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Post-critical analysis of highly deformable Joined Wings: The concept of snap-divergence as a characterization of the instability

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ABSTRACT

Theoretical modeling of the aeroelastic static instability with the possibility of tracing post-critical branches (via arc length technique) in the framework of Joined Wings has never been presented before. A complete formulation of the numerical iterative method of solution of the aeroelastic equations is presented.

The true critical condition is compared with the divergence speed evaluated by solving an eigenvalue problem about a steady state equilibrium, showing how this last approach may be unreliable and even nonconservative.

This work also explores the theoretical implications of using mechanical loads to mimic the real loading conditions.

A physical interpretation based on the aeroelastic effects, overconstrained nature of the system, and the bending/torsion coupling, is provided to interpret the conditions that lead to the snap-divergence.

1. Introduction

Typical joined-wing configurations (Wolkovitch, 1986; Chambers, 2005) are characterized by significant structural geometric nonlinearities (Blair et al., 2005; Kim et al., 2008; Liu et al., 2010). As a consequence, preliminary design complexity is increased (Blair et al., 2005): existing procedures successfully adopted by the aerospace industry rely mainly on linear tools not able to correctly reproduce these effects. Employment of these lower fidelity tools is actually a practical requirement since a Multi-Disciplinary Optimization (MDO) generally involves a large amount of analyses.

What has proven to be very effective in the past for classical cantilevered configurations, then, cannot (Kim et al., 2008) be directly translated into procedures that have the same degree of computational efficiency and accuracy, when Joined Wings are considered (Weisshaar and Lee, 2002).

On the other hand, neglecting structural nonlinearities in the early design stages may lead to a posteriori-verified unacceptable solutions and can determine a significant increase of design costs.

In this scenario, reduced order models specifically tailored to retain the important nonlinearities of Joined Wings can be an ideal solution. Unfortunately, even advanced reduced order modeling techniques proved not to be very effective (see Demasi and Livne, 2007; Demasi and Palacios, 2010; Phlipot et al., 2014; Teunisse et al., 2014) when Joined Wings were

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considered. This suggests taking one step back and focusing on the nature of the involved nonlinearities, with the final goal of capturing the essential underlying physics for a more accurate and efficient design of reduced order models.

Several efforts considered mechanical loading and showed a highly complex nonlinear behavior of Joined Wings. Besides numerical approach, also experimental work (Kim et al., 2011; Boston et al., 2010) was carried out to explore the joined-wing Sensocraft (Reichenbach et al., 2011; Scott et al., 2011; Heeg and Morelli, 2011) response when subjected to follower static loads. Different works discussed theoretical aspects related to the structural nonlinearities (Sotoudeh and Hodges, 2011) and also involved aeroelastic investigations (Patil, 2003; Demasi and Livne, 2005, 2009b; Cavallaro et al., 2014b).

Only recently (see Demasi et al., 2013b; Cavallaro et al., 2012, 2014a, 2014c), the research moved on the fundamental understanding of the peculiar nonlinear response of Joined Wings, with focus on the so-called *PrandtlPlane* configurations (e.g., Frediani, 1999, 2002, 2003, 2005; Frediani et al., 2012).

In particular, Demasi et al. (2013b) demonstrated via nonlinear investigations that the linear buckling analysis is not very reliable as far as the static critical condition is concerned. Moreover, the wing system might be sensitive to snap-buckling type of instability for some combinations of structural parameters. The so-called Snap-Buckling Region (SBR) for Joined Wings was then introduced. Load repartition between the wings, joint size, and sweep angle had an important impact on the stability properties.

Cavallaro et al. (2012, 2014a) presented several counter-intuitive aspects. Stiffening the compressed upper wing actually decreased the critical load; in addition, the lower-to-upper-wing bending stiffness ratio was shown to be one of the major parameters ruling the snap-buckling phenomenon. One of the most important physical aspects was the bending moment transferring through the joint: a reduction of the amount of transferred bending moment, obtained by changing the boundary conditions at the joint, significantly reduced the risk of snap-buckling instability, although at expense of the overall stiffness of the structure.

Cavallaro et al. (2014c) discussed the effects of the non-conservative loads of the follower type on the SBR. More important, the concept of bi-stability was discussed and shown to cause branch-jumping phenomena at load levels far below the nominal critical condition (identified through the nonlinear static analysis as the snap-buckling). This has theoretically a tremendous impact on design of Joined Wings: under certain conditions an apparently safe and quasi-linear steady-state condition may actually be unsafe if the post-critical analysis is ignored. Further investigations showed also stable branches completely detached from the main branch, suggesting that path-following techniques (like the arc-length) are not sufficient to unveil the whole picture.

This work will extend the last efforts introducing aerodynamic forces and investigating the nonlinear response of the Joined Wings, with particular focus on the stability property of the system (concept of snap-divergence) and on the differences with the cases in which mechanical loads (see Demasi et al., 2013b; Cavallaro et al., 2012, 2014c) are applied. For the first time on Joined Wings, post-divergence branches will be obtained and critically analyzed.

2. Contribution of the present study

It is common practice in the industry (e.g., ZONA Technology Inc., 2004; Rodden and Johnson, 1994) to calculate the divergence directly with the solution of an eigenvalue problem or via flutter analysis. The freestream velocity corresponding to the divergence is in general different than the one corresponding to the aeroelastic dynamic instability (flutter), thus, it has to be assessed which one represents the critical operative situation.

The above approaches, however, are based on an assumption that the structural properties of the system remain approximately constant. An open question is then how the divergence speed is calculated for a wing systems which experiences important geometric nonlinearity and how the divergence is precisely defined. This aspect is extensively addressed in the present work. It will also be assessed whether the eigenvalue approach, used to calculate the divergence speed, is reliable for Joined Wings.

A further contribution will be on the correlation of aeroelastic and structural static responses if mechanical conservative or nonconservative (follower type) loads are employed as a surrogate of the real aerodynamic forces. In fact, this approach is largely used as a mean of testing the structural response before more sophisticated and expensive campaigns are carried out. How reliable is this approach for Joined Wings? And, if not, could it at least give a conservative estimate?

Starting from the above points, the *real divergence* occurrence is more critically analyzed, and physical insight is gained by means of comparisons with previous results presented in the literature. In particular, aeroelastic load redistribution, overconstrained nature of Joined Wings and bending/stiffness coupling are discussed.

This work will also introduce the theoretical foundation of branch-follower numerical technique for static aeroelastic problems. These techniques are necessary to completely track the aeroelastic response, also after a critical (or turning) point is encountered.

2.1. *On the importance of a conceptual study of Joined Wings*

One conceptual question is how the findings of this work, carried out on simplified models, relate to a real flying aircraft. On this regard, several observations can be made:

1. Bi-stable regions (at macro-geometrical level) for a traditional configuration are generally not expected to be observed, whereas they are theoretically possible and shown for Joined Wing configurations. The presence of such regions impacts

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