Vibration analysis of fiber reinforced composite hydrofoils using finite element method

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Abstract. In this study, the natural responses of fiber reinforced composite hydrofoils are obtained using FEM. It is of great importance to estimate the vibrational responses of fiber reinforced composite hydrofoils correctly due to the flexible characteristics of the material. Modal analysis is performed on a cantilevered hydrofoil which has a cross-section of a modified NACA0009 profile using FEM software Abaqus 2019. Newly developed structured mesh modeling method is used, and the results are compared with the conventional modeling methods and experiment. In the developed mesh model, boundaries of the layers are modified in order to apply a structured mesh. By investigating the stress distribution of the hydrofoil for the bending mode case, it is evident that the developed mesh model results in the most accurate and physical result compared to existing modeling method.

1. Introduction

Fiber reinforced composites, also referred to as Fiber reinforced polymer or plastics (FRP) are currently used in various fields. Due to their high specific strength and resistance to corrosion [1], FRP is thought of as the next generation material which could replace metallic alloys in the field of naval engineering [2,3]. Small vessels such as leisure boats and yachts already put FRP to use as the primary source of structural strength [4]. Innovative designs are starting to be used in the rage of large ships such as commercial bulk carriers and naval vessels [2,3].

Marine propellers provide thrust and enable vessels to navigate through its course. Since propellers are crucial for ships to provide their original purpose, an adaptation of FRP has been delayed due to uncertainties. Until recent registrational changes by the International Maritime Organization (IMO), the main concern for propeller was to provide the appropriate thrust. However, new regulations require propellers to meet noise standards because sound radiated underwater may cause severe damage to the ocean environment.

Flexible properties of FRP provides the propeller the ability to adaptively change shape according to the nearby flow, which in result, reducing noise radiated by the propeller [5,6]. It is of common understanding that fluid-structure interaction (FSI) analysis is required to fully estimate the performances of fiber reinforced composite marine propellers. With a focus on acoustical performances of the FRP propellers, it is crucial to fully understand the structural characteristics and
vibrational characteristics of the propeller due to external forces [7]. Thus, the main concern is to correctly estimate the natural responses of FRP propellers while correctly reflecting the structural and material properties of FRP in the simulation.

Three-dimensional solid elements were used to include the effect of shear deformation in the analysis instead of plate or shell elements. Laminated composite theory based 2D elements commonly assume in-plane displacements and corresponding shear deformations [8]. Due to this assumption, 2D elements are unable to incorporate the appropriate amount of shear deformation effects for thick structures such as hydrofoils and marine propellers. Solid elements can be divided into structured and unstructured mesh. For laminated composites, structured mesh stacked in the thickness direction results in the most accurate displacements. [9]

Fiber reinforced composite hydrofoils were selected for analysis to incorporate simplicity of the analysis and modeling of the structure. The goal is to simulate the natural responses of these hydrofoils using 3D solid elements, which can be used similarly on marine propellers in future work. The composite hydrofoil models had complex lamination boundaries where structured mesh cannot be applied. To accurately simulate the responses of the hydrofoil, a new laminated composite structured mesh modeling method was developed in order to apply the structured mesh on composite hydrofoils. The FEM software Abaqus 2019 was used to perform the model analysis on the composite hydrofoils.

2. Methods

2.1. Geometry and lamination properties of hydrofoil

All information regarding the geometry and the lamination properties of the hydrofoil used are from experimental researches present in current literature [10-13]. Figure 1 shows the sectional geometry of the hydrofoil at plane \( z = 0 \) mm.

![Figure 1. Sectional geometry of the hydrofoil at z = 0 mm. The section has the profile of modified NACA0009 and the chord length is 120 mm.](image)

The profile was modified NACA0009 which can be expressed by equation (1). The modified profile had the same constants for variable \( x \) except for the constant for \( x \) to the power of four, which was changed from -0.1015 to -0.08890.

\[
y = 5t(0.2969x^{0.5} - 0.1260x - 0.3516x^2 + 0.2843x^3 - 0.08890x^4)
\]  

(1)

Variable \( t \) represents the thickness to chord length ratio which was 0.09 for NACA0009 profile. Variables \( x \) and \( y \) are nondimensionalized using the chord length. The profile in figure 1 is the plot of equation (1) shifted in the negative \( x \)-direction by half of the chord length. The positive \( x \)-direction indicates the trailing-edge direction while the negative \( x \)-direction is the leading-edge direction. The detailed profile of the hydrofoil is shown in figure 2.

The hydrofoil had 110 mm of root section where the profile was the same. This region was constructed in order to apply the boundary conditions. The regions where the boundary conditions were applied can be seen in figure 3. The rest of the profile had 300 mm in length in the positive \( z \)-direction which is the spanwise direction. The rest of the hydrofoil had a geometry where the chord length linearly decreased from 120 mm to 60 mm with the mid-chord line remaining straight.
Three different lamination configurations were considered. The stacking sequences of the three hydrofoils in question were $[(0^\circ/90^\circ)_g, (X)_c, (0^\circ/90^\circ)_g]$, with values of $X$ as $0^\circ$, $30^\circ$, and $-30^\circ$ for each structure. The reference direction was the span direction which is the same as the $z$-axis. Subscript ‘$g$‘ represents glass fiber and epoxy composite layer, whereas subscript ‘$c$‘ represents carbon fiber and epoxy composite layer. The number with the subscript represents the number of times each sequence is repeated. The last subscript ‘$s$‘ indicates that the plies were set to be laminated symmetrically with respect to the center plane which is the same as the $zx$-plane. The center of the hydrofoil was filled with glass-mat fabric to construct a core for the hydrofoil. The outermost surface of the hydrofoil was finished with basket weaved glass-epoxy layer. The details of the lamination boundaries are shown in figure 4. Color represents the same composite material and the structured mesh was constructed using the geometry in figure 4(b).

Figure 2. The geometry of hydrofoil with all lamination information included.  

Figure 3. Locations of fixed boundary condition application regions.

A new laminated composite hydrofoil modeling method was developed in order to apply structured mesh because it is impossible to apply a structured mesh on complicated inner boundaries of the original geometry. The proposed modeling method modifies the lamination boundaries according to two principles. One, only modify regions where structured mesh is inapplicable after partitioning, and two, keep main boundaries in thickness direction and modify only if necessary. Using this developed modeling method, the structured mesh was applicable on the composite hydrofoil.

The material properties of the fiber reinforced composite materials used are given in table 1.
Anisotropic material properties are defined with respect to the material axes is figure 4(d). Only one shear modulus in the xy-direction was provided in current literature [10-13], thus the rest of the shear modulus was set equal to that of the value in the xy-direction.

2.2. Conditions of FEM modal analysis

Fixed boundary conditions were applied on the root section of length 110 mm as shown in figure 3. This was done in order to mimic the experimental boundary conditions where the root section was camped mechanically using a contraption which had the same profile as the hydrofoil. The rest of the nodes were set to be free. Three eigenvalues and the corresponding eigenfunctions in the range between 0 Hz and 1 kHz were evaluated using the FEM software Abaqus 2019. This range was based on the experimental results where the natural frequencies were within that limit. Lanczos eigensolver was used in the process.

\[
[M]\ddot{\mathbf{x}} + [K]\mathbf{x} = \{f\}
\] (2)

The modal analysis obtains the eigen values and the eigen vectors of the governing equation of the structure. The governing equation of structured can be expressed as equation (2) where M and K represents the global mass and stiffness matrix respectively and x represents the node displacement vector.

Two kinds of FEM mesh were used. First, unstructured mesh using continuum three-dimensional ten nodes, quadratic tetrahedral elements (C3D10) was constructed. The hydrofoil geometry required 320,169 elements to mesh the whole structure. The geometry used is described in figure 4(a). The second mesh was the structured mesh where the new modeling method was applied in order to construct a structured mesh on pointy shaped regions. Using the continuum three-dimensional twenty nodes, quadratic hexahedral element (C3D20), the total number of elements required for the structured mesh was 436,840. The geometry used to create a structured mesh is shown in figure 4(b). Three eigenfrequencies for each type of mesh and each type of lamination direction was obtained.

3. Results of Hydrofoil modal analysis

Three eigenfrequencies in the range from 0 Hz to 1 kHz were obtained. Modal analysis was performed for each unstructured and structured mesh, and for each lamination sequence, X = 0°, 30°, -30°. The simulation results were compared with the experimental results of the same hydrofoil and same lamination configuration [13]. The results were also compared to that of the same reference were the authors performed a FEM frequency analysis. 3D solid elements and multiple plies per element method were used in the reference [11]. In contrast, in this study, one or more elements per ply method were used. The results of the modal analysis compared to that of the reference results are in table 2.

It is shown in table 2 that using FEM modal analysis method, the eigenfrequency of the FRP hydrofoil can be estimated within a reasonable error boundary. Even though the reference used multiple plies per element method [13], the eigenfrequency which can be thought of as a global response can be obtained with small error. However, observing the result in a local point of view, multiple plies per element method revealed its limits.

Table 1. Fiber reinforced composite material properties.

| Fiber Type          | ρ (kg/m³) | E₁₁, E₂₂, E₃₃ (GPa) | ν, G₁₂, G₂₃, G₃₃ (GPa) |
|---------------------|-----------|----------------------|------------------------|
| Carbon-Epoxy [0°]   | 1590      | 117.8, 13.4, 13.4    | 0.253, 3.9, 3.9         |
| Glass-Epoxy [0°/90°]| 1750      | 15.1, 19.3, 15.1     | 0.034, 4.2, 4.2         |
| Glass-Basket        | 1660      | 15.3, 12.8, 15.3     | 0.133, 3.0, 3.0         |
| Glass-Mat           | 1370      | 6.8, 5.0, 5.0        | 0.302, 2.5, 2.5         |

The geometry used is described in figure 4(a). The rest of the geometry used to create a structured mesh is shown in figure 4(b). Three eigenfrequencies for each type of mesh and each type of lamination direction was obtained.
Table 2. Modal analysis results and comparison with that of the reference.

| Case | X = 0° | X = 30° | X = -30° |
|------|--------|---------|----------|
|      | Mode FEM No. | Exp. (Hz) | Error (%) | Exp. (Hz) | Error (%) | Exp. (Hz) | Error (%) |
| Ref. | 1 | 118 | 120 | -1.67 | 72 | 74 | -2.70 | 78 | 79 | -1.27 |
| Unstructured | 125.52 | 4.60 | 76.754 | 3.72 | 83.388 | 5.55 |
| Developed Model | 121.85 | 1.54 | 74.052 | 0.07 | 80.425 | 1.80 |
| Ref. | 2 | 394 | 428 | -7.94 | 286 | 305 | -6.23 | 311 | 338 | -7.99 |
| Unstructured | 423.85 | -0.97 | 315.87 | 3.56 | 338.87 | 0.26 |
| Developed Model | 407.45 | -4.80 | 308.79 | 1.24 | 330.79 | -2.13 |
| Ref. | 3 | 464 | 482 | -3.73 | 594 | 611 | -2.78 | 598 | 591 | 1.18 |
| Unstructured | 500.82 | 3.90 | 633.48 | 3.68 | 643.67 | 8.91 |
| Developed Model | 494.44 | 2.58 | 613.84 | 0.46 | 626.37 | 5.98 |

*Ref. here indicates the FEM frequency analysis results of that of the reference [13].

Observing the mode shape of the hydrofoil, the deviation from the experimental results when one element represents multiple plies can be seen. Figure 5 shows the eigenmode of the hydrofoil with X = 30° lamination sequence. The results were compared with reference FEM results and reference experiment results [13]. The color legends are neglected because the exact values are of insignificance.

![Mode shapes of hydrofoil with X = 30° lamination sequence. 'T' represents the trailing edge and 'L' represents the leading edge.](image)

Figure 5. Mode shapes of hydrofoil with X = 30° lamination sequence. ‘T’ represents the trailing edge and ‘L’ represents the leading edge. (a), (b), (c) Mode shape of the first mode. (d), (e), (f) Mode shape of the second mode. (g), (h), (i) Third mode shape. The first column parts (a), (d) (g) Results of this paper using the developed model. (b), (e), (h) Reference experiment results [13]. (c), (f), (i) FEM results of the reference [13].

By analyzing the results shown in figure 5, the fact that the first mode is the first bending mode, the second mode is the second bending mode and the third mode corresponds to the first twisting mode is...
the same. Since exact values, which are the displacements for each node was not given in the reference [13]. Thus, quantitative comparisons between the FEM results and the results of that of the experiments were not possible. However, performing a qualitative comparison between the FEM results and the experimental results, it was found that by using one or more elements per ply method, the location of the shear center of the first twisting mode was correctly estimated. While using multiple plies per element method, which can be found in the reference FEM results, the shear center was not correctly located. Comparing figure 5(h) with figure 5(i), it can be easily picked out that the experimental results in figure 5(h) shows that the shear center is at 53.15% chord length location from the leading edge, which is leaned towards the trailing edge while the reference FEM results in figure 5(i) the shear center is located towards the leading edge.

In order to find the differences between using an unstructured mesh and the structured mesh from the developed modeling method, the stress distributions were analyzed for a bending mode case. Figure 6 shows the interlaminar shear stress (ILSS) for an unstructured mesh and the developed modeling method. The shear stress, S23 is in structural coordinates. The lamination sequence is when X = 0°. The ILSS was plotted instead of all the other stresses because for laminated composites, the estimation of shear stress between individual layers is one of the important objectives of FEM analysis. From ILSS distribution information, further analysis is possible such as fatigue analysis. It is clearly seen in this figure, that the structured mesh using the new modeling method results in more physically reliable stress distribution. While the unstructured mesh shows local peaks in the stress where it is not plausible.

![Figure 6](image_url)

**Figure 6.** Interlaminar shear stress (ILSS) plot of the hydrofoil for first bending mode. The lamination sequence is when X = 0°. The location of the section is at the root where z = 110 mm. (a) Color legend which is identical for parts (b) and (c). (b) ILSS plot for an unstructured mesh case. (c) ILSS plot for a structured mesh using developed modeling method.

4. Conclusion
Modal analysis was performed on hydrofoils which had a modified NACA0009 sectional profile. The natural frequencies were compared between the FEM results and experimental results. FEM frequency analysis shows that it can estimate the natural responses within a small error range. Whether multiple plies per element method was used, or one or more elements per ply method was used, did not show any significant difference. In addition, whether an unstructured mesh or a structured mesh was used did not show any meaningful variations in natural frequency.

On the other hand, observing the eigenmode FEM analysis it can be concluded that the one or more elements per ply method must be used to correctly capture the local responses of the FRP hydrofoils. Analyzing the results of the interlaminar shear stress for bending condition, it is evident that a structured mesh combined with laminated composite modeling method is required for an accurate assessment of stress in FRP hydrofoil. The main downside of using FRP materials when constructing a marine propeller is the uncertainty of material failure. Thus, an accurate estimate of the internal stress distribution from the structural simulation is mandatory, and the structured mesh is the only type
which can deliver correct results of the stress.

In conclusion, a structured mesh, together with laminated composite modeling method must be applied in order to correctly simulate FRP hydrofoils. Using the developed modeling method, a modified lamination geometry was constructed in order to apply a structured mesh. For future work, it may be required to develop a mesh model which can consider all the lamination information without any simplification.

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