# A fluid-structure interaction approach to the evaluation of deformation in a composite propeller blade submitted to hydrodynamic flow

**Ramona B. Barber[a], Antoine Ducoin[b], Stuart J. Wildy[c], Alban Leroyer[d]**

a. Laboratoire d'Hydrodynamique, Energétique et Environnement Atmosphérique (LHEEA), Centrale Nantes, France ; ramona.barber@ec-nantes.fr
b. LHEEA, Centrale Nantes, France ; antoine.ducoin@ec-nantes.fr
c. Centre for Maritime Engineering, Control & Imaging, Flinders University, Australia ; stuart.wildy@flinders.edu.au
d. LHEEA, Centrale Nantes, France ; alban.leroyer@ec-nantes.fr

## Résumé :

*L'utilisation du matériau composite pour les hélices marines peut entrainer une augmentation significative sur leurs performances hydrodynamiques, de par leur capacité à se déformer en fonction des conditions d'écoulement, de la vitesse de rotation et de l'agencement des plis de composite. Malgré leurs avantages, ces hélices marines restent complexes à mettre en œuvre, ce qui les rends complexe à caractériser. De façon à optimiser au mieux leur performance, une compréhension poussée du couplage dynamique entre la réponse structurelle et l'écoulement est nécessaire. Ce travail présente une approche numérique couplée fluide structure d'une pale composite sous chargement hydrodynamique. Les simulations sont menées avec le code CFD (Computational Fluid Dynamic) Fine/Marine développé au laboratoire LHEEA de Centrale Nantes, simulant la solution couplée du problème à travers une approche modale pour la structure, permettant de déduire les déformations structurelles dues à l'écoulement.*

## Abstract :

*The use of fiber-reinforced polymer composites for marine propellers can provide significant performance improvements ; additional benefits can be gained by exploiting their capacity to deform based on flow conditions, rotational velocity, and laminate design. Despite their advantages, however, advanced composite propellers are complex and their behavior is difficult to characterize. In order to fully optimize the performance and control of these blades, a detailed understanding of the dynamic coupling between the hydroelastic response of a composite blade and the surrounding flow under a wide variety of operating conditions is required. This work will present a numerical, fully-coupled fluid-structure interaction (FSI) study of a single composite propeller blade. The simulations are carried out using the Fine/Marine computational fluid dynamics solver to predict the flow behavior, which is coupled with a modal approach to capture structural deformations.*

**Keywords : Fluid-structure interaction, Modal analysis, Marine composites, Marine propellers**

# 1 Introduction

The use of fiber-reinforced polymer composites in marine propellers has recently been extensively investigated. These composite materials provide excellent strength-to-weight and stiffness-to-weight ratios, improved fatigue performance, and reductions in corrosion, noise generation, and magnetic signature. Another advantage of composites is their increased mechanical flexibility relative to metals and thus their capacity to deform based on flow conditions, rotational velocity, and laminate design [7]. This ability to deform permits passive or active shape adaptation, obviating the need for complex mechanisms such as in controllable pitch propellers.

In order to fully optimize the performance and control of these blades, a detailed understanding of the dynamic coupling between the hydroelastic response of a composite blade and the surrounding flow under a wide variety of operating conditions is required. To that end, a coupled fluid-structure interaction model is presented in this paper. The numerical model combines the computational fluid dynamics solver FineMarine developed at Centrale Nantes, France with a modal structural analysis directly implemented into the CFD code. The coupled simulation will be used to inform a set of towing tank experiments of a single, non-rotating composite propeller blade to be performed at Central Nantes. It is essential to highlight that, as a first step, this configuration will not fully represent a rotating blade ; i.e, it will not take into account the spanwise variation of velocity due to rotation. The composite blade in the experiment will be based on the INSEAN E779A propeller with FBG optical fibers embedded in both the pressure and suction sides to measure deformation ; additionally, forces and moments will be measured at the blade root. Due to the highly twisted nature of a propeller blade as compared to a hydrofoil, however, a higher level of multi-scale dynamic excitation in the flow and in the hydroelastic response of the blade can be expected. The method will later be extended to include the study of flexible, variable-stiffness, and rotating propeller blades.

# 2 Methods

In this work, a fully-coupled FSI approach is used with a structural modal analysis coupled to a CFD solver. The FSI simulation combines the computational fluid dynamics solver Fine/Marine [4], developed at Centrale Nantes, France, with a modal structural analysis solved initially in the commercial finite element software ABAQUS [1] and directly implemented in the CFD code. A single, non-rotating composite blade is modeled. The blade geometry is derived from the INSEAN E779A geometry [3], scaled such that the length of the single blade is 500 mm overall. Further details of the experimental setup and modeling methods can be found in [2].

The CFD code ISIS-CFD in Fine/Marine [4] solves the incompressible Unsteady Reynolds-Averaged Navier-Stokes (URANS) equations in a strongly conservative manner. It uses a fully-unstructured, cell-centered finite-volume method to build the spatial discretization of the conservative equations. Further details of the solver can be found in [5, 6]. Two CFD domains were considered in this study. The first domain considers the full test setup and fully represents the free surface with a volume of fluid method, while the reduced domain considers only the blade, with a horizontal plane with a symmetry condition (i.e, $\vec{V} \cdot \vec{n} = 0$) set parallel to the root section. For brevity, only results from the reduced domain are presented here. A $k-\omega$ SST turbulence transport model was employed. Grid and time step independence were verified before running the complete computations ; time steps of $dt$ = 0.001 s were used.

To carry out the FSI coupling, a modal approach is used. Modal analysis allows the simplification of the linearized governing equation of motion of size $n$ using the eigen modal matrix. Assuming Rayleigh damping, the eigen modal matrix allows the diagonalization of the mass and damping matrices ; normalizing the eigen mass matrix simplifies the problem into a resolution of $n$ uncoupled single-DOF systems. These equations are fully coupled with the resolution of the fluid flow, as added mass effects (defined as the part of the pressure force proportional and opposed to body acceleration) are naturally included in the calculation of the fluid force. An artificial added mass method is added via an internal implicit coupling algorithm in order to better capture the energy exchange at the interface and to ensure stability of the algorithm. The deformation of the structure is thus solved and the mesh updated within one time step. ISIS-CFD takes as input the shapes and frequencies of the first $m$ natural modes of vibration of the structure in air, allowing the reduction of the model by excluding modes that do not have a significant impact on the case studied. The coupled model is solved in time with options for both a quasi-steady and fully unsteady approach, allowing the user to optimize the solver for computational efficiency or high resolution.

# 3 Modal Analysis

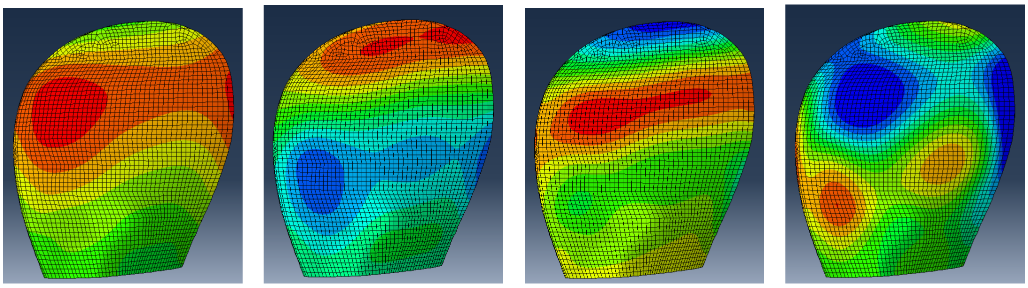
In this simulation, the commercial finite element software ABAQUS [1] is used to solve for the modal shapes and frequencies. The deformed shape as determined by the sum of the amplitudes of the given mode shapes in the CFD solver is then returned to ABAQUS during post-processing via a user-defined subroutine in order to analyze the structural response of the blade. The finite element representation of the blade has approximately 6k 4-node reduced integration shell elements (S4R). In order to determine the appropriate number of structural modes to employ in the FSI model, a single study was performed repeatedly with an increasing number of modes ; the final coupled analysis employs the first four natural vibration modes of the structure.

To validate the calculated modal shapes and frequencies, a 1D Scanning Laser Doppler Vibrometer was used to capture the natural frequencies and vibration shapes of the experimental blade. The numerically calculated mode shapes and frequencies of the first four modes are compared to the experimental values in Figure 1. High correlation was found in the mode shapes and frequencies.

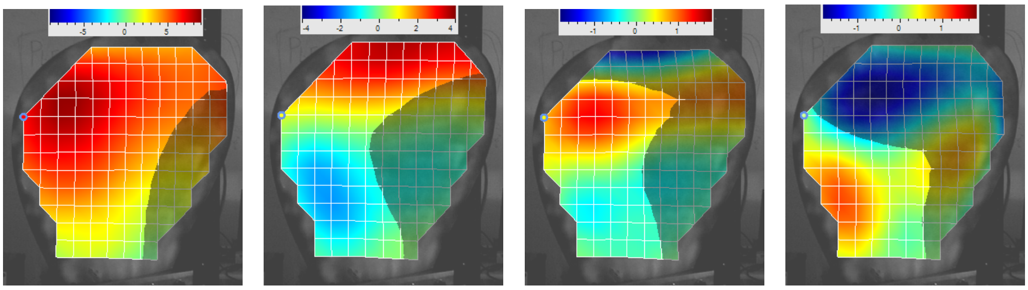
# 4 Results and Discussion

Due to the lack of blade rotation, this test setup is closer to a highly twisted hydrofoil rather than a true propeller blade, causing flow detachment at various locations along the blade depending on the operating condition. In this study, the angle of attack $\alpha = 0°$ is defined as the orientation that produces zero lift. Figure 2 shows the results of the dynamic analysis for $\alpha = 4°$ at an inflow speed of $V = 4m/s$. In Figure 2(a), the coefficients of lift and drag along with the maximum displacement are shown over a period of 0.5 s. The data exhibit a strongly periodic behavior due to partial vortex shedding.

In Figure 2(b), the variation of each modal contribution is shown over the same time span. The main forcing frequency due to the dynamic loading is apparent, as well as the higher frequency vibrations in the higher modes. Please note the difference in scale between the variations in the first mode and the higher modes ; the range of variation in the first mode is an order of magnitude higher than the others. Though the mean value for the second mode amplitude is higher than the first, the contribution from the first mode ends up defining a large majority of the deformation due to the hydrodynamic excitation evidenced by

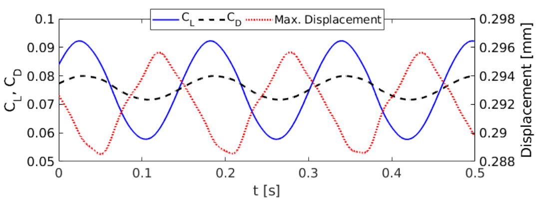


(a) Mode 1, $\omega_1 = 60Hz$ (b) Mode 2, $\omega_2 = 97Hz$ (c) Mode 3, $\omega_3 = 164Hz$ (d) Mode 4, $\omega_4 = 210Hz$

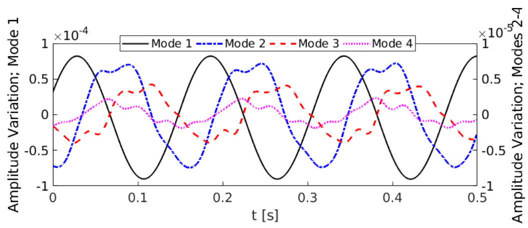


(e) Mode 1, $\omega_1 = 56Hz$ (f) Mode 2, $\omega_2 = 99Hz$ (g) Mode 3, $\omega_3 = 154Hz$ (h) Mode 4, $\omega_4 = 186Hz$

FIGURE 1 – Numerical (top) and experimental (bottom) mode shapes and frequencies shown from the suction side and shaded by relative displacement magnitude. The gray region on experimental figures is an artifact of the laser alignment and is not significant to the results.




(a) Coefficients of lift and drag, maximum displacement



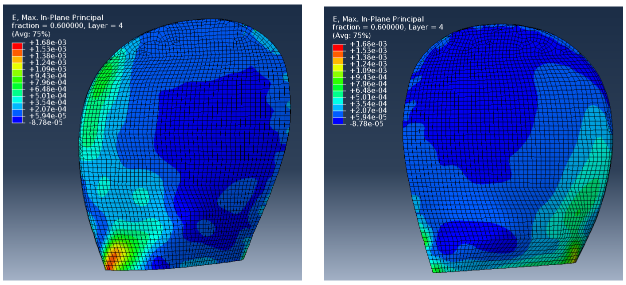

(b) Modal amplitude variation

FIGURE 2 – Results of dynamic analysis for $\alpha = 4°$, $V = 4m/s$.

the fluctuation in the lift coefficient. Moreover, the added mass effect reduces the first natural frequency to a value near the vortex shedding frequency, suggesting a possible interaction between the flow and the first mode.

Overall, the magnitude of the calculated deformation indicates that it will be possible to capture the changes in shape with the optical fiber system. It is also possible to examine the strains at the level of the optical fibers, between the fourth and fifth (outermost) plies of the composite layup, as shown in Figure 3. Although the deformation at the blade root is not large, there is a significant strain concentration at the leading edge of the root and, to a lesser extent, along the trailing edge at this level in the material. This shows the importance of a full structural analysis before the implementation of the optical fiber sensors ; it is necessary to place the fibers such that it is possible to capture the strain concentrations without subjecting the fibers to excess loading.

Despite their advantages, advanced composite propellers are complex and their behavior is difficult to characterize. In order to fully optimize the performance and control of these blades, a detailed understanding of the dynamic coupling between the hydroelastic response of a composite blade and the surrounding flow under a wide variety of operating conditions is required. In the future, experimental studies



(a) Suction side (b) Pressure side

FIGURE 3 – Instantaneous strain at the ply level of the optical fibers at 12° and 4 m/s.

will be executed to validate and expand on the FSI calculations presented in this work. Optical fibers with an array of fiber Bragg gratings will be used for strain measurement and damage detection, and forces, moments, and vibrations will be captured at the blade root. These data will be used to asses the ability of the optical fiber to evaluate the static and dynamic response of the blade submitted to hydrodynamic flow.

# 5 Acknowledgments

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