Progress in Aerospace Sciences (xxxx) xxxx–xxxx

Contents lists available at ScienceDirect

Progress in Aerospace Sciences

journal homepage: www.elsevier.com/locate/paerosci

A review on non-linear aeroelasticity of high aspect-ratio wings

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ARTICLE INFO

MSC:
00-01
99-00

Keywords:
Non-linear aeroelasticity
High aspect-ratio wings
Flexible structures
Geometric non-linearities
Computational aeroelasticity

ABSTRACT

Current economic constraints and environmental regulations call for design of more efficient aircraft configurations. An observed trend in aircraft design to reduce the lift induced drag and improve fuel consumption and emissions is to increase the wing aspect-ratio. However, a slender wing is more flexible and subject to higher deflections under the same operating conditions. This effect may lead to changes in dynamic behaviour and in aeroelastic response, potentially resulting in instabilities. Therefore, it is important to take into account geometric non-linearities in the design of high aspect-ratio wings, as well as having accurate computational codes that couple the aerodynamic and structural models in the presence of non-linearities. Here, a review on the state-of-the-art on non-linear aeroelasticity of high aspect-ratio wings is presented. The methodologies employed to analyse high aspect-ratio wings are presented and their applications discussed. Important observations from the state-of-the-art studies are drawn and the current challenges in the field are identified.

1. Introduction

If one looks at current commercial jet designs, one can observe that their aspect-ratios are increasing, either by simply increasing wing-span, or alternatively, by equipping wings with tip devices (for example, there is an increase of 10.2% and 8.7% in aspect-ratio for the A320-200 and B737 NG, respectively). This is mainly due to the fact that by increasing wing aspect-ratio, the aerodynamic induced drag is reduced resulting in higher lift-to-drag ratios and longer ranges [1]. According to Abbas et al. [2], aerodynamic induced drag can represent 43% of the overall aerodynamic drag for a large transport aircraft during cruise, thus the importance to reduce this type of drag in order to achieve lower fuel consumptions. According to Torenbeek [3], higher benefits can be expected for lower speed regimes, thus improving also the off-design operating conditions. This aerodynamic benefit has been explored in non-planar aircraft designs such as the Joined-Wing [4], the Strut-Braced-Wing [5] and the C-Wing [6].

Fig. 1 illustrates the wing aspect-ratio for three different categories of aircraft (RJ - Regional Jets, MH - Medium-Haul Aircraft and LH - Long-Haul Aircraft) as a function of the number of passenger (PAX) (Fig. 1(d)) and year of first flight (Fig. 1(a–c)). In Fig. 1(d), one may identify a “Pareto Front” for the LH aircraft that relates number of passengers (PAX) with wing aspect-ratio (*AR*). This resembles a *AR* vs Root Bending Moment (RBM) Pareto Front obtained from design optimization constrained by the materials capacity to withstand the RBM. However, these trends can not be identified for the MH and RJ aircraft. Two reasons that may explain this observation: (1) for the MH, the wing designs have been kept relatively unchanged for the last 15 years; (2) for the RJ, one may infer that the lack of knowledge on the non-linear aeroelastic behaviour of higher aspect-ratio wings may be postponing the adoption of high aspect-ratio configurations in regional jets.

Despite the aforementioned aerodynamic benefits, there are structural design issues inherent to wings with high aspect-ratio: higher structural flexibility, and higher stress levels at the wing root. Moreover, if the approach to increase wing aspect-ratio is by increasing the wingspan, there are limitations to the allowable span for operation in airport terminals and maintenance facilities that impose a span constraint to the design (which resulted in the adoption of wing-tip devices instead of longer span wing designs). This is the main reason that commercial aircraft still have relatively short wing spans.

With reference to the increase of wing structural flexibility, the wing becomes more susceptible to higher deflections at the same operating conditions, which can affect the dynamic behaviour (modal properties) and consequently the aeroelastic behaviour, thus originating aeroelastic instabilities at lower speeds than in a comparable stiffer wing

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http://dx.doi.org/10.1016/j.paerosci.2016.12.004
Received 13 August 2016; Received in revised form 16 December 2016; Accepted 20 December 2016

Nomenclature

ACT	Active Control Technology
AR	Aspect-Ratio
CAE	Computational Aeroelasticity
CSD	Computational Structural Dynamics
CFD	Computational Fluid Dynamics
DLM	Doublet-Lattice Method
DNS	Direct Numerical Simulation
DPM	Doublet Point Method
ECFT	Enhanced Correction Factor Technique
EI_2/EI_1	Ratio between chord and flap bending stiffness
FE	Finite Element
FFT	Fast Fourier Transform
FSI	Fluid-Structure Interaction
GAM	Generalised Aerodynamic Matrix
GECB	Geometrically Exact Composite Beam
GVT	Ground Vibration Test
HALE	High Altitude Long Endurance
HB	Harmonic Balance
LCO	Limit Cycle Oscillation
LQG	Linear Quadratic Gaussian
LQR	Linear Quadratic Regulator
LUR	Linearised Unsteady Reynolds–Averaged Navier-Stokes
LES	Large-Eddy Simulation
M	Mach number
MCF	Modal Characterizing Function
MDO	Multidisciplinary Design Optimization
PID	Proportional Integral Derivative
PM	Panel Method
RANS	Reynolds-Averaged Navier-Stokes
ROM	Reduced Order Model
SOF	Static Output Feedback
TLTSD	Time-Linearised Transonic Small Disturbance
TSD	Transonic Small Disturbance
UDLM	Unsteady Doublet-Lattice Method
URANS	Unsteady Reynolds-Averaged Navier-Stokes
UVLM	Unsteady Vortex Lattice Method
VLM	Vortex Lattice Method

structure. According to Hodges and Dowell [7], for high aspect-ratio beam-like wings, the flap[1] bending mode, the chord bending mode and the torsion mode may couple and result in significant structural non-linearities. Hence, the importance of assessing the effects of non-linearities on the aeroelastic behaviour of high-aspect ratio wings.

Earlier studies on non-linear aeroelasticity arose mainly due to the need to understand rotorcraft aeroelastic phenomena. Helicopter blades have very high aspect-ratio, which are usually made from composite material and during its operation there is blade-wake interaction, possibly in transonic flow with shock and stall [8].

The interest in non-linear aeroelastic analysis in fixed wing aircraft first appeared due to the need to understand aeroelastic response in the transonic regime [9], where aerodynamic non-linearities are observed. In the last decade, this interest intensified due to novel unmanned aircraft design with very high aspect-ratio wings [10] such as the High Altitude Long Endurance (HALE) aircraft [11] that is prone to the influence of geometric non-linearities even in cruise conditions [12].

Research findings on non-linear aeroelasticity of high aspect-ratio aircraft is not readily available in the open literature. All experimental studies presented in this review are based on simple, straight and planar wings [13] for flutter and Limit Cycle Oscillation (LCO) response under aerodynamic loading at speeds within the operating range of the wind tunnel [14,15], and some studies also present gust response [16,17]. It should be noted that a great number of studies (analytical, computational or experimental) include the effect of stores mounted in the wing tip or in other positions along the span. Experimentally, the store has the effect of reducing the frequency of the first torsional and bending modes of the test subject.

Due to the reduced data available, many model validations are made using the same experimental data reported in the open literature, namely the data published by Tang and Dowell [14], or analytical and experimental data from studies performed in the last 50 years in lower aspect-ratio wings: Goland Wing [18]; BAH Wing [19–21]; Delta-cropped Wing [22]; Isogai Wing [23]; AGARD 445.6 Wing [24]; BACT Wing [25]; NAL SST Wing [26]; MAVRIC Wing [27]; and Aerostabil Wing [28].

Some non-linear aeroelastic static and dynamic analysis in time domain are based on Fluid-Structure Interaction (FSI) algorithms and procedures, and the literature is abundant on this subject and there are methods for coupling the various types of fidelity models [29–32].

Several survey papers concerning aeroelasticity have been published over the past decades [33–45] on aeroelastic models and experimental efforts. In the year of the centenary of the first ever successful flight heavier than air, several review papers of the efforts conducted in numerical and experimental aeroelasticity were presented [46,43,47–52]. Despite several non-linearities being discussed in the aforementioned surveys, fewer review papers on non-linear aeroelasticity can be found in the literature [33,39,42,47,44,45].

The current survey paper is mainly focused on non-linear aeroelasticity of high aspect-ratio wings, and it constitutes an important and necessary complement to the reported survey studies. Here, the structural, aerodynamic and control non-linearities are identified as well as the computational methods most appropriate to perform non-linear aeroelastic analyses of high aspect-ratio wings. The current numerical and experimental developments in non-linear aeroelasticity of high aspect-ratio wings are discussed, including the influence of non-linearities, at subsonic and transonic flows, and in flight manoeuvres of aircraft with flexible structures. Finally, the main observations and challenges in modelling and testing of high-aspect ratio wings are identified and summarized.

2. Types of non-linearities

A system response is generally characterized as non-linear when an increase in an input ceases to cause a response linearly proportional to the magnitude of that input [53]. In this context, structural, aerodynamic and control non-linearities are identified. Sources of structural non-linearities of interest to HARW: (i) geometric, where the system response in altered due to the significant changes in the initial geometry of the structure; (ii) damping, where the damping forces contribute to the non-linear response [47]; (iii) material, when the yield stress is exceeded leading to a non-linear stress-strain relationship. Other sources of less relevance to HARW include contact and friction. Sources of aerodynamic non-linearities include: (i) flow separation due to the increases in angle of attack, (ii) shock, where it represents a discontinuity in the pressure distribution of the flow field, especially in the transonic regime, when it interacts with the boundary layer causing separation; (iii) wake roll up, due to the large wing deformation [54,55]; and (iv) geometric, resulting in coupling of load-displacement. Other types of less relevance to HARW include aerodynamic interference, free-play and interference between lifting sur-

[1] Different nomenclatures can be found in the literature for: 1) flap bending is in regard to the bending in the out of wing in plane (also known as flapwise, flatwise or plunge bending); 2) chord bending is related to the wing plane bending (also referred as chordwise, edgewise or lag bending).