characteristics of a ship.

This study presents an enhanced method for the ship's longitudinal strength assessment in general case of the oblique quasi-static equivalent waves [1,6,7] using an own non-linear iterative procedure and in-house program code. The ship's mass distribution and hull offset lines are the input data of the numerical approach, from which result the ship-wave system equilibrium parameters, floating, roll and pitch trim, and the induced wave loads into the ship's girder.

As study case we consider a large LPG liquefied petroleum gas carrier ship [8]. The ship has a slender hull with length over the breadth ration 6.25, with extended prismatic shape over the cargo holds domain, a V shape and bulb profile at fore peak and a U shape at aft peak which are contributing significantly to the geometric non-linearities of the ship's offset.

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The still water and wave induced loads into the LPG ship’s girder, computed by the numerical iterative approach, are compared to the statistical values by classification societies’ rules [2,3,4,5], pointing out closer values to the vertical wave design loads and more scattered values to the horizontal and torsion wave design loads.

Besides the correlation between the maximum wave induced loads into the LPG ship's girder and the ship - oblique wave relative position, this study is pointing out the necessity of the direct numerical approach based on non-linear iterative procedure for better accuracy of the ship’s longitudinal strength assessment.

2. Theoretical basis of the ship’s longitudinal strength analysis by non-linear iterative method

Due to the geometric non-linearities of a ship hull, with V, U and bulbous shapes at fore and aft peak parts, in order to assess the ship's longitudinal strength in oblique equivalent quasi-static waves, a non-linear iterative method is required.

In figure 1 the main flowchart of the own developed method for the ship's longitudinal strength analysis is presented. The algorithm is numerically implemented in the own program code P_QSW.

Figure 1. The flowchart of the longitudinal strength analysis on oblique equivalent quasi-static waves.
As input for the computational approach the following data are required:
- the ship’s characteristics: the hull CAD offset lines (figure 2) and the loading case parameters, \( \Delta \) the ships’ displacement, \( x_G, y_G \) the ship’s gravity centre longitudinal and transversal position;
- the oblique equivalent quasi-static wave characteristics: \( h_w, \lambda \) the wave height and length, \( \mu \) the ship-wave heading angle.

According to [6,7,9], the maximum wave loads are obtained in the case when the relative wave length \( \lambda_1 \) is equal to the ship's length \( L \) (figure 2).

\[
\lambda_1 = L; \quad \lambda = L \cos \mu
\]  

In the first part of the numerical method (figure 1), the ship-wave equilibrium parameters, floating draught \( d_m \), pitch angle \( \theta \) and roll angle \( \phi \), are obtained by iterative procedures, defining the position of the oblique equivalent quasi-static wave's median plane into the ship's base plane reference.

The iterative algorithm (figure 1) has the following cycles’ parameters:
- floating condition [9,10,11]

\[
\left. d_m \right|_{\text{initial}} = 0; \quad \delta d_m = 0.001 \text{ m}; \quad d_m^{\text{iter-1}} + \delta d_m; \quad V = \Delta / \rho; \quad \theta = 0; \quad \phi_{\text{current}}
\]  

convergence criterion \( |V - V_c| \leq 0.001V \)

where: \( \rho \) is the water density, \( V_c \) is the ship's buoyancy volume from the iterative procedure.
- pitch condition [9,10,11]

\[
\left. \theta \right|_{\text{initial}} = 0; \quad \delta \theta = 10^{-5} \text{ rad}; \quad \theta_{\text{iter-1}} + \delta \theta; \quad d_m|_{\text{initial}} = d_m|_{\text{floating}}; \quad d_m^{\text{iter}} = d_m^{\text{iter-1}} + \left( V - V_c^{\text{iter-1}} \right) / A_{WL}^{\text{iter-1}}
\]  

\[
\phi_{\text{current}}; \quad \text{convergence criteria} \quad |x_G - x_B| \leq 0.001 L \quad \text{and} \quad |V - V_c| \leq 0.001V
\]

where: \( x_B \) is the ship’s buoyancy centre longitudinal position from the iterative procedure, \( A_{WL} \) is the wave median plane area. The \( d_m \) parameter is also updated at each iteration, so that the floating convergence criterion is satisfied.
- roll condition [9,10,11]

\[ \delta \varphi = 10^{-5} \text{rad}; \quad \varphi_{iter} = \varphi_{iter-1} + \delta \varphi; \quad \text{cycles on } d_m, \theta \]

\[ |y_G - y_B| \leq 0.001 B; \quad |x_G - x_B| \leq 0.001 L; \quad |V - V_i| \leq 0.001 V \]

where: \( y_B \) is the ship's buoyancy centre transversal position from the iterative procedure, \( B \) is the ship's breadth. The roll cycle has to include the previous two cycling steps (2), (3), in order to ensure also the floating and pitch conditions convergence criteria.

At the end of the cycling process on the \( d_m, \theta, \varphi \) parameters results the oblique equivalent quasi-static wave free surface with the following expression:

\[ z_w(x,y) = d_m + (x-x_F)\theta + (y-y_F)mg(\varphi) \pm \frac{h_s}{2} \cos \left[ \frac{2\pi}{\lambda} (x \cos \mu + y \sin \mu) \right]; \quad x \in [0,L]; \quad y \in [-\frac{B}{2}, \frac{B}{2}] \]

where: \( x_F, y_F \) are wave median plane centre longitudinal and transversal position resulting from the iterative procedures, ",+" sign is for wave sagging condition, "-" sign is for wave hogging condition.

In the second part of the numerical method (figure 1), for a given loading case \((\Delta, x_G, y_G)\) and wave condition \((h_s, \mu, \lambda)\), sagging or hogging, based on the ship-wave equilibrium parameters \( d_m, \theta, \varphi \) and \( x_F, y_F \), the wave induced loads \( F, T \), vertical bending moments and shear forces, \( M, \mu \) horizontal bending moments and shear forces, \( M_t \) torsion moment are computed. These results are used for the ship's longitudinal strength assessment, based on the design wave's loads criteria required by the ship's classification societies rules [2,3,4,5].

The ship-wave equilibrium parameters can be used for the computation of the oblique equivalent quasi-static pressure acting over the external ship's hull shell and used for a 3D-FEM numerical detailed strength analysis [9], based on the yielding stress and buckling criteria [2,3,4,5].

### 3. The large LPG numerical model for longitudinal strength analysis

Table 1 presents the main characteristics of the large LPG gas carrier made of high grade steel: \( L, B, H \) are the ship's length, breadth, height; \( T, A, V, x_G, y_G, z_G \) are the ship's draught, displacement, buoyancy volume and gravity centre position for the full loading case; \( u_s \) is the ship's speed; \( \rho \) is the sea water density; \( g \) is the gravity acceleration; \( z_s \) is the average torsion centre position of the closed amidships structural sections; \( N_e \) is the number of the offset lines stations for the numerical model; \( \delta \kappa \) is the dimension of the model segments; \( m_s \) is the ship's mass per unit length; \( h_s, \lambda, \lambda_1, \mu \) are the wave parameters, for \( h_s = 10.27 \text{ m} \) reference rules' wave height [2,3,4,5].

Figure 3 presents the large LPG ship offset-lines stations and figure 4 presents the mass diagram, considering the numerical model with \( N_e = 40 \) stations.

#### Table 1. The main characteristics of the large LPG gas carrier ship.

| Parameter | Value |
|-----------|-------|
| \( L \)   | 238.7 m |
| \( B \)   | 38.2 m  |
| \( H \)   | 23.2 m  |
| \( T \)   | 11.440 m |
| \( A \)   | 76939 t |
| \( V \)   | 75062 m³ |
| \( u_s \) | 8.475 m/s |
| \( \rho \) | 1.025 t/m³ |
| \( g \)   | 9.81 m/s² |
| \( h_s \) | 0 ÷ 12 m (10.27 m) |
| \( \delta \kappa \) | 1 m |
| \( \lambda_1 \) | \( \lambda / \cos \mu \) |
| \( \lambda_1 \) | \( L \) |
4. The large LPG gas carrier ship-wave equilibrium parameters

Based on the method from section 2 and the own program code P_QSW, tables 2 ÷ 4 present the LPG ship-oblique wave equilibrium parameters, \(d_m, \theta, \varphi, x_F, y_F\) and \(z_{iH}\) horizontal forces centre position, \(\epsilon_R = z_{iR} - z_R\), by the non-linear iterative method (figure 1), for wave height \(h_w = 10.27\) m, sagging and hogging (\(h_s = 0\) is still water condition), relative wave length \(\lambda_r = L = 238.7\) m, heading angle \(\mu = 5, 15, 30, 45, 60, 75\) deg. Figures 5 ÷ 10 present the LPG ship and oblique equivalent quasi-static waves position for wave height \(h_n = 10.27\) m reference, sagging and hogging, \(\lambda_r = L\), \(\mu = 0, 45, 75\) deg.

Table 2. The LPG ship - oblique equivalent quasi-static wave equilibrium parameters, \(\mu = 0\), 15 deg.

| \(\mu\) deg | sagging | hogging |
|-------------|---------|---------|
| 0           |         |         |
| 5           | 0.020   | 0.000   |
| 10           | 0.002   | 0.000   |
| 15           | 0.000   | 0.000   |

Table 3. The LPG ship - oblique equivalent quasi-static wave equilibrium parameters, \(\mu = 30\), 45 deg.

| \(\mu\) deg | sagging | hogging |
|-------------|---------|---------|
| 30           |         |         |
| 45           |         |         |

Table 4. The LPG ship - oblique equivalent quasi-static wave equilibrium parameters, \(\mu = 60\), 75 deg.

| \(\mu\) deg | sagging | hogging |
|-------------|---------|---------|
| 60           |         |         |
| 75           |         |         |
5. The large LPG gas carrier longitudinal strength assessment

Based on the ship-wave equilibrium parameters for the large LPG ship (section 4), with the own numerical non-linear iterative procedure (section 2), the oblique equivalent quasi-static wave induced loads in the ship's girder are computed.

Table 5 presents the maximum still water plus equivalent quasi-static wave induced vertical and horizontal bending moments and shear forces, $M_v$, $M_h$, $T_v$, $T_h$, for the reference wave height $h_w=10.27$ m with relative wave length $\lambda/L=238.7$ m and heading angle $\mu=0-75$ deg.

Figures 11 - 14 present the vertical bending moments and shear forces diagrams, for sagging and hogging case, heading angle $\mu=0$ deg. Figures 15 - 20 present the horizontal bending moments and shear forces, torsion moment diagrams, for sagging and hogging case, heading angle $\mu=75$ deg.

Table 6 presents the rules' statistical maximum admissible loads [2,3,4,5], for the LPG on 20 years reference period, still water and wave $h_w=10.27$ m, and the maximum computed loads from Table 5.
Table 5. The maximum ship's girder still water plus wave induced loads, reference \( h_w = 10.27 \) m, \( \lambda_f = L \).

| \( \mu \) | \( \lambda_f \) | \( M_h \) | \( T_v \) | \( M_v \) | \( T_h \) | \( M_t \) |
|---|---|---|---|---|---|---|
| 0 | 1.000 | 1.24E+6 | 3.93E+4 | 1.39E+5 | 3.93E+4 | 3.93E+4 |
| 15 | 0.966 | 1.21E+6 | 3.89E+4 | 2.23E+5 | 3.74E+4 | 5.83E+5 |
| 30 | 0.866 | 1.10E+6 | 3.75E+4 | 3.74E+5 | 3.74E+4 | 5.83E+5 |
| 45 | 0.707 | 8.48E+5 | 3.39E+4 | 3.74E+5 | 3.74E+4 | 5.83E+5 |
| 60 | 0.500 | 6.33E+5 | 2.68E+4 | 5.87E+5 | 7.30E+5 | 5.83E+5 |
| 75 | 0.259 | 1.17E+6 | 2.68E+4 | 5.87E+5 | 7.30E+5 | 5.83E+5 |

\( \mu = 0 \) deg, sagging.
\( \mu = 75 \) deg, hogging.

Figure 11. \( M_h \) [kNm], LPG, \( \mu = 0 \) deg, sagging.

Figure 12. \( M_h \) [kNm], LPG, \( \mu = 0 \) deg, hogging.

Figure 13. \( T_v \) [kN], LPG, \( \mu = 0 \) deg, sagging.

Figure 14. \( T_v \) [kN], LPG, \( \mu = 0 \) deg, hogging.

Figure 15. \( M_v \) [kNm], LPG, \( \mu = 75 \) deg, sagging.

Figure 16. \( M_v \) [kNm], LPG, \( \mu = 75 \) deg, hogging.

Figure 17. \( T_h \) [kN], LPG, \( \mu = 75 \) deg, sagging.

Figure 18. \( T_h \) [kN], LPG, \( \mu = 75 \) deg, hogging.
6. Conclusions
For the large LPG ship (section 3), based on the numerical results (sections 4 and 5), using the own non-linear iterative computational method (section 2), the next conclusions result:

1. The own non-linear iterative method (figure 1) for ship-wave equilibrium computation (figures 5-10) makes possible to take into account all the non-linearities of ship's hull shape (figure 3).

2. The maximum vertical bending moments and shear forces are obtained in the case of head waves $\mu=0\,\text{deg.}$, $\lambda=\lambda_i=L$, (figures 5 and 6), on sagging and hogging conditions (table 5, figures 11+14).

3. The maximum horizontal bending moments, horizontal shear forces and torsion moments are obtained in the case of oblique waves $\mu=75\,\text{deg.}$, $\lambda=0.259\,L$, (figures 9 and 10), on sagging and hogging conditions (table 5, figures 15+20).

4. The maximum wave and still water loads obtained by the non-linear iterative approach (figure 1) are close to the rules' statistical admissible loads (table 6), which have scattered values according to the ships' classification society considered for the design reference [2,3,4,5].

5. Based on the equilibrium ship-wave parameters (section 4) and a 3D-FEM hull model [9], in further studies the hull stress can be computed and the yielding stress and buckling criteria can be assessed.

7. References
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