Nonlinear damper approaches to body-freedom flutter mitigation in highly-flexible aircraft

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1 Introduction

The High-Altitude Long Endurance (HALE) aircraft is an innovative concept with great potential in telecommunications and surveillance applications due to its ability to function as a "pseudo-satellite" within the stratosphere. Its unique features are accomplished in practice through numerous design requirements that ensure maximal efficiency. Regarding the airframe in particular, these lead to light wings with extremely high aspect ratios. The resulting -very flexible- structure is consequently sensitive to dynamic instabilities emerging from aeroelastic effects (i.e., flutter), which produce large-amplitude oscillations and drastically diminish the aircraft's flight envelope. Hence, accurate prediction of flutter and the ability to mitigate it are crucial to enable reliable HALE aircraft design and operation. While numerous works have focused on this problem for a wing alone (e.g. [1]), flight dynamics is rarely taken into account. This aspect is important, as aeroelastic instabilities in this case can be of a different nature than the flutter of a cantilever beam, involving coupling between aircraft rigid-body modes and wing elastic modes [2]. In the present work, we explore passive control strategies for flexible-wing aircraft flutter based on the nonlinear effects of an added damper subsystem. To this end, an original aeroelastic model of the wing is introduced, which provides a degree of accuracy and complexity that lies at a midpoint between linear and geometrically-exact nonlinear beam models. The focus of this contribution is on damper optimization and mitigation performance evaluation.

2 Model

In this work, the fuselage and tail are modelled as rigid elements, whereas a uniform, high aspect-ratio beam with constant cross-section is used for the wings. The aircraft is assumed to be in longitudinal flight, i.e. its motion is constrained to the plane $(\mathbf{y}_0, \mathbf{z}_0)$, as seen in Fig. 1. A trim state is characterized by level flight at the constant forward speed V_0 which depends on the engine thrust T, considered as the main bifurcation parameter in this study. This motion induces aerodynamic forces on wing and tail which are assumed quasi-steady and computed through classical strip theory [3]. Even though these are linear in a local frame of reference, they introduce nonlinear effects due to considerable wing deformations. Under these hypotheses, we consider a simplified dynamical description of the aircraft, consisting of: the $(y(t), z(t))$ coordinates of its center of mass, its pitch angle $\beta(t)$, and transverse elastic bending $w(x,t)$ and elastic torsion $\phi(x,t)$ of the wings. The Lagrangian formalism is used to derive equations of motion, with distributed elastic displacements w and ϕ discretized through a modal approach. Geometrical nonlinearities are kept to account for large displacements and rotations. It should be noted that the latter are typically linearized in beam models, which leads to neglecting a critical cubic stiffness term in the bending equations [4]. The damper is attached to a single point on the wing -as per Fig. 1- through an essentially nonlinear spring, thus making the damper a *nonlinear energy sink* (NES) [5]. Its mass is fixed to a small fraction of the wing's, leaving four free design parameters: span-wise position (x_N), chord-wise position (l_N), viscous damping c_N and nonlinear stiffness k_{NL}. All of these have a potential influence on the damper's performance, and thus must be chosen carefully.

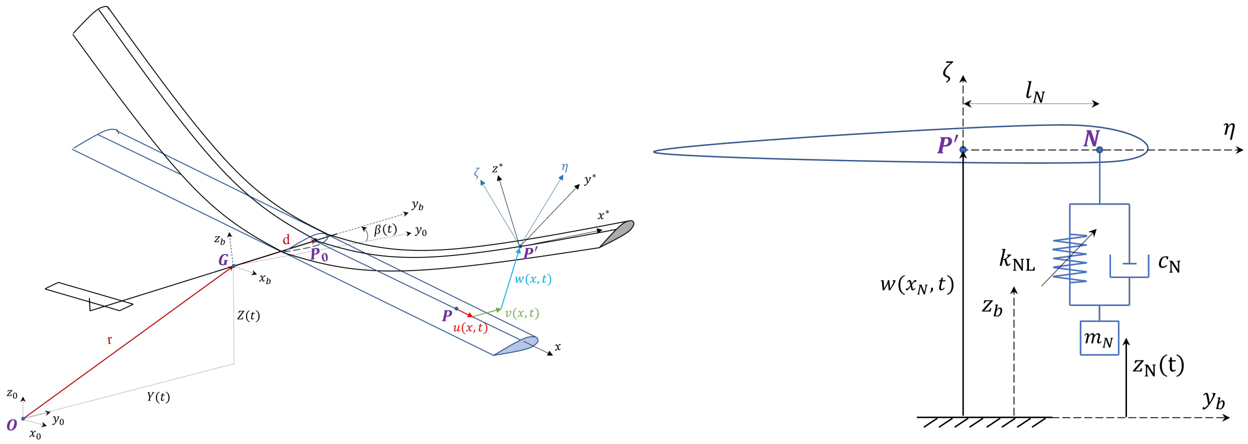

Figure 1: Schematic representation of aircraft with NES subsystem (left: main structure, right: NES).

3 Results

The wing geometric and material properties are chosen to be identical to [6]. Mitigation performance is evaluated with respect to two aspects: critical flutter speed (U_{cr}) and post-instability limit cycle amplitude in torsion ($||\phi_{LC}||$). The optimal damper design maximizes U_{cr} within the acceptable ranges of free parameters while also minimizing $||\phi_{LC}||$ in a neighborhood of the critical speed. Ideally, the NES should be furthermore configured in order to prevent the Hopf bifurcation from being subcritical [7]; this property can be expressed as a function of the bifurcation's first Lyapunov coefficient: $l_1(0) < 0$ [8]. As seen in Fig. 2, the evolution of these quantities is highly nonlinear and not intuitive at all, thus motivating the use of specialized optimization techniques, e.g. genetic algorithms. We present a detailed study of the limit cycle branches following the onset of flutter and show how an optimally designed NES greatly improves the wing's stability, whereas a poor choice of parameters can actually lead aggravated unstable behavior.

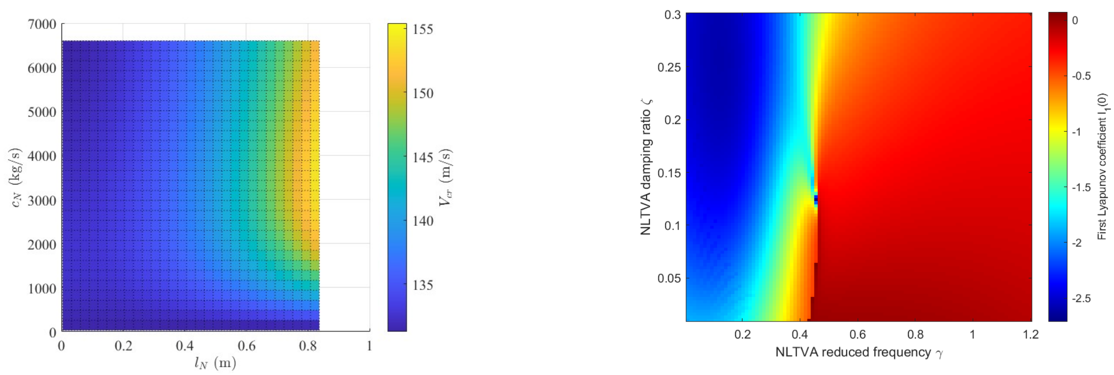

Figure 2: Optimization objectives as function of NES parameters (left: critical speed, right: first Lyapunov coefficient).

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