1. Introduction

The increase in world trade has largely contributed to the expansion of sea traffic. As a result, the market demand is leading to Ultra Large Container Ships (ULCS), with expected capacity up to 18000 TEU and length about 400 m, without changes of the operational requirements (speed around 27 knots). The particular structural design of the container ships, leads to open midship sections, resulting in increased sensitivity to torsional and horizontal bending loads which is much more complex to simulate numerically. At the same time, due to their large dimensions, the structural natural frequencies of ULCS become significantly lower so that the global hydroelastic structural responses (springing & whipping) can become a critical issue in the ship design and should be properly modelled by the simulation tools since the present Classification Rules don’t cover described operating stages completely.

The methodology of hydroelastic analysis includes the definition of the structural model, ship and cargo mass distributions, and geometrical model of ship surface. First, dry natural vibrations are calculated, and then modal hydrostatic stiffness, added mass, damping and wave load are determined. Finally, wet natural vibrations, as well as the transfer functions (RAO – response amplitude operator) for determining ship structural response to wave excitation, are obtained (Senjanović et al., 2008a, Tomašević, 2007).

The hydroelastic problem can be solved at different levels of complexity and accuracy. The best, but highly time-consuming way is to consider 3D FEM structural model and 3D hydrodynamic model based on the radiation-diffraction theory. Such an approach is recommended only for the final strength analysis. However, in this paper the beam model is coupled with 3D hydrodynamic model that is especially appropriate for the preliminary strength assessment, Figure 1. After the global hydroelastic response is calculated in the frequency domain, the modal displacements are imposed to the 3D FEM fine mesh substructure model and stress concentration RAOs in the considered structural detail is obtained (Vladimir, 2011). Both, the global and local hydroelastic responses are compared to those obtained by fully coupled 3D FEM + 3D BEM hydroelastic model.

2. Hydroelastic numerical model

The governing modal matrix differential equation for coupled ship motions and vibrations yields:

$$\left[ k + C - i\omega d - F B(\omega) \right] \xi + \omega^2 \left[ m + A(\omega) \right] \xi = F$$

where $k$, $d$, and $m$ are structural stiffness, damping and mass matrices, respectively, $C$ is restoring stiffness, $B(\omega)$ is hydrodynamic damping, $A(\omega)$ is added mass, $\xi$ are modal amplitudes, $F$ is wave excitation and $\omega$ is encounter frequency. All quantities, except $\omega$ and $\xi$, are related to the dry modes.

The structural part of the hydroelastic model includes sophisticated beam model based on the advanced beam theory (Senjanović et al., 2009a). It takes into account shear influence on both bending and torsion (Pavazza, 2005, Senjanović et al., 2009a,b), contribution of transverse bulkheads to hull stiffness (Senjanović et al. 2008b,c) as well as effective stiffness of relatively short engine room.
structure of ULCS (Senjanović et al., 2010, 2011a,b). The hydrodynamic part is based on the potential theory assumptions and it is described for zero advancing speed case as the simplest one in (Malenica et al., 2003), since the coupling procedure, in general case, does not depend on the used hydrodynamic model. The hydrostatic part of the hydroelastic model includes consistent restoring stiffness formulation (Senjanović et al., 2012).

If 1D analysis is applied, as in case of the hydroelastic model used in this investigation, the beam vibration modes should be spread to the ship wetted surface. The general expression for spreading nodal displacements to the wetted surface (valid for vertical and coupled horizontal and torsional vibrations) yields:

$$h = \left[ \frac{d\psi}{dx} (Z - z_s) + \frac{d\psi}{dx} Y + \overline{n} \frac{d\psi}{dx} \right] \mathbf{i}$$

$$+ \left[ -w_y - \psi (Z - z_s) \right] \mathbf{j} + \left[ -w_z + \psi Y \right] \mathbf{k}.$$  

(2)

where $w$ is hull deflection, $\psi$ is twist angle, $y$ and $z$ are coordinates of the point on ship surface, and $z_N$ and $z_S$ are coordinates of centroid and shear centre respectively, and $\overline{n} = \overline{n}(x, y, z)$ is the cross-section warping intensity reduced to the wetted surface (Senjanović et al., 2009c).

From the Eq. (2) the expressions for transmitting nodal displacements from beam model to 3D FEM substructure model can be extracted

$$\delta_x = \frac{d\psi}{dx} (Z - z_s) + \frac{d\psi}{dx} Y + \overline{n} \frac{d\psi}{dx},$$

$$\delta_y = -w_y - \psi (Z - z_s),$$

$$\delta_z = -w_z + \psi Y.$$  

(3)

These displacements are then imposed to the aft and fore 3D FEM substructure boundaries, and stress concentrations as result of their differences is calculated.

3. Computer codes

Based on the developed theory computer programs have been developed. Both theory and programs are checked by correlation analysis of the simulation results and the measured ones for a flexible segmented barge consisting of 12 pontoons, for which tests results are available, Figure 2 (Malenica et al., 2003, Remy et al., 2006).

Stiffness properties of ship hull are calculated by program STIFF, based on the theory of thin-walled girders, Figure 3 (STIFF, 2010). It calculates cross-section area, moments of inertia of cross-section, shear areas, torsional modulus, warping modulus and shear inertia modulus, for closed and opened cross-sections. The effective values of the above quantities can be also determined for the assumed sinusoidal modes.

For the hydroelastic analysis DYANA program has been developed based on the advanced beam theory and finite element technique, taking shear, bending, pure torsion, shear torsion and warping of cross-section into account (DYANA, 2007). The
restoring stiffness is calculated for the deformed wetted surface, determined by spreading the beam deformation. The hydrodynamic part in DYANA is taken from the program HYDROSTAR and adopted for hydroelastic analysis (HYDROSTAR, 2006).

4. Numerical example

A large container ship of 11400 TEU, \( L_{pp} \times B \times H = 348 \times 45.6 \times 29.74 \) m, is considered, Figure 4. The equivalent torsional modulus due to influence of transverse bulkheads reads \( I_t' = 1.9 I_t \).

The reliability of the beam model is checked by correlating the natural frequencies and mode shapes with those of 3D FEM analysis performed by NASTRAN, Figures 5 and 6.

Figure 4. 11400 TEU container ship, general arrangement.

The wetted surface of hydrodynamic model of the considered ship is presented in Figure 7.

Figure 5. The first dominantly torsional mode, lateral and bird view, light weight, 1D model, \( \omega_1 = 0.639 \) rad/s.

Figure 6. The first dominantly torsional mode, lateral and bird view, light weight, 3D model, \( \omega_1 = 0.638 \) rad/s.

Wetted surface of hydrodynamic model of the considered ship is presented in Figure 7.

Figure 7. Wetted surface hydrodynamic model.

Transfer functions of torsional moment and horizontal bending moment at the midship sections are shown in Figures 8 and 9, respectively. They are compared to the rigid body ones determined by program HYDROSTAR. Very good agreement is obtained in the lower frequency domain, where the ship behaves as a rigid body, particularly due to usage of consistent restoring stiffness formulation (Senjanović et al., 2012). Discrepancies are very large at the resonances of the elastic modes, as expected.

Figure 8. Transfer function of torsional moment, \( \psi = 120^\circ \), \( U = 24.7 \) kn.
Transfer functions of vertical bending moment, horizontal bending moment and torsional moment obtained by beam and 3D hydroelastic model are shown in Figures 10, 11 and 12, respectively. Very good agreement can be noticed.

The selected structural detail for stress concentration assessment is a knee in the hatch corner at the upper deck level in the middle part of the 11400 TEU container ship, Figures 13 and 14, with particulars presented in (Boutillier et al., 2010). Deformed fine mesh 3D FEM substructure model is presented in Figures 15 and 16.

It should be mentioned that the real and imaginary component of the response should be calculated separately, and at the end, at the
level of stresses should be summed up as complex numbers.

Figures 17 and 18 show the stress distributions in the considered structural detail. The analyzed stress is normal stress along the knee boundary. In order to register it, bar elements are fitted on the knee boundary.

Transfer functions of stress concentrations obtained by 1D FEM + 3D BEM and 3D FEM + 3D BEM hydroelastic models are presented in Figure 19. In the low frequency domain rather high discrepancies can be noticed, while in the high frequency domain, where the springing influence on fatigue damage accumulation is pronounced, quite good agreement is achieved.

5. Conclusion

The hydroelastic model based on the sophisticated beam model, which is proven to be reliable for the global hydroelastic response calculations can be extended for the assessment of stress concentrations in combination with 3D FEM substructure model. Although, very good agreement in the high frequency range is obtained, some minor improvements in the low frequency domain are still necessary to increase the fatigue damage assessment accuracy.

In order to complete hydroelastic analysis of container ships and confirm its importance for ship safety, it is necessary to proceed further to ship motion calculation in irregular waves for different sea states, based on the known transfer functions.

At the end of a complete investigation, which also has to include model tests and full-scale measurements, it will be possible to decide on the extent of the revision of Classification Rules for the design and construction of ultra large container ships.

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6. References


