INFLUENCE OF UNCERTAINTIES ON THE RELIABILITY OF SELF-ADAPTIVE COMPOSITE ROTOR

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1 Introduction

Composite marine structures are attractive because of their ability to conserve weight, reduce maintenance cost, and to improve hydrodynamic and structural performance via 3-D passive hydroelastic tailoring of the load-dependent deformations. As shown in [1-3], a self-adaptive composite rotor can be tailored such that the blades passively adjust its morphology according to dynamic changes in load, resulting in improved performance over a typical fixed-geometry rotor. However, self-adaptive composite structures may be more susceptible to changes in material, geometry, and operating conditions due to the complex manufacturing process of composite materials, the dependence of the response on fluid-structure interaction, and the complex material failure mechanisms.

For composite materials, in addition to the anisotropic nature of the material and generally larger variations in material failure strengths than metallic materials, the failure modes are complicated as there are multiple failure modes including fiber, matrix, shear pull-out, and delamination failure. In general, for composite propeller blades in flexure, the dominant failure mode is matrix tensile cracking and delamination. There are many different failure models for composite structures and selection of an appropriate model is not trivial. This is clear from a review of the literature in which there are over 100 models for failure initiation for composite materials and that there exists no one universal model that works for all loading scenarios, specimen sizes, and configurations [4-6]. A series of matrix tensile and delamination failure initiation criteria were previously applied by the authors [7] and it was found that the Cuntze [8] matrix tensile failure and Ochoa-Englbom [9] delamination initiation criterion provide the most conservative estimates. The objective of this research is to investigate the effects of material, geometry, and loading uncertainties on the response and overall system reliability of self-adaptive composite marine propellers. Results are shown for a pair of carbon fiber reinforced polymer (CFRP) propellers optimized for a twin-shafted naval combatant. However, the methodology and results shown herein are applicable for any structure that operates in a dynamic loading environment, especially those that are designed to interact with the flow.

2 Numerical Formulation

A previously developed, fully-coupled, 3-D boundary element method-finite element method (BEM-FEM) is used to analyze the propeller performance. The 3-D BEM-FEM method is able to consider the effects of nonlinear geometric coupling, fluid-structure interactions (FSI), spatially varying flows, transient fluid sheet cavitation, material anisotropy, as well as potential material and hydroelastic instability failures. The fluid behavior is assumed to be governed by the incompressible potential flow equations in a blade-fixed rotating coordinate system. The total fluid velocity is decomposed into an effective inflow velocity that accounts for vortical interactions between the propeller and the inflow, and a perturbation potential velocity caused by the presence of the propeller that is assumed to be incompressible, inviscid, and irrotational.

The total hydrodynamic pressure and perturbation velocity potential are decomposed into components associated with rigid blade rotation and elastic blade deformation to consider FSI effects. The solid equation of motion is modified to include the spatially and temporally varying added mass and hydrodynamic damping matrices. The commercial

FEM solver, ABAQUS/Standard (ABAQUS 2005), is used to solve the modified dynamic equation of motion via user-defined hydroelastic elements and subroutines. Additional details of the formulation, numerical implementation, and validation studies can be found in [10-14].

3 Modeling Material Strength Uncertainties

For each of the reliability analyses herein, a series of detailed stress analyses of the adaptive CFRP propeller (shown in Figure 1) was performed over its probabilistic operational space. The propeller operating condition depends on the vessel resistance, and is expressed as a function of the advance speed, V_a, and sea state, SS. The effects of propeller-hull interactions were considered by applying appropriate thrust deduction and wake fraction parameters (see [7,15] for details). The resulting probabilistic operational space of the propeller, shown as contours in Figures 2 and 3, represents the probability of operation, where the darker areas correspond to more probable regions of operation.

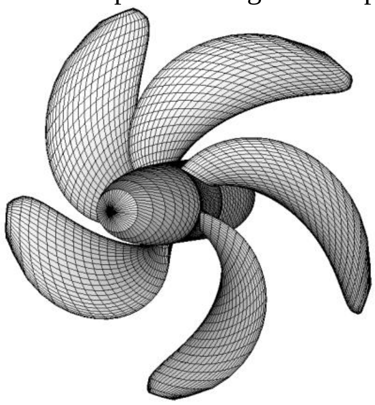

Figure 1: Optimized adaptive propeller geometry.

Parameter	Mean	Parameter	Mean
E_1	80.0 GPa	X_T	1950 MPa
E_2	10.0 GPa	X_C	1480 MPa
G_{12}	3.30 GPa	$Y_T = Z_T$	48 MPa
ν_{12}	0.32	$Y_C = Z_C$	200 MPa
ν_{23}	0.32	$S_{XY} = S_{XZ}$	79 MPa
ρ_s	2150 kg/m^3	S_{YZ}	50 MPa

Table 1: Summary of mean CFRP stiffness and strength parameters.

At each point in the probabilistic operational space, 10,000 Monte Carlo simulations of the failure initiation models with variable strength parameters were conducted. A summary of the mean material parameters is shown in Table 1.

Each strength parameter was given a Gaussian distribution with a coefficient of variation $\sigma/\mu=0.15$ (σ = standard deviation, μ = mean). For each failure simulation, the percentage of the overall blade where failure has initiated was determined, which allows the probability of exceeding a specific level of blade failure initiation to be estimated. For the purposes of this research, blade failure is considered to occur when material failure has initiated in more than 0.05% of the blade. This is because the current structural model assumes fixed boundary conditions at the root of the blade, which tends to overestimate the stresses near the blade leading edge and trailing edge at the root region due to stress concentrations. An estimate of the total probability of failure, $(P_f)_{total}$ and corresponding propeller reliability, R, can be determined as:

$$R = 1 - \left(P_f\right)_{total} = 1 - \int_{SS}\int_{V_a} \left[P_f(V_a, SS) f(V_a, SS)\right] dV_a\, dSS$$

4 Stiffness, Geometric, and Material Strength Effects on Structural Reliability

A composite propeller blade can consist of tens to hundreds of laminate layers, which is very computationally expensive to analyze if a detailed probabilistic hydroelastic analysis is needed across the entire operational space. The varying fiber orientations within each laminate layer contribute directly to the overall stiffness distribution and related bend-twist coupling characteristics of the adaptive blades. It has been shown, however, that a multilayer composite laminate can be modeled using an equivalent unidirectional fiber angle, θ_{eq}, which results in approximately the same load-deformation characteristics [13]. The 10-layer optimized laminate stacking sequence of $[15^o/30^o/-15^o/0^o/-30^o]_s$ was found to correspond to $\theta_{eq}=5.0^o$. Since θ_{eq} is directly a function of both the laminar fiber angle and the corresponding material constituent properties, variability in both laminar fiber angles and material stiffness parameters can be represented through variability in θ_{eq}.

To demonstrate, a Monte Carlo analysis of θ_{eq} was performed by considering random variations in laminate fiber angles and stiffness parameters. Each parameter and fiber angle was given a Gaussian distribution, with coefficients of variation of σ/μ = 0.10 for the stiffness parameters shown in Table 1, and $\sigma/\mu = 1^o$ for the laminate fiber angles for each of the ten layers. The resulting distribution of θ_{eq} has a range of 3.0^o-7.0^o. It should be noted that in general, a higher θ_{eq} corresponds to a more flexible blade, and a lower θ_{eq} corresponds to a stiffer blade, in bending along the spanwise direction.

To quantify the effects of stiffness, geometric, and material strength variability on the structural reliability and safe operating envelopes, the response of the adaptive propeller blades with $\theta_{eq}=3.0^o$, 5.0^o, and 7.0^o and $\phi_{tip}=26.0^o\pm0.5^o$ (undeformed or unloaded tip pitch angle of the adaptive blades) are analyzed. Estimates of the safe operating envelopes based on probability of failure initiation, $P_f(V_a,SS)$, of 0.1% and 1.0% from the Monte Carlo analysis are shown in Figures 2 and 3 within the probabilistic operational space described in Section 3. Only the matrix tensile failure boundaries are shown because that was the dominant failure mode.

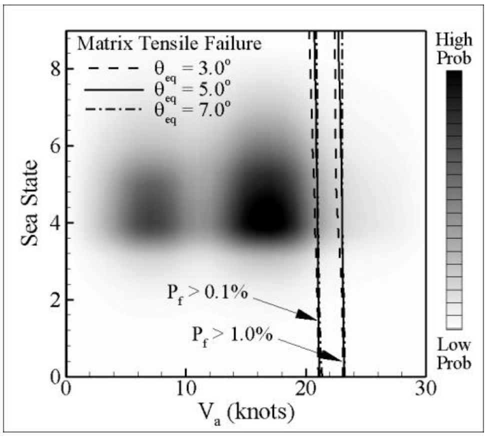

Figure 2: Safe operating boundaries corresponding to P_f=0.1% and P_f=1.0%for adaptive propeller blades with $\theta_{eq}=3.0^o$, 5.0^o, and 7.0^o within the probabilistic operational space.

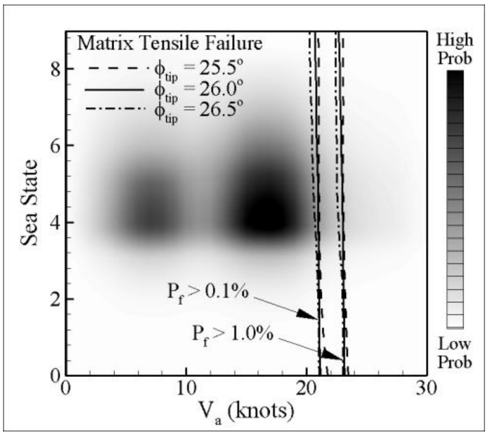

Figure 3: Safe operating boundaries corresponding to P_f=0.1% and P_f=1.0% for adaptive propeller blades with $\phi_{tip}=26.0^o\pm0.5^o$ (right) within the probabilistic operational space.

It is clear that both changes in θ_{eq} and ϕ_{tip} have a small effect on the safe operating envelopes. The stiffer blade ($\theta_{eq}=3.0^o$) shows a slightly higher susceptibility to failure initiation, which would be expected as a stiffer blade will result in a higher deformed (or loaded) pitch angle distribution, which produces higher loads and stresses. For similar reasons, the blade with higher unloaded ϕ_{tip} shows slightly higher susceptibility to failure initiation. The resulting reliability against matrix tensile failure initiation is approximately R=98.0% for all three material configurations and all three blade geometries, suggesting uncertainties in material stiffness and geometric parameters have a negligible effect on overall system reliability against material failure initiation when compared with uncertainties in material strength parameters.

5 Structural Reliability Estimates

Because of the use of the effective unidirectional fiber angle, θ_{eq}, the material failure initiation limits shown in Figures 2 and 3 may be slightly overestimated although the general trend has been found to be similar. By using a more realistic multilayer laminate stacking sequence, the stress patterns and resulting failure initiation indicators will change. Figure 4 shows a comparison of the matrix tensile failure initiation indicators for the multilayer and unidirectional models. The failure indicators for the multilayer model are higher because the individual lamina, in general, have higher fiber angles than θ_{eq}, i.e. weaker in bending because the axis of the fibers deviates further from the bending axis of the blade.

An analysis on the actual multilayer laminate layup sequence is shown in Figure 5. It is evident that the boundaries for $P_f(V_a,SS)$ = 0.1% and 1.0% of matrix tension failure having initiated on over 0.05% of blade elements have shifted approximately 1.0-1.5 knots by incorporating the 10-layer laminate stacking sequence. The reliabilities were found to be 97.6% against matrix tension failure initiation, a slightly lower reliability estimate than the unidirectional model provided.

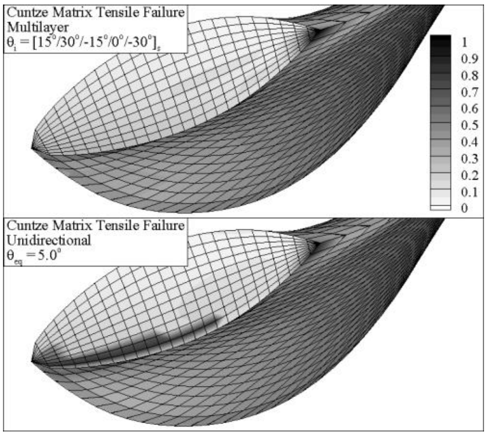

Figure 4: Comparison of matrix tensile failure initiation between the multilayer and unidirectional models at the blade's root.

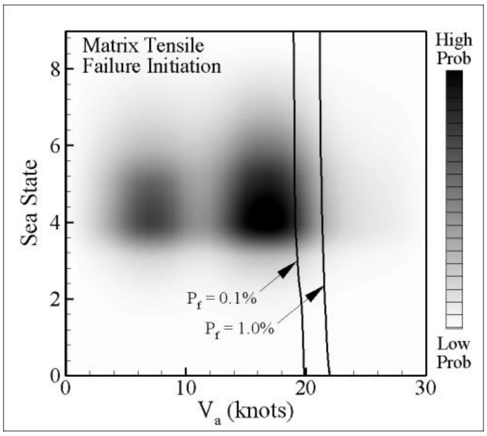

Figure 5: Safe operating boundaries corresponding to P_f=0.1% and P_f=1.0% for adaptive propeller blades with multilayer stacking sequence $\theta_n=[15^o/30^o/-15^o/0^o/-30^o]_s$ within the probabilistic operational space.

6 Effects of Strength and Stiffness Degradation on Structural Reliability

For a complete reliability analysis, considerations must be made for changes to the safe operating envelope at various stages of the propeller life. It is well understood that the strength and stiffness of composite materials degrade over time. As the number of operating cycles, n, increases, the strength and stiffness of the material decreases until ultimate material failure at cycle N. There are many different models for fatigue of composites depending on the material composition, stacking sequence, and loading. While finding an appropriate estimate of the fatigue life of a structure can be very challenging when considering the extent of modeling, loading, and material uncertainties that have been discussed ~~in~~ herein, it can be beneficial to consider the effects of stiffness and strength degradation and their impact on the probability of failure initiation in the blades. The linear residual strength model applied to the adaptive blades is shown in Figure 6. In addition to degradation of the mean material strength parameters, there is an increasing coefficient of variation of $(\sigma/\mu)_{residual}$ to account for increased variability due to load sequence effects and failure mode interactions [16-18].

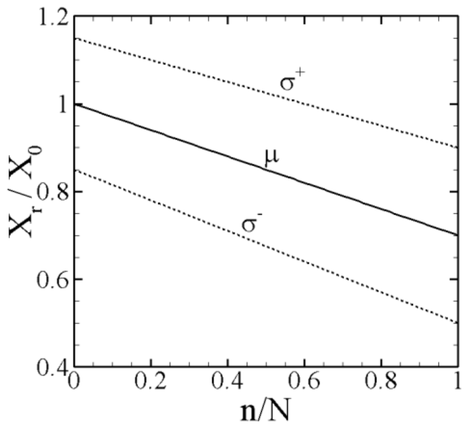

Figure 6: Linear residual strength model applied for analysis of strength degradation effects on structural reliability.

Figure 7 shows similar boundaries for potential safe operating envelopes corresponding to $P_f(V_a,SS)$=0.1% against matrix tensile failure initiation for a case where the residual strength parameters of the blade vary from 80-100% of the static strength parameters. As a result of the reduced strengths, there is a notable shift in the safe operating envelopes. The result is that the structural reliability is reduced from 97.6% to 93.3% against matrix tensile failure initiation over time, as shown in Figure 8.

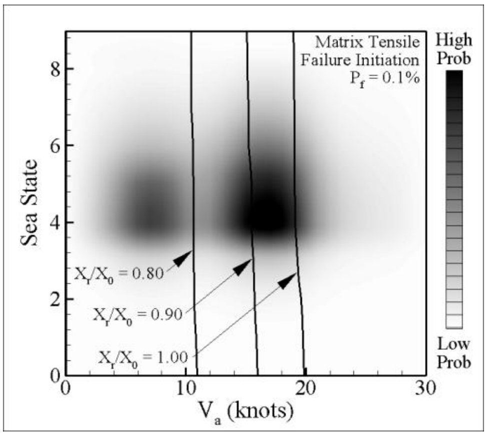

Figure 7: Change in safe operating boundaries corresponding to probability of matrix tensile failure initiation of 0.1% for adaptive propeller blades as a result of strength degradation.

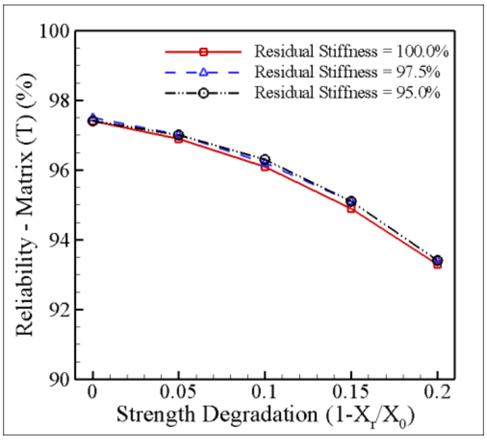

Figure 8: Structural reliability estimates against matrix tensile failure initiation as a function of reduced material strength and stiffness.

Additional analyses were performed for degraded stiffness. In general, stiffness degradation is not as severe as strength degradation and thus the analysis was performed for 97.5% and 95.0% of the static material stiffness. The reduced stiffness was found to have a negligible effect on structural reliability and safe operating envelopes. Structural reliabilities increased by approximately 0.1-0.2% due to the increased flexibility that resulted in stress alleviation in the blades.

7 Summary

This paper aims to quantify the effects of material, geometric, and loading uncertainties on the overall structural reliability of self-adaptive composite propellers within a probabilistic operational space. The probabilistic operational space was developed using probabilistic estimates of the expected ship speed and sea states. Applying assumed random variations in geometric, stiffness, and strength parameters, structural reliability and safe operating envelopes are estimated for a previously optimized adaptive composite propeller. It was shown that the effects of material strength variability were much more critical to the reliability of the blades than geometric and stiffness variability. The probability of blade failure was obtained across the probabilistic operational space, and estimates of the safe operating limits and the blade reliability were obtained for both the static strength and the residual strength due to material degradation. Stiffness degradation was found to have a negligible effect on structural reliability.

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