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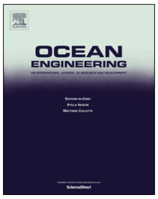

Experimental eigenfrequency study of dry and fully wetted rectangular composite and metallic plates by forced vibrations

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ABSTRACT

This paper deals with the shortcomings in current design methods for dynamically loaded composite structures in underwater applications. This is done through an experimental study to evaluate the eigenfrequencies of rectangular plates made from metals as well as composites that are tested in air (dry) and completely submerged under water (fully wetted). The eigenfrequencies are studied using forced vibrations. The test series comprises 19 specimens that are made from various materials including aluminium, steel, glass-fibre, and carbon-fibre with aspect ratios varying from 3.7 to 11.2 and breadth to thickness ratios ranging from 2.7 to 20.5. The test method is based on electro-mechanical excitation by random vibrations as well as stepped sine refinements in the vicinity of the identified eigenfrequency. The results clearly show how differently the specimens are affected by the “added mass” from the water when fully wetted compared to the dry condition. Slender and more lightweight configurations are more profoundly affected by water than heavier and more rigid specimens. The results clearly show that for advanced composite materials and more complex geometries the current rule-of-thumb methods used by the industry today are inadequate in predicting the shift in natural frequency due to the effect of the surrounding water.

1. Introduction

Polymer composite materials are used extensively within maritime applications where high performance is of importance because of their high specific-stiffness and strength, and their ability to be tailored to optimise performance. The field of applications range from entire hull structures to cantilevered structural components such as hydrofoils, fins, keels, turbines, and propeller blades (e.g. Marsh, 2004; Young, 2008; Mouritz et al., 2001). For optimised design of these dynamically loaded components it is essential that the natural frequencies can be calculated accurately. For structures submerged in water a complicating factor is however the accentuated effect of “added mass” from the surrounding water that lowers the natural frequencies. While, dynamics of viscoelastic structural materials (including composites) have been studied extensively in the research community (e.g. Beranek, 1971), the research on structures in sub-sea applications has been focused on submerged cantilevered metallic beams and plates (e.g. Lindholm et al., 1962; Marsh, 2004; Mouritz et al., 2001; Muthuveerappan et al., 1979a, 1979b; Sahin et al., 1993; Sedlar et al., 2011). As the focus has been on metallic structures the knowledge about the behaviour of composite materials in sub-sea applications is limited. The focus on steel structures naturally also influences the typical design methods, or “rule of thumb”, used in the industry today. This is limiting the designers from developing optimized structures utilising the full potential of composite materials in sub-sea applications.

With the rapid development of computer- simulation and design methods (e.g. FEM, CFD, FDM, and coupled multiphysics tools), designers are today equipped with powerful tools to perform complex 3D simulations of structures, hydrodynamics, fluid flows as well as coupled fluid structure interaction problems (e.g. Stenius, 2009). This gives designers refined analysis methods and improved accuracy with the ability to obtain optimized solutions. However, the success of these methods is of course depending on accurate verification by e.g. experimental analysis to validate as well as calibrate and tune the different simulation models. The main motivation for this work is to serve as a benchmark for calibration of numerical fluid–structure interaction simulations. The results in this paper are a complement to studies on submerged composite plates, in addition to the previous work on “added mass” effect on metallic plates (e.g. Lindholm et al., 1962; Marsh 2004; Mouritz et al., 2001; Muthuveerappan et al., 1979a, 1979b; Sahin et al., 1993; Sedlar et al., 2011), to enable improved design methods for composite structures in sub-sea applications.

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For design purposes, it is desirable however to have simplified expressions for the shift in natural frequency defined as a frequency reduction ratio (e.g. Carlton, 2007; Korotkin, 2009). For a cantilevered beam the undamped natural frequency relation can be mathematically expressed as:

$$f_{nf} = \frac{(\lambda_n)^2}{2\pi}\sqrt{\frac{EI}{mL^4}}, \tag{1}$$

where EI is stiffness, m is mass per unit width, L is length of the beam, and λ_n is the nth eigenvalue. Following (Carlton, 2007) the frequency reduction ratio may be expressed as:

$$\Delta = \sqrt{\frac{m_s}{m_s + m_a}}, \tag{2}$$

where m_s is the structural mass and m_a is the added mass from the surrounding medium. Propeller designers, today, typically have developed an industry standard for estimating the wet eigenfrequencies whereby the “added mass effect” is incorporated in their designs by simply doubling the weight of steel or brass propellers. Hence this “rule-of-thumb” method in the industry yields an approximate 30% reduction in the eigenfrequency in water compared to that in air. It is currently perceived that lighter composite materials with high specific stiffness, should be more influenced by the surrounding water and hence the “added mass” effect should therefore have an even greater influence on the natural frequencies than for the heavier steel or aluminium structures. For instance, in Kramer et al. (2013), the natural frequencies for composite panels and beams are shown to be between 50% and 70% lower in water compared to the natural frequencies in air. By only considering the mass and using a rather blunt “doubling the weight” rule-of-thumb method, this does not take into consideration geometry or material properties. In the development of more accurate design methods, taking into account the shift in natural frequency due to a surrounding medium, it is desirable to include geometry as well as material properties in order to handle more complex geometries and advanced material concepts.

This paper serves to provide experimental data on the natural frequencies of plates and beams both in air and submerged in water, that are made from composites as well as metals. The aim is to further quantify the wetted natural frequencies of composite specimens and clarify how the wetted natural frequencies are affected by aspect ratio, slenderness, thickness, and stiffness (examined for glass-fibre and carbon-fibre). The test series comprises 19 specimens that are tested in dry and wet conditions, with natural frequencies measured by small and lightweight accelerometers.

2. Experimental setup

2.1. Test series

The test series consists of 19 rectangular plates with varying aspect and thickness ratios as well as with varied materials, as listed in Table 1. The test specimens have nominal dimensions and actual measured properties according to Table 1. Note that the measured length is 59 mm longer than the specified length because the additional 59 mm of the plate is utilised for clamping the specimen to the test rig as illustrated in Fig. 1c. This 59 mm clamping distance applies to all 19 specimens tested. Depending on the width of the specimen the number of bolts used is varied between 4 and 12.

The studied materials are made of quasi-isotropic carbon-fibre reinforced plastics (CFRP), quasi-isotropic glass-fibre reinforced plastics (GFRP), steel, and aluminium. The composite plates were manufactured by vacuum infusion using a T700 equivalent fibre and E-glass respectively with Vinylester.

The dimensions of the specimens have been varied in length, width, and thickness from the base dimensions of a rectangular plate that is 500 mm long, 100 mm wide and 6 mm thick (Fig. 1b), according to the test series description in Table 1. All geometry parameter variations (length, width, and thickness) have been studied for the CFRP series, for both, single parameter variation (e.g. length variation only) as well as simultaneous variation of all three parameters (simultaneous length, width, and thickness variation for the extreme cases; see Test# 8–9 in Table 1). A limited number of variations are performed for the other materials.

The equivalent bending Young's modulus of both the composite and metallic plates was determined using impulse hammer tests

Table 1
Test series description and specimen characterisation.

Test#	Specimen specifications					Specimen measurements						Derived properties	
	Material	Length [mm]	Width [mm]	Thick. [mm]	Note	Length [mm]	Width [mm]	Thick. [mm]	Weigh [kg]	Nr. holes	FFE[a] [Hz]	Density [kg/m^3]	Young’s Modulus [GPa]
1	CFRP	500	100	6	Baseline	559	99.83	5.85	0.472	8	105.09	1458	43.23
2	CFRP	500	150	6	Wide	559	149.90	5.77	0.702	12	104.83	1463	44.35
3	CFRP	500	50	6	Narrow	559	49.90	5.76	0.232	4	103.04	1456	42.81
4	CFRP	750	100	6	Long	809	99.86	5.75	0.676	8	49.54	1463	43.79
5	CFRP	400	100	6	Short	459	99.90	5.81	0.388	8	157.57	1469	45.00
6	CFRP	500	100	10	Thick	559	99.90	10.22	0.844	8	200.32	1490	52.54
7	CFRP	500	100	4	Thin	559	99.90	4.08	0.320	8	67.58	1414	35.55
8	CFRP	400	50	10	Short/narrow/thick	459	49.97	10.22	0.348	4	299.14	1498	53.43
9	CFRP	750	150	4	Long/wide/thin	809	150.02	4.11	0.700	12	32.64	1409	35.82
10	GFRP	500	100	6	Baseline	559	99.95	7.26	0.750	8	82.43	1864	22.07
11	GFRP	400	100	6	Short	459	100.10	7.29	0.614	8	122.50	1851	21.79
12	GFRP	750	100	6	Long	809	99.90	7.08	1.058	8	37.38	1858	20.87
13	Steel	500	100	6	Baseline	560	99.98	6.00	2.628	8	103.42	7880	216.35
14	Steel	500	100	4	Thin	560	99.97	3.96	1.732	8	67.97	7874	214.63
15	Al	500	100	6	Baseline	560	100.00	6.20	0.932	8	105.22	2706	72.13
16	Al	500	100	4	Thin	560	99.97	4.00	0.604	8	68.10	2715	72.62
17	Al	500	150	6	Wide	560	149.80	6.22	1.394	12	105.47	2693	71.67
18	Al	500	50	6	Narrow	560	49.95	6.19	0.466	4	104.96	2710	71.94
19	Al	750	100	6	Long	810	100.02	6.20	1.350	8	50.30	2703	72.26

[a] FFE – First eigenfrequency of impinged free hanging plate.