# COMPARATIVE AEROELASTIC ANALYSIS OF DISTRIBUTED ELECTRIC PROPULSION WINGS

***Yunus Emre Dogru*, Ali Eken, Seher Eken***

**Gebze Technical University,*
*Gebze, 41400 Kocaeli*
*Türkiye*

## ABSTRACT

The transition toward greener aviation has accelerated the development of Distributed Electric Propulsion (DEP) systems, where multiple propellers are mounted along flexible wings. This configuration introduces complex aeroelastic interactions between wing deformation and propeller dynamics, leading to phenomena such as whirl flutter. Accurate prediction of these instabilities is critical for safety. However, the choice of aerodynamic modeling fidelity significantly impacts the predicted stability boundaries. This study focuses on understanding the dynamic interaction between flexible wings and multiple propellers by employing and comparing three distinct aerodynamic modeling strategies ranging from steady approximations to full unsteady time-domain simulations.

The structural dynamics of the wing are modeled using Euler-Bernoulli beam theory, while the equations of motion are derived using the Extended Galerkin Method. To provide a comprehensive analysis of the coupled system, this work adopts a multi-fidelity aerodynamic approach:

- Quasi-Steady Formulation: First, a baseline stability analysis is performed using quasi-steady aerodynamics to establish general trends and understand the static aeroelastic behavior.
- Unsteady Frequency-Domain Analysis (p-k Method): To capture the critical effects of wake dynamics and circulatory flow, Theodorsen’s theory is applied for the wing, coupled with the modified Houbolt-Reed theory for the propellers. The stability boundaries in this domain are determined using the p-k method, allowing for precise tracking of damping evolution and eigenvalue roots.
- Unsteady Time-Domain Analysis: Finally, transient responses are investigated in the time domain using Wagner’s function approximation for the unsteady aerodynamic build-up. This approach verifies the frequency-domain results and allows for the analysis of the system's behavior under specific initial conditions.

A critical challenge in aeroelastic analysis is the "mode switching" phenomenon that occurs as flight speed increases. Regardless of whether the quasi-steady or unsteady frequency-domain formulation is used, the system stability is evaluated by solving the eigenvalue problem at iterative airspeeds. To ensure consistent identification of the structural and aeroelastic modes across all analyses, the Modal Assurance Criterion (MAC) algorithm is implemented globally. This technique tracks the evolution of eigenvectors based on shape correlation, preventing numerical sorting errors and ensuring that the coalescence of bending, torsion, and whirl modes is accurately interpreted throughout the entire velocity sweep.

The developed framework is applied to both a single-propeller and a distributed (two-propeller) wing configuration. The study compares the critical flutter and divergence speeds obtained from the Quasi-Steady and Unsteady (p-k) approaches to highlight the impact of unsteady aerodynamics on stability margins.

Table 1 presents the stability boundaries for the one-propeller case. As observed, the inclusion of unsteady terms significantly affects the predicted critical speeds.

Table 1: Critical Stability Speeds for Single-Propeller Configuration

| | Ref. [1] | Quasi Steady | Unsteady Frequency-Domain |
|---|---|---|---|
| Divergence speed (m/s) | 152 | 149 | 149 |
| Wing flutter speed (m/s) | 174 | 160 | 172 |
| Wing flutter frequency (Hz) | 9,48 | 9,75 | 9,65 |
| Whirl flutter speed (m/s) | 181 | 179 | 174 |
| Whirl flutter frequency (Hz) | 7,17 | 7,15 | 7,09 |

Subsequently, the analysis is extended to a Distributed Propulsion (Two-Propeller) configuration to investigate the coupling effects between multiple propulsors. Table 2 summarizes the preliminary findings for this case.

Table 2: Critical Stability Speeds for Two-Propeller (DEP) Configuration

| | Ref. [1] | Present Study | Unsteady Frequency-Domain |
|---|---|---|---|
| Divergence speed (m/s) | - | 149 | - |
| Forward whirl speed (m/s) | 184 | 138 | 196 |
| Forward whirl frequency (Hz) | 12,62 | 12,53 | 12,45 |
| Backward whirl speed (m/s) | 251 | 262 | 244 |
| Backward whirl frequency (Hz) | 6,28 | 6,3 | 6,08 |

It is important to note that the quantitative data presented above represent preliminary findings from the current phase of the study. While the p-k method reveals that phase lags inherent in oscillatory motion can lead to earlier onset of instability compared to quasi-steady predictions, further validation is ongoing. Subsequent phases of this work will apply the time-domain simulations using Wagner’s function to cross-verify these frequency-domain results and to rigorously investigate the transient response characteristics of the coupled system. The final comparison will provide a robust guideline for selecting appropriate modeling strategies in the design of next-generation eVTOL aircraft.

[1] Xu V. Q. L., (2020), Propeller-wing whirl flutter: An analytical study, Master’s thesis, TUDelft University