AN INTEGRATED FRAMEWORK FOR AEROELASTIC RESPONSE ANALYSIS OF PROPELLER-WING SYSTEMS

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ABSTRACT

The integration of high-performance propulsion systems with flexible wing structures presents a significant challenge in modern aircraft design, particularly for propeller-driven aircraft. Unlike conventional fixed-wing configurations, propeller-wing systems operate in a highly complex aerodynamic environment characterized by intense slipstream interference and unsteady wake interactions. With the increasing adoption of high-aspect-ratio designs and lightweight composite materials, the aeroelastic coupling between the propeller and the wing has become increasingly pronounced.

Accurate load analysis in these configurations must be conducted within an integrated aeroelastic framework that accounts for fluid-structure interaction (FSI), involving the periodic aerodynamic loads generated by the propeller and the elastic deformations of the wing. Therefore, developing robust time-domain aeroelastic response models is crucial for the safe expansion of flight envelopes and the optimization of next-generation aircraft.

This article develops an integrated and robust time-domain simulation framework that utilizes the Unsteady Vortex Lattice Method (UVLM) coupled with structural dynamics models. This framework captures the unsteady aerodynamic interferences between the propeller and the wing while accounting for the follower force effects of the propeller. This research provides a comprehensive analysis of the aeroelastic behavior of a propeller-wing configuration and identifies the key mechanisms of the system's aeroelastic response. These insights provide critical engineering guidance for the design of next-generation propeller aircraft, emphasizing the necessity of detailed aeroelastic analysis for these systems.

The aerodynamic and structural meshes of the wing are modeled in a global frame of reference located at the wing root. To account for the time-varying orientation of the propeller's aerodynamic loads resulting from wing deformation, a local reference frame is established at the hub that tracks the elastic motion of the wing. Furthermore, a rotating blade frame is defined for each propeller blade, rotating at the operational angular velocity relative to the hub frame.

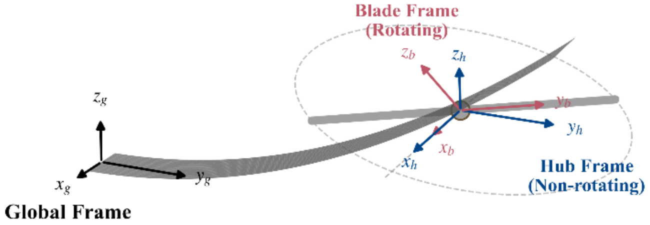

Fig. 1. Frame of reference.

Consequently, the position of an arbitrary point on the propeller can be transformed from the rotating blade frame to the global reference frame using the following relationship:

$$\vec{P} = L_2 \cdot (R_{wing} \cdot (L_1 \cdot \vec{P}_{local}) + \vec{O}_{hub}) \tag{1}$$

The aerodynamic forces of the propeller and wing are solved simultaneously through UVLM, thereby inherently capturing the aerodynamic interactions between the two components. Specifically, the Neumann boundary condition incorporates the total velocity field, which accounts for the mutual influence of the wing, the propeller, and their respective wakes:

$$\mathbf{K\Gamma} = \mathbf{RHS} \tag{2}$$

By projecting the physical displacements onto the orthogonal modal basis, the governing equations of motion are decoupled into a set of independent second-order ordinary differential equations (ODEs):

$$\ddot{q}(t) + 2\zeta\omega_n\dot{q}(t) + \omega_n^2 q(t) = Q(t) \tag{3}$$

It is noteworthy that the generalized force vector $Q(t)$ incorporates not only the instantaneous distributed aerodynamic loads acting on the wing but also the follower loads generated by the propeller.

Surface spline interpolation is applied to couple the aerodynamics and structure, ensuring consistent transfer of deformations and loads between the two domains.

$$\begin{aligned} \mathbf{U}_A &= \mathbf{G}\mathbf{U}_S \\ \mathbf{F}_S &= \mathbf{G}^T\mathbf{F}_A \end{aligned} \tag{4}$$

The computational model comprises a flat rectangular wing with no spanwise twist. The wing profile employs a NACA0015 airfoil with a span of 1675 mm, a chord length of 300 mm, and an installation angle of 0°. The propulsion system consists of a two-bladed rigid propeller model positioned at 1308.5 mm along the wingspan. The aeroelastic response is simulated at an inflow velocity of 19 m/s, an angle of attack (AOA) of 2° relative to the wing chord line, and a propeller rotation speed of 8000 rpm.

As demonstrated by the vertical wing-tip displacement (Fig. 2), the response is dominated by the first bending mode of the wing, and the peak frequency (2.33Hz) in the FFT results is higher than the first structural natural frequency (2.19Hz).

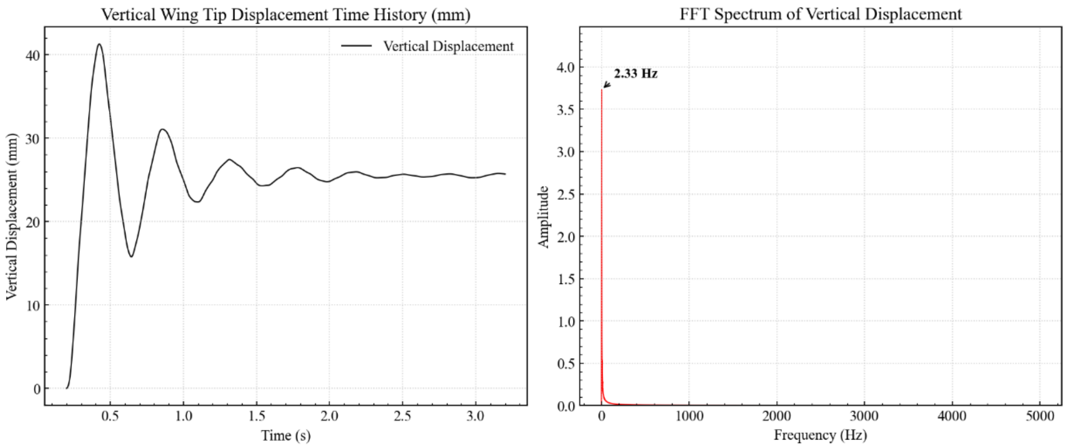

Fig. 2. Time history of vertical wing tip displacement and FFT result.

The time history of wing lift and the corresponding FFT results are shown in Fig. 3. The response is also dominated by the first bending mode. Critically, the propeller 2-P frequency (266.67 Hz) and higher-order harmonics are successfully captured in the wing lift response.

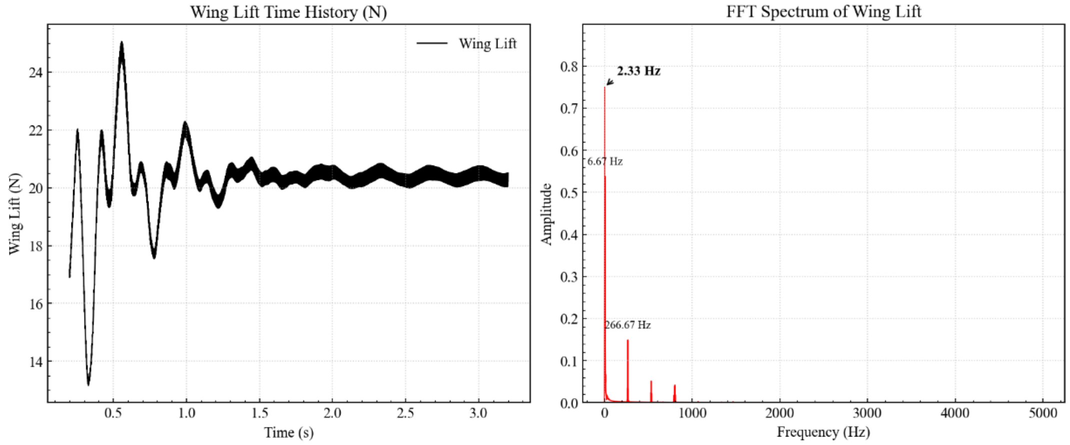

Fig. 3. Time history of wing lift and FFT result.

The lift distribution during the last two propeller revolutions is shown in Fig. 4, highlighting the periodic aerodynamic influence of the propeller on the wing.

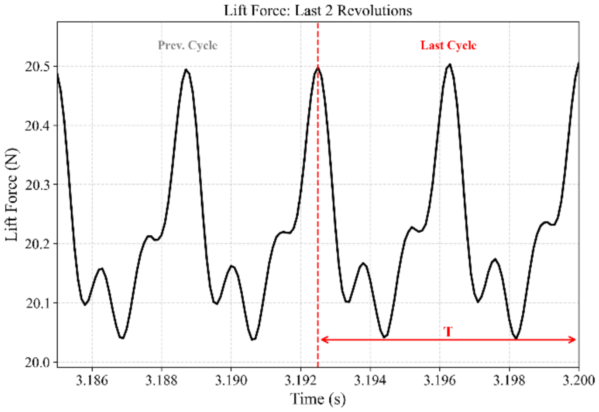

Fig. 4. Wing lift in the last two propeller revolutions.

This research contributes to the field by providing a comprehensive aeroelastic dynamic analysis framework that accounts for the unsteady aerodynamic interactions inherent in integrated propeller-wing systems. The findings not only offer deeper insights into the fundamental physics of aeroelastic coupling but also provide critical engineering guidance for accurate load analysis in advanced aerial platforms. The full manuscript will present extensive parametric studies and sensitivity analyses, focusing on the azimuthal thrust distribution across blade sections and the spanwise distribution of sectional lift, among other key aeroelastic response characteristics.