NUMERICAL ANALYSIS OF HYDROELASTIC EFFECT ON SHIP STRUCTURAL RESPONSE

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ABSTRACT: In the last years very large floating structures (VLFS) are continuous appearing in the waters of developed coastal cities under different layouts like floating airports, floating bridges, floating storage facilities, mobile offshore structures and even for habitation. Their size is growing up rapidly and the structure become more and more flexible and prone to wave induced vibrations. In case of relatively “soft” floating bodies the springing phenomenon can appear and it represents a steady state dynamic response produced at the resonance case associated with first few structural natural frequencies excited by wave actions. For large floating structures using the classical rigid body seakeeping analysis and modelling the hydro-structure interface by the transfer of the pressure is not sufficient and hydroelastic coupling is necessary to solve the interaction between the surface waves and the rigid-elastic body. This paper is concerned with the importance of analysing the influence of hydroelastic vibratory response on structural fatigue damage for VLFS. The hydro-structure analysis was performed using HOMER software by coupling 3D potential flow code for hydrodynamics and 3D FEM structural model of a very large floating structure. The modal superposition method is used, which means that the total structural response is represented by a series of eigenvalue structural modes pre-calculated by the 3D-FEM structural software. By defining additional boundary value problems for radiation potential associated with dry structural modes the coupling with hydrodynamics model is performed. By resolving the interaction between the surface waves and the floating elastic body the hydroelastic response is obtained. Top-down technique was used to determine the influence of the hydroelastic effect called springing on structural fatigue damage of several fatigue details. In order to clearly evaluate the influence of springing on the overall ship structural response the total structural response is decomposed into quasi-static and dynamic part.

INTRODUCTION

Nowadays, many countries with long coastlines start to create vast and valuable land from the sea. In order to protect the environment a better solution than land reclamation is to use very large floating structures. Some advantages of very large floating structures comparing to traditional land reclamation method are:

- possibility to relocate, remove or expand;
- construction is cheaper, faster and easier;
- can be installed near the shore as well as rather far into open sea;
- are environmental friendly;
- availability of interior spaces.

During the years very large floating structures have been used for a variety of purposes like floating bridges, floating energy bases, floating storage facilities, floating entertainment facilities, floating container terminals/docks, floating airports/cities, floating wind/solar plants, etc.
A typical very large floating structure has large horizontal dimensions ranging from one hundred meters to several kilometres, on the other hand the depth to length ratio is really small and the behaviour of very large floating structure is almost like an elastic plate [9]. Thus the very large floating structure response in vertical direction cannot be analysed using rigid-body approach and the hydroelastic analysis is necessary for the design of very large floating structures.

In this paper only springing phenomenon is considered. Springing is usually defined as the global ship structural vibrations induced by waves, in contrast to whipping which is a transient ship vibrational response, springing is a resonant phenomenon. Although due to the gap between the ship wet natural frequencies and the wave frequencies encountered the springing phenomenon is usually not considered for the design of conventional ships. In the case of very large floating structures, due to their large horizontal dimensions which reduce the structural natural frequencies, a linearly induced springing becomes possible. This paper is focused on the fatigue assessment of a very large floating structure taking into account the springing effect. Homer software, developed by Bureau Veritas, is used for the hydro-structure coupling. Hydrodynamic problem is solved by using radiation diffraction software Hydrostar and Nastran is used as the structural solver.

THEORETICAL BACKGROUND

Linear hydroelastic model in frequency domain

The general methodology for hydroelastic seakeeping model is rather well known and the first developments can be attributed to Bishop & Price [1]. In their work they used Timoshenko beam model for structural modelling and strip theory for seakeeping part.

Below we briefly recall the basic principles of the model used in this study [2],[3]. Radiation diffraction code Hydrostar used for seakeeping is coupled to a 3D FEM model of the ship structure.

In contrast to the well-known rigid body seakeeping model, the hydroelastic model basically extends the motion representation with the additional modes of motion/ deformation chosen as a series of the dry structural natural modes. We write:

\[
H(x, y, z, t) = \sum_{i=1}^{N} \xi_i(t) h^i(x, y, z) = \sum_{i=1}^{N} \xi_i(t) [h^i_x(x, y, z) i + h^i_y(x, y, z) j + h^i_z(x, y, z) k] \quad (1)
\]

where \( h^i(x, y, z) \) denotes the general motion/deformation mode which can be either rigid or elastic.
The above decomposition leads to the additional radiation boundary value problems (BVP) for elastic modes, with the following change in the body boundary conditions:

\[ \frac{\partial \varphi_{Rj}}{\partial n} = h^l_n \]  

(2)

After solving the different BVPs the resulting pressure is calculated using Bernoulli's equation and integrated over the wetted surface in order to obtain the corresponding forces, so that the following coupled dynamic equation can be written:

\[ \{-\omega_e^2([m] + [A]) - i\omega_e[B] + [k] + [C])\xi = \{F^{Dj}\} \]  

(3)

Where:
- \( [m] \) - modal genuine mass
- \( [k] \) - modal structural stiffness
- \( [A] \) - hydrodynamic added mass
- \( [B] \) - hydrodynamic damping
- \( [C] \) - hydrostatic stiffness
- \( \xi \) - modal amplitudes
- \( \{F^{Dj}\} \) - modal excitation

The solution of the above equation gives the motion amplitudes and phase angles \( \xi_i \) and the problem is formally solved. Note that the motion equation includes both 6 rigid body modes and a certain number of elastic modes.

The solution of the hydroelastic motion equation (3) includes the linear springing response automatically. Indeed, once this motion equation solved, all necessary quantities (motions, accelerations, stresses, etc.) can be easily calculated because the modal decomposition remains valid for any particular quantity. This means that, for example, we can write for the stress distribution \( \sum(x, y, z, \omega) \):

\[ \sum(x, y, z, \omega) = \sum_{i=1}^{N} \xi_i(\omega)\sigma^i(x, y, z) \]  

(4)

where \( \sigma^i(x, y, z) \) represents the spatial distribution of the stresses corresponding to each mode of motion/deformation and \( \xi_i(\omega) \) are the modal amplitudes.

**Separation of the quasi static and dynamic contributions**

In order to clearly evaluate the influence of springing on the overall ship structural response the total structural response is decomposed into quasi-static and dynamic part. In the present approach the decomposition of the different parts of the response is done by first schematically rewriting the motion equation (3) in the following form:

\[ \begin{pmatrix} [RR] & [RE] \\ [ER] & [EE] \end{pmatrix} + \begin{pmatrix} [0] & [0] \\ [0] & [k] \end{pmatrix} \begin{pmatrix} \xi^R \\ \xi^E \end{pmatrix} = \begin{pmatrix} F^R \\ F^E \end{pmatrix} \]  

(5)
where $R$ stands for the rigid body parts, $E$ for the elastic ones and $k$ is the structural modal stiffness matrix. At the same time we separate the total response amplitudes into the quasi static and dynamic parts:

$$\xi^R = \xi^R_0 + \xi^R_d, \quad \xi^E = \xi^E_0 + \xi^E_d \tag{6}$$

The quasi static part of the response is defined by the following equations:

$$[RR]\{\xi^R_0\} = \{E^R\} \tag{7}$$

$$[k]\{\xi^E_0\} = \{E^E\} - [ER]\{\xi^R_0\} \tag{8}$$

After inserting (6), (7) and (8) into (5), the following linear system of equations for dynamic parts is obtained:

$$\begin{bmatrix}
[RR] & [RE] \\
[ER] & [EE]
\end{bmatrix}
\begin{bmatrix}
\xi^R \\
\xi^E
\end{bmatrix}
= -
\begin{bmatrix}
[RE]\xi^E_0 \\
[EE]\xi^E_0
\end{bmatrix} \tag{9}$$

As mentioned before, the above procedure was adopted in order to be able to keep the classical direct approach for the quasi static part [4] and to clearly identify the dynamic part as a correction of the quasi static one.

**Top down analysis of structural details**

Springing hydroelastic analysis is usually performed using the relatively coarse structural mesh and some additional manipulations are necessary in order to obtain the local stresses in the critical structural details. Therefore the so called top down analysis is applied. The calculations are performed in two steps:

- calculation of the global structural response on the coarse mesh;
- application of the structural deformations of the coarse mesh on the fine mesh and calculation of the local stresses.

After having solved the rigid body seakeeping boundary value problems, the resulting pressure is applied on the FEM mesh together with the inertia loads resulting from the rigid body accelerations. Since, in the rigid body, the hydrodynamic and structural parts of the problem are independent they can be performed separately and the transfer, of the resulting deformations of the coarse mesh, onto the fines mesh is relatively straightforward. In the case of dynamic structural analysis, which is of main concern here, the additional loading cases for fine meshes need to be created. These additional loading cases correspond to each structural natural mode deformations. The resulting local stresses should be added to the quasi static ones, after being previously multiplied by the associated dynamic modal amplitudes $\xi^E_d$.

**VLFS DESCRIPTION**

A very large floating structure (VLFS) is considered for this study with the main particulars given in Table 1. The very large floating structure will be located in the south part of Singapore.

<table>
<thead>
<tr>
<th>Table 1. Main characteristics of VLFS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length between perpendiculars [m]</td>
</tr>
<tr>
<td>Breadth [m]</td>
</tr>
</tbody>
</table>
Global FE model of the considered VLFS is presented in Figure 2. Fine mesh FE models of the selected structural details are presented in Figure 3.

The next step is to generate the hydrodynamic mesh (Figure 4) and the integration mesh (Figure 5), the first one is generated on the basis of lines plan of the ship and the second one is extracted from the structural model.

**NUMERICAL RESULTS**

First we present the results of the modal analysis for the considered VLFS. For the hydroelastic computations 10 elastic modes were used, in Figure 6 are shown the first 6 elastic modes and corresponding dry natural frequencies.
Global response in waves is represented with RAOs of vertical shear force and vertical bending moment at 0.25L, 0.5L. Global response is decomposed in quasi-static response and dynamic response.

Figure 6. Mode shapes and dry natural frequencies

Mode 3, $\omega_3 = 0.859 \, Hz$

Mode 4, $\omega_4 = 1.612 \, Hz$

Mode 5, $\omega_5 = 1.649 \, Hz$

Mode 6, $\omega_6 = 1.855 \, Hz$

Figure 7. RAOs of internal loads at 0.25L and 0.5L

Vertical shear force RAO at 0.25L, $\beta = 120^\circ$

Vertical bending moment RAO at 0.25L, $\beta = 120^\circ$

Vertical shear force RAO at 0.5L, $\beta = 120^\circ$

Vertical bending moment RAO at 0.5L, $\beta = 120^\circ$
Hereafter are presented the FE stress RAOs for one structural detail. Figure 8 contains the FE stress RAO decomposed into quasi-static and dynamic response for $\beta = 120^\circ$ at one representative element and in Figure 9 are shown only total stress RAOs for selected structural detail.

![Figure 8. FE Stress RAO decomposed into quasi-static and dynamic response](image)

![Figure 9. Total FE stress RAOs for $\beta = 120^\circ$](image)

For each selected structural detail based on the material stress-cycle diagram S-N, FE stress RAOs and wave scatter diagram the spectral fatigue analysis is performed. In order to clearly evaluate the influence of hydroelastic effect on the overall fatigue damage the total fatigue damage is decomposed into quasi-static and dynamic part.
In Table 2 are presented the results of spectral fatigue analysis with a return period of 100 years. For each structural detail 10 different hot spot locations have been analysed where D1, and D2 denotes the location of the selected structural details as detail 1, at 0.25L, respectively detail 2, at 0.5L.

Table 2. Fatigue life for selected structural details

<table>
<thead>
<tr>
<th>Detail</th>
<th>Fatigue life [yr]</th>
<th>Detail</th>
<th>Fatigue life [yr]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Total</td>
<td>Quasi-static</td>
<td>Total</td>
</tr>
<tr>
<td>D1-1</td>
<td>60.75</td>
<td>71.67</td>
<td>D1-6</td>
</tr>
<tr>
<td>D1-2</td>
<td>2385.2</td>
<td>3195.4</td>
<td>D1-7</td>
</tr>
<tr>
<td>D1-3</td>
<td>83.54</td>
<td>88.06</td>
<td>D1-8</td>
</tr>
<tr>
<td>D1-4</td>
<td>112.5</td>
<td>144.2</td>
<td>D1-9</td>
</tr>
<tr>
<td>D1-5</td>
<td>1994.1</td>
<td>2361.2</td>
<td>D1-10</td>
</tr>
<tr>
<td>D2-1</td>
<td>17.63</td>
<td>24.89</td>
<td>D2-6</td>
</tr>
<tr>
<td>D2-2</td>
<td>419.1</td>
<td>520.3</td>
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<tr>
<td>D2-3</td>
<td>89.80</td>
<td>114.7</td>
<td>D2-8</td>
</tr>
<tr>
<td>D2-4</td>
<td>93.30</td>
<td>122.6</td>
<td>D2-9</td>
</tr>
<tr>
<td>D2-5</td>
<td>1078</td>
<td>1413</td>
<td>D2-10</td>
</tr>
</tbody>
</table>

CONCLUSIONS

Results of the numerical analysis of hydroelastic effect on ship structural response are presented in this paper. Hydro-structure analysis was performed using HOMER software by coupling 3D FEM structural model of very large floating structure and 3D potential flow code for solving seakeeping problem. The modal superposition method is used, which means that the total structural response is presented as a series of eigenvalue structural modes pre-calculated by the 3D-FEM structural software. By defining additional boundary value problems for radiation potential associated with dry structural modes the coupling with hydrodynamics model is performed. By resolving the interaction between the surface waves and the floating elastic body the hydroelastic response is obtained. Top-down technique was used to determine the influence of the hydroelastic effect called springing on structural fatigue damage of several fatigue details.

Fatigue life of selected structural details, presented in Table 2, shows the importance of taking into account the hydroelastic effect in designing and analysis of very large floating structures. Numerical results are showing that fatigue life is reduced by an average of 35% when hydroelastic effect called springing is considered.
REFERENCES