AEROELASTIC MODELLING AND ANALYSIS OF CURVED COMPOSITE PROPELLER BLADES

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ABSTRACT

Propellers are a promising option for future sustainable aviation, as they can achieve higher potential propulsive efficiency than ducted fans for a given thrust requirement due to their ability to operate at larger diameters without incurring significant nacelle drag and weight penalties. The main challenge for propeller-driven aircraft is to reduce noise while maintaining high efficiency. Unlike turbofans, propellers lack a nacelle with acoustic liners, so noise reduction relies on optimization of blade geometry and operating conditions. Modern propeller designs therefore feature advanced sweep and lean distributions. Sweep is used to enhance both aerodynamic and acoustic performance by reducing aerodynamic losses associated with shock wave formation and inducing destructive interference in noise signals. Lean, in turn, is introduced to alleviate the structural stresses that arise in swept blades. Additionally, for curved blades, structural flexibility can significantly expand the operational efficiency envelope [1].

This work contributes to the state of the art in the field of aeroelastic propeller modelling and analysis. An aeroelastic analysis tool for composite propeller blades with sweep and lean is developed, based on a low-fidelity aerodynamic model tightly coupled to a structural model. This tool is used to study the effect of sweep and lean on the aerodynamic performance and structural response of composite propeller blades. Furthermore, it is developed to be suitable for future propeller design optimization.

The aerodynamic loads are computed using blade element momentum (BEM) theory developed in [2], which does not inherently account for sweep and lean. Therefore, a correction for sweep is applied to the BEM model, as it changes the orientation of the airfoils relative to the blade's rotational velocity. On the other hand, no correction is needed for lean, because it does not affect the airfoil orientation with respect to either the freestream or the rotational velocity. The aerodynamic model was validated against experimental data from [3] for two baseline propellers, the unswept TUD-XPROP and the swept TUD-XPROP-Λ, as shown in Fig. 1. While BEM tends to overestimate the aerodynamic performance of these blades, it accurately captures the trends in thrust as well as the sensitivity of thrust and efficiency to sweep. Additionally, both the experimental measurements and the BEM results indicated that, for the low freestream Mach number of M=0.12 and modest sweep amplitude of TUD-XPROP-Λ, the effects of sweep and lean on aerodynamic performance are limited.

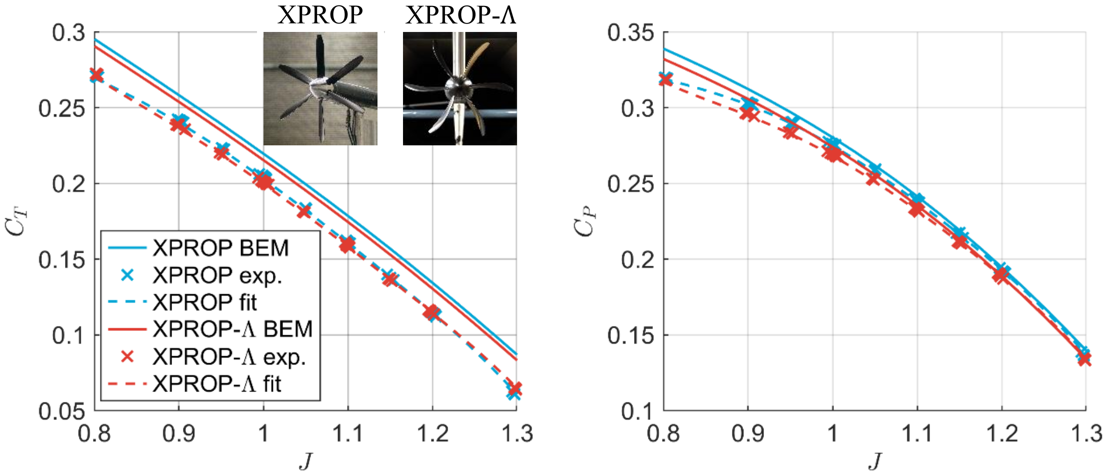


Figure 1: Comparison of the aerodynamic performance predicted by the extended BEM model and the experimental data for the TUD-XPROP and TUD-XPROP- Λ propellers, including a third-order polynomial fit to the experimental data points.

Aeroelastic analysis is performed using PROTEUS, developed by TU Delft in [4, 5]. Within this tool, the BEM model is tightly coupled to the structural model through sensitivities of the aerodynamic, centrifugal, and structural loads with respect to structural deformations. These aerodynamic sensitivities of the extended BEM model are analytically derived in this work to reduce computational cost. For example, according to the blade element theory, the derivative of the aerodynamic loads with respect to twist deformation of the blade is given by Eq. (1),

$$\frac{d}{d\beta}\begin{bmatrix}\overrightarrow{f_a}\\ \overrightarrow{m_a}\end{bmatrix} = q_\infty S \frac{d}{d\beta}[C_x \ \ 0 \ \ C_z \ \ 0 \ \ C_m c \ \ 0]^T \tag{1}$$

where β is the local twist angle, $\overrightarrow{f_a}$ and $\overrightarrow{m_a}$ are the aerodynamic forces and moments, q_∞ is the freestream dynamic pressure, S is the blade element planform area, C_x and $C_z$are the tangential and axial force coefficients, C_m is the moment coefficient, and c is the local chord length. Aerodynamic sensitivities with respect to other degrees of freedom are also included in the tight coupling, such as sensitivities to the blade's in-plane and out-of-plane bending.

All relevant sensitivities were validated. However, for the sake of brevity, only the validation of the sensitivity of the tangential force coefficient with respect to twist deformation, $dC_x/d\beta$, which appears in Eq. (1), is shown in Fig. 2. The figure presents the spanwise distributions of analytically and numerically computed results for three advance ratios, along with a contour plot of their absolute differences. For the numerical differentiation, central differencing was applied. With absolute differences roughly two orders of magnitude smaller than the magnitude of the sensitivities, the results show close agreement, which confirms that the analytical expressions accurately capture the aerodynamic sensitivities. Finally, compared to the loosely coupled method, which computes aerodynamic and structural loads iteratively, this tightly coupled approach reduced the computational time of the aeroelastic analysis by approximately 30%.

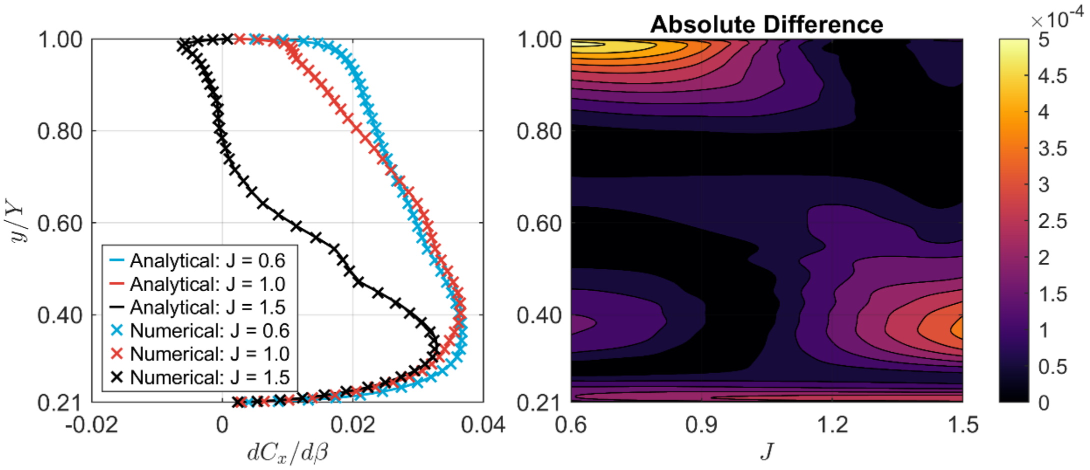
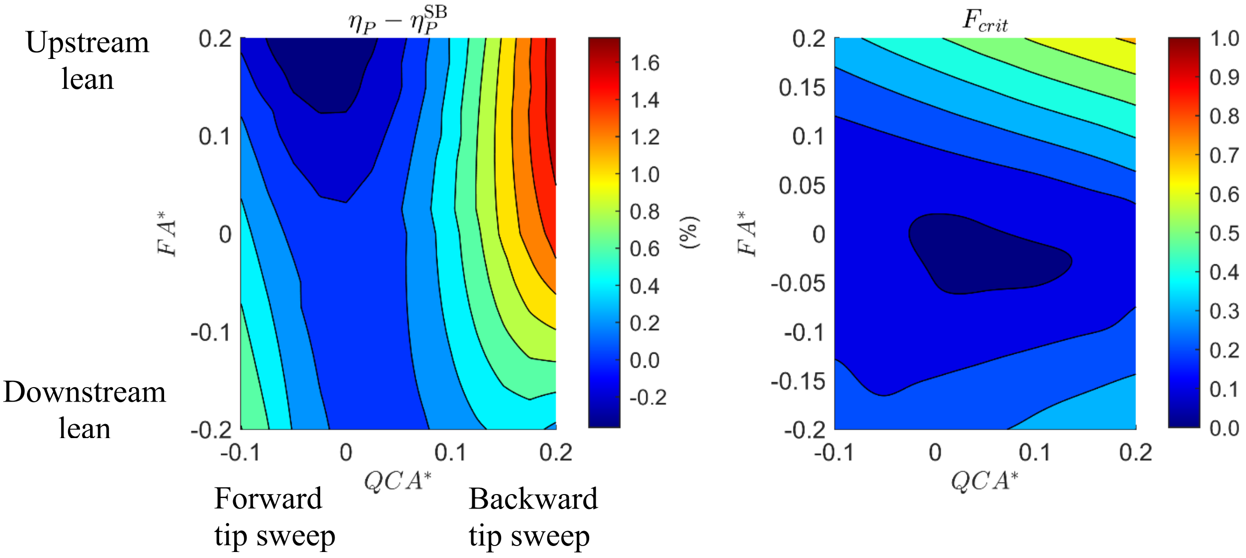


Figure 2: Comparison between analytically and numerically computed sensitivities of the tangential force coefficient with respect to twist deformation for TUD-XPROP- Λ.

The developed analysis tool was applied in a parameter study to investigate the effects of sweep and lean on the aerodynamic performance and structural response of flexible propeller blades. Sweep distributions were obtained by scaling the sweep distribution of the baseline TUD-XPROP-Λ propeller blade (see Fig. 1), which is forward-swept at the root and backward-swept at the tip, while the lean distributions were defined to increase monotonically in the up- or downstream direction.

Flexible blades were first compared to rigid counterparts under a constant pitch setting to assess the effect of structural flexibility on the aerodynamic performance across a range of blade geometries. The results indicated that while flexibility affects the thrust and power coefficients, it has a minimal impact on peak aerodynamic efficiency, with differences typically within ±0.3%. Next, the aerodynamic performance of flexible curved blades was compared to that of the straight blade under constant thrust coefficient, which ensures each propeller is compared under the same disk loading. This condition was achieved by varying the pitch setting. Blades combining backward sweep with upstream lean achieved the highest efficiency, as shown in Fig. 3a, with gains up to 1.7%.

Finally, the blades' structural response was assessed under constant thrust in terms of the Tsai-Wu failure index and root bending moments. An example is given in Fig. 3b, which shows the maximum value of the Tsai-Wu failure index for the top skin laminate of each blade configuration, indicating that blades with backward sweep and upstream lean experience most stress. The root bending moment was dominated by out-of-plane bending. It was found that applying upstream lean can significantly reduce this bending moment by changing the spanwise distribution of the centrifugal loads, while the aerodynamic loading distribution remains nearly unchanged. This allows the loads to cancel each other out, which results in a more favourable root bending moment at the propeller hub.



(a) Aerodynamic efficiency compared to the straight blade (SB).

(b) Maximum value of the Tsai-Wu failure index for the top skin laminate.

Figure 3: Contour plots of aerodynamic efficiency and the Tsai-Wu failure index, with sweep on the horizontal axes and lean on the vertical axes.

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