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PrandtlPlane Joined Wing: Body freedom flutter, limit cycle oscillation and freeplay studies

R. Cavallaro [a,b,*], R. Bombardieri [a,c], L. Demasi [a], A. Iannelli [a,c]

[a] Department of Aerospace Engineering, San Diego State University, United States
[b] Department of Structural Engineering, University of California, San Diego, United States
[c] Dipartimento di Ingegneria Civile e Industriale, Sezione Aerospaziale, Università di Pisa, Italy

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ABSTRACT

Dynamic aeroelastic behavior of a joined-wing *PrandtlPlane* configuration is investigated herein. The baseline model is obtained from a configuration previously designed by partner universities through several multidisciplinary optimizations and ad hoc analyses, including detailed studies on the layout of control architecture. An equivalent structural model has then been adopted to qualitatively retain similar aeroelastic properties.

Flutter and post-flutter regimes, including limit cycle oscillations (LCOs), are studied. A detailed analysis of the energy transfer between fluid and structure is carried out; the areas in which energy is extracted from the fluid are identified to gain insights on the mechanism leading to the aeroelastic instability. Starting from an existing design of control surfaces on the baseline configuration, freeplay is also considered and its effects on the aeroelastic stability properties of the joined-wing system are investigated for the first time.

Both cantilever and free flying configurations are analyzed. Fuselage inertial effects are modeled and the aeroelastic properties are studied considering plunging and pitching rigid body modes. For this configuration a positive interaction between elastic and rigid body modes yields a flutter-free design (within the range of considered airspeeds).

To understand the sensitivity of the system and gain insight, fuselage mass and moment of inertia are selectively varied. For a fixed pitching moment of inertia, larger fuselage mass favors body freedom flutter. When the moment of inertia is varied, a change of critical properties is observed. For smaller values the pitching mode becomes unstable, and coalescence is observed between pitching and the first elastic mode. Increasing pitching inertia, the above criticality is postponed; meanwhile, the second elastic mode becomes unstable at progressively lower speeds. For larger inertial values "cantilever" flutter properties, having coalescence of first and second elastic modes, are recovered.

1. Introduction

It is a recurring circumstance, in aircraft design, to re-size layout after a preliminary assessment of a solution outcome of a conceptual design stage. For classical cantilever configurations, after years of practice and experience this problem has

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[*] Corresponding author at: Department of Aerospace Engineering, Technion - Israel Institute of Technology, Israel.
E-mail address: rauno@technion.ac.il (R. Cavallaro).

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been mitigated and does not represent an insurmountable issue. For Joined Wings there is no similar industrial experience. Thus, attempts to conceptually design such a configuration using traditional procedures, handbook or very low fidelity tools have often resulted in non-competitive layouts (see Cavallaro and Demasi, 2015; Chambers, 2005; Wolkovitch, 1986 for an in-depth discussion). For example, using standard structural design tools calibrated on traditional configurations may lead to considerably heavier configurations than a reference optimized traditional one, with *consequent unsubstantiated claims about non-competitiveness* of the joined-wing aircraft. An interesting discussion about the need for an ad hoc design practice in order to exploit the potential benefits is given in several works (Chambers, 2005; Wolkovitch, 1986). However, the situation is actually even more challenging. Due to the geometrical layout of a typical Joined Wing, there is an unavoidable coupling of the different disciplines. Although true for traditional configurations, for Joined Wings this is pushed to the limit. For example, the flight mechanics requirements on low speed conditions may not be completely satisfied with a fine-tuning of the flap/slats design, and this constraint may completely change the layout in terms of twist distribution and sweep angle. In other words, a multidisciplinary optimization seems to be unavoidable. An example of *PrandtlPlane* applied optimization process (although structural constraints were not considered) is presented in Rizzo (2009) and Rizzo and Frediani (2009).

One of the major challenges in the design of Joined Wings is represented by important structural nonlinearities which are significant even at very low incidence and attached (linear) flow. Moreover, as shown in the literature (Blair et al., 2005; Cavallaro et al., 2012, 2014a; Demasi et al., 2013b, 2015), the typical joined-wing layout, featuring an overconstrained system at global level, is responsible for introducing strong structural nonlinearities and counterintuitive behaviors. This high complexity implies that at early design phases of the configuration, even adopting a multidisciplinary optimization, but relying on linear tools, may lead to far-from-optimal or even impossible-to-fly configurations. Several theoretical studies (Demasi and Livne, 2007; Demasi and Palacios, 2010; Phlipot et al., 2014; Teunisse et al., 2014, 2015) tried to address this difficulty by employing reduced order models. However, their efficiency was found to be unsatisfactory.

Given this scenario, efforts to better understand possible problems of geometrical nonlinearities at the structural level were made in Cavallaro et al. (2012, 2014a) as well as Demasi et al. (2013a, 2015). The results were obtained for conceptual wind-tunnel-like models, and snap-types of instabilities were observed. Aeroelastic static analyses showed that an eigenvalue approach for aeroelastic divergence speed assessment was overpredicting the true instability speed. In Cavallaro et al. (2014c, 2015) nonlinear aeroelastic dynamic responses were shown: not only was the *true* critical speed found to be lower than the one predicted linearizing about the undeformed configuration, but several phenomena such as flip-bifurcation, multi-stability and eventually chaos were observed. When a source of *nonlinearity* of aerodynamic origin (wake roll-up) was incorporated, the effects were noticeable.

A natural extension of these efforts is to apply the gained knowledge and the in-house computational tools to study the nonlinear aeroelastic response of a more *realistic* layout, obtained through preliminary optimization and fine-tuning, as the ones presented in Dal Canto et al. (2012), Divoux and Frediani (2012), Ginneken et al. (2010) and Voskuijl et al. (2012). This design features a commercial aircraft application and thus, differently than previously investigated cases, is characterized by smaller displacements.

2. Contribution of the present study

Considering the literature on design of Joined Wings, with emphasis on *Box Wing* (Miranda, 1974) and *PrandtlPlane* (Frediani, 2002, 2003, 2004) configurations, a significant amount of work has been carried out; see for example Buttazzo and Frediani (2012). Thus, a *realistic* reference configuration based on these works is available for thorough aeroelastic analysis, where it is well known (Bisplinghoff and Ashley, 2002; Clark et al., 2005) that the stiffness and inertial distributions play a primary role in the occurrence of flutter.

This paper will feature a *PrandtlPlane* layout *similar* to the one studied in Dal Canto et al. (2012), Divoux and Frediani (2012), Ginneken et al. (2010) and Voskuijl et al. (2012). This model was obtained through a partial multidisciplinary optimization (MDO) and then progressively fine-tuned (Buttazzo and Frediani, 2012; Dal Canto, 2009; Divoux, 2008; Quattrone and Contini, 2010; Frediani et al., 2012).

Given also the studies on flight mechanics and control surfaces (Ginneken et al., 2010; Voskuijl et al., 2012), this configuration represents an interesting starting point for studying nonlinear aeroelasticity and freeplay effects. Impact of control surface freeplay on flutter (Dowell et al., 2003; Tang and Dowell, 2006) has never been studied before for Joined Wings. As opposed to traditional configurations, PrandtlPlane Joined Wings have multiple control surfaces located on both wings. Thus, the response of the system will be the result of a complicated interaction of each control surface freeplay. The contributions of this paper are here outlined.

- Starting from the joined-wing model presented in Divoux and Frediani (2012), a structurally "equivalent" model is designed. The control surfaces are considered being perfectly connected to the wing around the hinge line (no freeplay), and flutter analysis is carried out. However, a further step is taken: the post-flutter response is tracked with a time-domain capability, showing the limit cycle oscillation. Aerodynamic-structure energy transfer is also investigated and discussed.
- The second contribution is on the impact of control surface freeplay on flutter response of this configuration. Control surfaces have been previously designed for this specific configuration complying with handling qualities requirements at