Aeroelastic Analysis of a Flexible Wing with Distributed Electric Propellers

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4 authors:

Samet Talha Dede
University of Bristol

Ali Tatar
Istanbul Technical University

Djamel Rezgui
University of Bristol

Jonathan Cooper
University of Bristol

Aeroelastic Analysis of a Flexible Wing with Distributed Electric Propellers

Samet T. Dede *, Ali Tatar†, Djamel Rezgui‡, Jonathan E. Cooper§
School of Civil, Aerospace and Design Engineering
University of Bristol, Bristol, BS8 1TR, United Kingdom

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The pursuit of net-zero commercial aviation is driving advancements in alternative propulsion technologies, such as Distributed Electric Propulsion (DEP), which utilises multiple small engines distributed along the wing span. While DEP offers significant potential for emission reductions, it introduces aeroelastic challenges, including wing flutter and whirl flutter, which must be addressed early in the design process. This study presents the development of a low-order numerical aeroelastic model for the coupled rotor/wing systems. The developed model effectively captures the dynamic behaviour of a flexible cantilever wing equipped with multiple flexibly mounted propellers. Validation against existing literature confirms the model's accuracy in predicting both wing flutter and whirl flutter. Parametric studies reveal that the number and spanwise positions of propellers significantly influence aeroelastic instabilities. The obtained results highlight the importance of optimizing propeller/rotor configurations and stiffness to mitigate flutter risks in DEP wing designs. This work provides a valuable tool for early-stage design and analysis of next-generation, emission-reducing aircraft.

I. Introduction

To reduce in-flight emissions in commercial aviation, hybrid and fully electric aircraft with Distributed Electric Propulsion (DEP) systems have gained significant attention [1], [2]. DEP configurations utilize multiple electric motors distributed over the wing to improve aerodynamic efficiency [3]. One such configuration is employed in NASA's X-57 Maxwell aircraft, as shown in Figure 1. However, these novel designs introduce aeroelastic instabilities, including whirl flutter driven by aerodynamic and gyroscopic propeller forces. Unlike classical wing flutter, whirl flutter can lead to dangerous spiral motions, necessitating early-stage aeroelastic analysis in DEP wing design.

*PhD Student, st.dede@bristol.ac.uk
†Assistant Professor, ali.tatar@bristol.ac.uk
‡Associate Professor, djamel.rezgui@bristol.ac.uk
§Professor, j.e.cooper@bristol.ac.uk

Figure 1: NASA X-57 Maxwell [4]

While classical wing flutter and propeller whirl flutter have been extensively studied [5]–[7], there remains a notable gap in understanding the aeroelastic behaviour of flexible wings equipped with distributed electric propulsion (DEP) systems. Existing studies have largely relied on high-fidelity finite element methods [8]–[12], but none have utilized the Rayleigh-Ritz approach to develop a low-order yet representative aeroelastic model for a flexible wing with flexibly mounted DEP systems. This creates a critical need for a computationally efficient methodology that captures both wing and whirl flutter phenomena while enabling rapid parametric studies. The present study addresses this gap by proposing a coupled wing-propeller model that incorporates flexible mounting dynamics, aerodynamic loads, and gyroscopic effects within a low-order framework suitable for early aeroelastic stability evaluation.

II. Methodoloy

This study focuses on developing a low-order coupled aeroelastic model in MATLAB to analyse flutter and whirl flutter instabilities in flexible wings equipped with distributed electric propellers. The structural dynamics of the wing are formulated using the assumed-mode Rayleigh-Ritz method, where bending and torsion deformations are represented through generalized coordinates. The aerodynamic forces acting on the wing are calculated by combining a modified strip theory with Theodorsen's unsteady aerodynamic theory. For the propeller dynamics, Reed's approach is employed to model a rotor-nacelle system with pitch and yaw degrees of freedom. Aerodynamic moments acting on the propeller hub are obtained through strip theory and gyroscopic effects are accounted for using a first-order state-space representation. The coupled aeroelastic system integrates the wing and propeller models through Lagrange's equations by including structural and aerodynamic coupling terms. The resulting equations of motion are expressed in matrix form and transformed into a state-space model for eigenvalue analysis. This approach enables the prediction of critical flutter and whirl flutter speeds, as well as the identification of instability modes. A series of parametric studies are conducted to evaluate the influence of the number and spanwise positions of the propellers on the aeroelastic behaviour of the coupled propeller-wing model. The proposed methodology allows rapid assessment of the impact of key design parameters on aeroelastic instabilities during the early design phases of DEP aircraft.

III. Numerical Analysis

A. Baseline Wing

The main parameters of the baseline wing from [9] are outlined in Table 1.

Table 1: Baseline wing parameters

Parameter	Value	SI unit
Wing span	11.4	m
Root chord	1.25	m
Tip chord	0.8	m
Mass per unit length	25	kg/m
Aerodynamic centre from leading edge	25% chord	-
Elastic axis from leading edge	50% chord	-
Centre of gravity from leading edge	50% chord	-
Radius of gyration about centre of gravity	25% chord	-
Bending rigidity	7×10^5	Nm^2
Torsional rigidity	2×10^5	Nm^2
Lift curve slope	2π	-
Density of air	0.96287	kg/m^3

B. Baseline Propeller

A baseline propeller from [9] is represented by two concentrated masses: Rotor mass and motor-nacelle mass. The main parameters of this cruise propeller used in the NASA X-57 Maxwell electric aircraft are summarized in Table 2.

Table 2: Baseline propeller parameters

Parameter	Value	SI unit
Number of blades	3	-
Rotor radius	0.762	m
Rotor mass	8	kg
Rotor position	1.16	m
Motor/nacelle mass	35	kg
Motor position	0.86	m
Blade chord	0.094	m
Advance ratio	1.96	-
Pitch/yaw frequency	7	Hz
Pitch/yaw damping coefficient	0.005	-

C. Coupled Wing-Propeller Model

The schematic of the coupled wing-propeller model from [9] considered in this study is illustrated in Figure 2. The propeller is installed at a spanwise location of 31 % from the wing root. The pivoting point of the propeller is located exactly on the elastic axis of the wing (the wing mid-chord axis). The propeller hub is situated 0.6 m from the leading edge, while the electric motor is positioned 0.3 m behind the propeller hub.

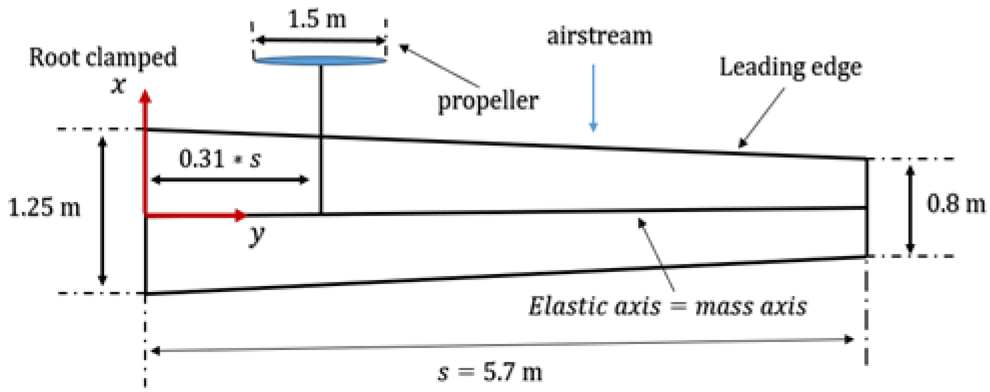
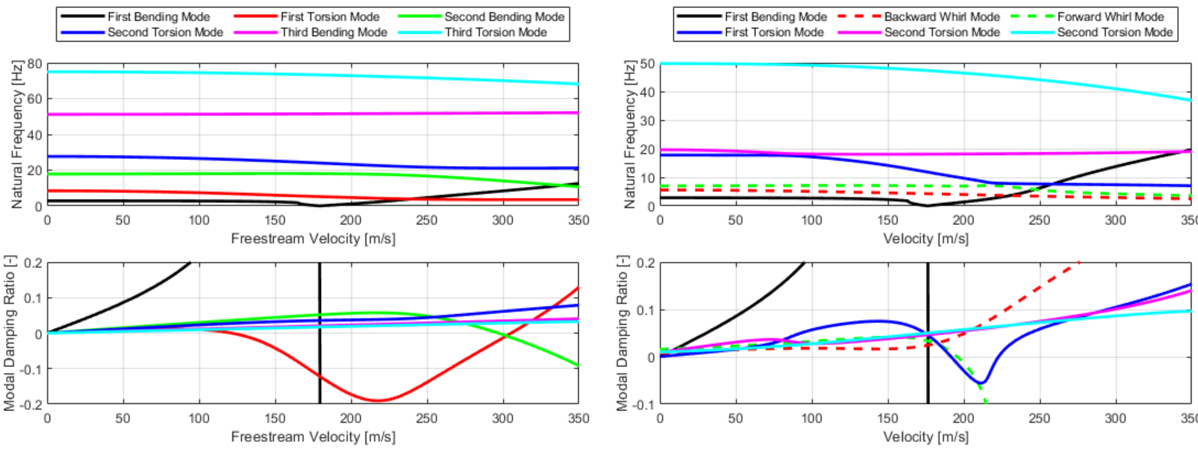


Figure 2: Schematic of the wing-propeller model

The velocity-damping and velocity-frequency curves of the propeller-wing model with both a rigidly mounted propeller and a flexibly mounted propeller are depicted in Figure 3.

Table 3: Aeroelastic results of the rigidly and flexibly-mounted propeller wings

Parameter	Rigid Mounts	Flexible Mounts
Wing Flutter Speed	125 m/s	193 m/s
Wing Flutter Frequency	6.74 Hz	10.29 Hz
Whirl Flutter Speed	-	197 m/s
Whirl Flutter Frequency	-	6.92 Hz



(a) Coupled model with rigid mounts

(b) Coupled model with flexible mounts

Figure 3: Variations of modal frequency and damping with freestream velocity for the coupled models

D. Parametric Studies

1. Investigation of Effect of Propeller Spanwise Position on Critical Instabilities of Coupled Model

The parametric study investigates the influence of the flexibly mounted propeller spanwise position on the aeroelastic stability of the coupled wing-propeller system. The critical flutter velocity exhibits significant variations depending on the propeller's location along the wing, as shown in Figure 4, with the lowest velocity defining the flutter boundary.

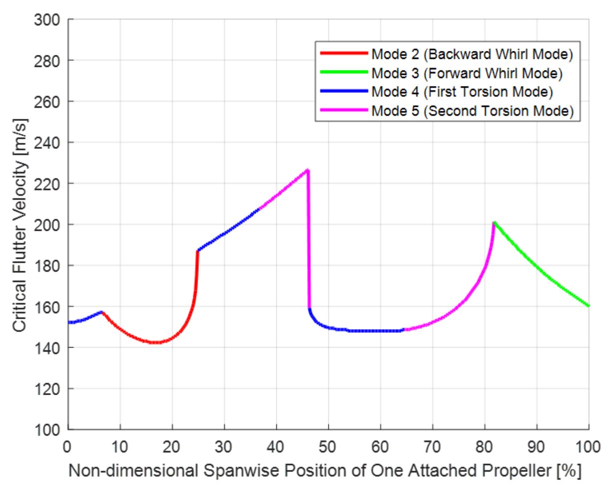
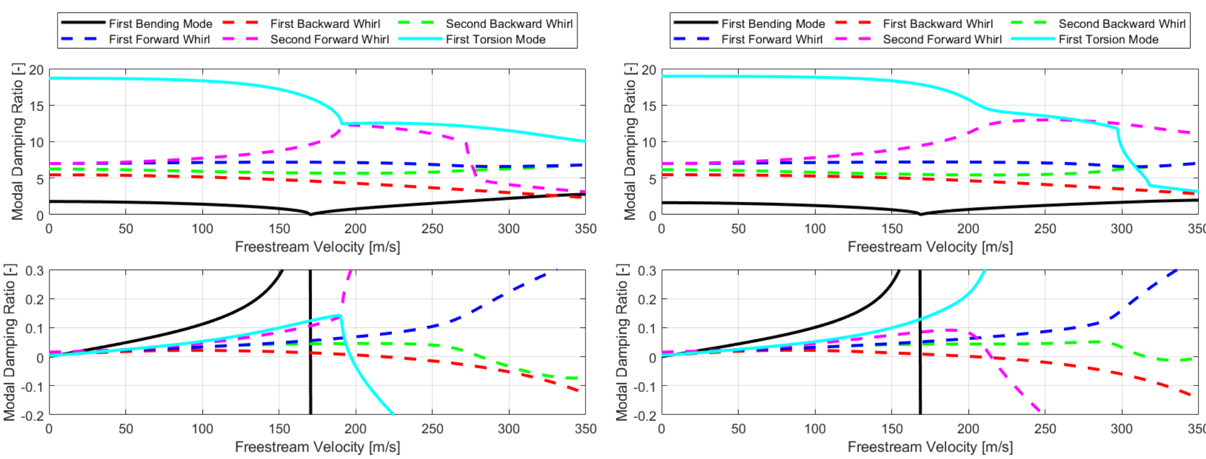


Figure 4: Flutter Velocities for the Coupled Model versus Spanwise Position of the Attached Propeller

Two notable dips in flutter speed are observed: the first (7%–25% span) is attributed to Mode 2, a backward whirl mode that stabilizes beyond 25% span, after which flutter is governed by Mode 4, a wing-dominated torsion mode. The second dip (47%–82% span) arises from the destabilization of Mode 5, a wing-bending dominant mode, which later restabilizes. Beyond 82% span, Mode 3, a forward whirl mode, becomes critical, further reducing flutter speed. While wing-dominated modes (Modes 4 and 5) control flutter between the two dips, propeller-dominated whirl flutter (Mode 3) dictates stability beyond the second dip. These transitions highlight the complex interplay between wing and propeller dynamics in determining aeroelastic behavior.

2. *Investigation of Effect of Two Attached Propellers on Critical Instabilities of Coupled Model*

In the second parametric study, two propellers are mounted on the wing. Both propellers are identical in model and parameters to the reference. One propeller is fixed at the wingtip, while the other is positioned at varying spanwise locations. The addition of the second propeller introduces two new modes. The critical flutter velocity changes depending on the movable propeller's position along the span, as shown in Figure 5.



(a) Wingtip and inboard propeller (31% Half-Span) **(b)** Wingtip and inboard propeller (70% Half-Span)

Figure 5: Variations of modal frequency and damping with freestream velocity for different coupled model configurations

IV. Conclusions

In this study, a low order coupled aeroelastic model has been developed to evaluate the dynamic stability of a flexible wing equipped with distributed electric propulsion (DEP) systems. The proposed model combines the structural dynamics of the wing, derived using the assumed-mode Rayleigh-Ritz method, with propeller dynamics based on Reed's approach, and unsteady aerodynamic loads calculated using a combination of modified strip theory and Theodorsen's theory. The formulation enables the capture of both classical wing flutter and whirl flutter phenomena, and is particularly well-suited for early-stage design assessments due to its computational efficiency.

Initial analyses were conducted for a standalone flexible wing and a standalone baseline propeller model. The numerical results for both configurations exhibited strong agreement with reference data from the literature, validating the accuracy of the modelling approach. In the wing-alone configuration, flutter was observed to arise from the interaction between the first bending and first torsional modes, with predicted flutter speed and frequency closely matching previous findings. Similarly, the standalone propeller model accurately reproduced forward and backward whirling modes, with whirl flutter identified in the backward whirling mode, as expected for systems under windmilling conditions.

Initial analyses were conducted for the coupled wing-propeller system. Two scenarios were explored: one with a non-rotating, rigidly mounted propeller, and another with a rotating propeller attached via flexible mounts. Results indicated that the inclusion of a non-rotating propeller lowered the flutter speed due to increased local mass and inertia. In contrast, when the propeller was allowed to rotate and flexibly mounted, gyroscopic effects emerged, altering the modal characteristics and leading to both wing flutter and whirl flutter instabilities depending on configuration. The forward whirling mode became destabilized due to its coupling with wing torsion.

The results obtained from parametric studies shows that a flexible wing can mitigate whirl flutter, especially when the propeller is mounted with sufficient stiffness and at outboard locations. Therefore, appropriate selection of the attached propeller's spanwise position is critical in the preliminary design of DEP wings to avoid the early onset of dynamic instabilities.

Acknowledgments

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