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Refined beam finite elements for static and dynamic analysis of hull structures

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ABSTRACT

The accuracy and reliability of structural analyses are significantly compromised owing to the utilization of simple beam elements to model the global mechanical behaviour of ship hulls. These 1D models entail various assumptions and do not provide accurate and reliable results for hulls with complex structural details, such as cut-outs or reinforcements. The 3D FEM solutions, on the other hand, are computationally expensive. In the present study, refined 1D FE models for the analysis of simplified naval engineering structures have been developed by using the well-known Carrera Unified Formulation (CUF). According to CUF, refined kinematics beam models that go beyond classical theories (Euler, Timoshenko) can be easily developed by expressing the displacement field as an expansion in terms of generic functions, whose form and order are arbitrary. Hence, the stiffness and mass matrices are written in terms of fundamental nuclei, which are independent of the adopted class of beam theory and the FE approximation along the beam axis. As a particular class of CUF models, Lagrange polynomials have been used to formulate beam models at the component scale. According to this approach, each structural component (e.g. hull, longerons, bulkheads, and floors) can be modelled by means of the same 1D formulation. The results clearly demonstrate the enhanced capabilities of the proposed formulation, which is able to replicate solid/shell ANSYS solutions with very low computational efforts.

1. Introduction

Ships are the largest man made structures used for transportation purposes. Owing to the growing needs, their sizes continue to grow bigger in parallel to the speed and endurance in highly dynamic environment. Ship structure designers are challenged by the need to stiffen the large ships, such as container vessels, against these dynamic loads as well as increase their capacity to carry maximum payload.

At global level, large container ships more resemble like a beam and thus are highly flexible with large amplitudes in vertical bending vibrations as compared to the others. As much as for the ship structure itself, such vibration behaviour is detrimental for various installations on board the ships that cannot withstand such large amplitudes. Thus, an accurate and reliable structural behaviour needs be predicted. The problem has been addressed by the structural analysts by employing both beam models, which are overly simple, as well as 3D solid FEM, which is computationally expensive.

The famous Euler–Bernoulli [1] and Timoshenko [2,3] Beam Models (hereinafter referred to as EBBM and TBM, respectively) have been considerably used in the early works to model global structural behaviour of ships. According to EBBM, it is assumed that the plane cross-sections of a beam will remain plane during bending. This assumption is acceptable as long as one is interested only in vertical deflection of beam center line and is valid only for the cases of simple, solid and homogenous sections and long beams. The transverse shear stresses that become pronounced in short beams are ignored in EBBM. TBM adds one more degree of freedom to EBBM by removing the perpendicularity condition of cross section from beam axis but the plane cross sections remain plane. One of the limitations in TBM is assuming the constant shear stress distribution over beam cross-section and a correction factor is needed to be introduced to account for the homogenous stress conditions at cross-section edges. Both EBBM and TBM theories do not capture cross-section warping.

The famous British scientist Young (*Young's Modulus* named after him) employed beam theory to find the shear stress and bending moment distributions under the distributed load and

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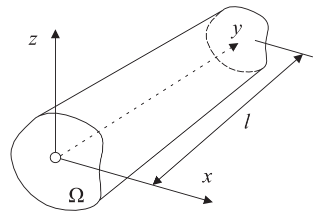

Fig. 1. Generic beam model and related Cartesian reference system.

buoyancy forces. In a paper presented by John [4], a ship was considered as a beam and plate thickness was determined based on ultimate strength compared to the normal stresses. The cross-section warping of the open-sectioned ships under torsional loading was analysed by Paik et al. [5]. The first review article on hull girder strength [6], is a commendable effort citing a number of articles with hull girder modelled as beams.

The area of ship global vibration behaviour is addressed as part of the hydroelastic study of marine structures. The pioneering works of Bishop and Price [7–9] mainly focused on the surface loads and their effects on marine structures, establishing symmetric, anti-symmetric, and asymmetric two-dimensional (2D) hydroelasticity theories to determine structural behaviour, based on 2D modelling of both the ship structure and the surrounding fluid. In later decades, there has been extensive development of linear and non-linear 2D and 3D hydroelasticity theories of ships, mainly covering global load assessment and determining springing or whipping behaviour of ships and other arbitrary shaped marine structures [10–12]. For the cases with structure in stationary waves, the approach of 3D hydroelastic analyses was simplified and was applied to various hydroelastic problems of ships and marine structures [13–15]. These works include the analysis of stationery floating structures in waves, as product carrier [14], floating dock [15], towed jack-up [16], submerged cylinder [17], and Very Large Floating Structures (VLFSs) [18–21], to the loads and safety assessment of mono-hull and multi-hull ships travelling in a seaway [22,23]. Considerable increase in ship dimensions such as container ships and tankers has drawn interest of researchers in their hydroelasticity of springing and whipping behaviour. Malenica et al. [24] presented global hydroelastic model for ship-type bodies and validated both in frequency and time domains. The so called "Non-uniform Timoshenko beam model" employing Finite Element Method (FEM) was used to model structural part, while the hydrodynamic part was modelled by the classical 3D Boundary Integral Equation (BIE) technique. Modal approach was used to couple the two parts whereby the final structural deflection was split into a number of the structural 'dry' modes. The hydroelastic response of a barge to regular waves by employing 3D hydroelasticity was presented by Chen et al. [25] and findings were compared with experimental results.

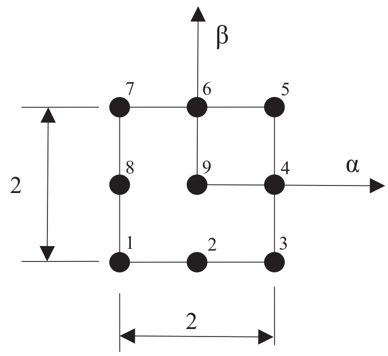

Fig. 2. L9 element in natural coordinates.

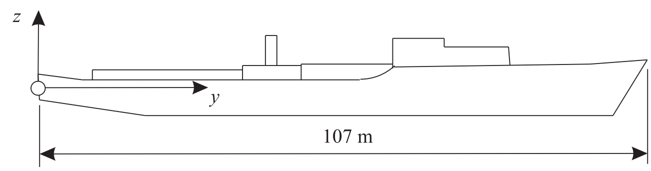

Fig. 3. Destroyer ship geometry.

Table 2
Natural vibration frequencies in vertical bending for destroyer of Fig. 3.

Mode	LE beam (Hz)	Ref. [9] (Hz)	ANSYS Beam (Hz)
1	1.97	2.16	2.22
2	3.97	4.33	4.64
3	6.13	6.37	5.04
4	8.94	9.24	8.28
5	11.63	11.8	12
6	13.56	13.76	13.32

Leibowitz [26] and Jensen and Madsen [27] demonstrated the use of beam models for idealized ships analysis and hull vibrations at lower natural frequencies. Considering them as thin walled beams, the cross-section warping was considered using the St. Venant torsion theory by Kawai [28] and using Vlasov thin-walled beam theory [29]. In [30,31] classical beam girder theories with some improvements to account for discontinuous cross-sections were used, but lacked satisfactory results for open-sectioned beams and results for higher vibration modes. Advanced theories have been implemented in beam girder idealization of ships in several papers by Senjanović and his co-workes, see for example [32–38]. These works pertain to the fact that many ship structures have large deck openings (such as container ships) making them resemble like open-section girders whose shear centres lie outside of cross-section. For example, in the paper by

Table 1
Input data for destroyer shown in Fig. 3.

Section ID	Mass/length (ton/m)	I_{xx} (m^4)	A (m^2)	Section ID	Mass/length (ton/m)	I_{xx} (m^4)	A (m^2)
1	10.21	0.68	0.044	11	26.56	4.33	0.089
2	10.81	1.20	0.054	12	28.77	4.26	0.088
3	13.58	1.79	0.064	13	23.48	4.26	0.086
4	43.17	2.50	0.072	14	46.25	4.25	0.077
5	39.88	3.34	0.079	15	39.07	4.08	0.070
6	26.06	3.76	0.085	16	15.40	3.71	0.069
7	25.04	4.04	0.089	17	12.11	3.24	0.070
8	25.26	4.30	0.090	18	10.90	2.74	0.071
9	35.90	4.38	0.089	19	6.75	2.24	0.072
10	27.01	4.38	0.089	20	1.18	2.10	0.071