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Nonlinear aeroelastic scaling of high aspect-ratio wings

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ABSTRACT

The aeronautical industry is currently facing the simultaneous and conflicting demand to enhance flight efficiency while reducing emissions. One potential solution for reducing fuel consumption is to increase the wing aspect-ratio as it improves the lift-to-drag ratio. However, higher aspect-ratio wings result in higher deflections which in turn may lead to nonlinear aeroelastic behavior. In this work, the aeroelastic behavior of a conventional regional aircraft with high aspect-ratio wings is investigated. Aeroelastically scaled models using different scaling methodologies have been evaluated and compared. These methodologies use scaling factors derived from the governing aeroelastic equations of motion to set the target values to be matched through the optimization of the scaled model structure. Two linear scaling approaches were used: the first method consists of a direct modal response matching; while the second method uncouples the mass and stiffness distribution to achieve the modal response. An alternative nonlinear aeroelastic scaling methodology using equivalent static loads is presented, which uses two different optimization routines to match the nonlinear static response and the mode shapes of the full model. The aeroelastic response agreement was found to be considerably better when the nonlinear approach is applied and the accuracy is noticeably better than the results obtained using the traditional linear scaling methods.

1. Introduction

Presently, the original aircraft manufacturers (OEM) are looking at new aircraft designs with high aspect-ratio wings, especially for civil and commercial aircraft. High Aspect-Ratio Wings (HARW) present considerable performance advantages. In general, HARW produce more lift and provide a higher lift-to-drag ratio resulting in increased endurance [1]. Also, HARW increase not only aircraft stability but also efficiency because they produce less induced drag leading to lower fuel consumption. To make HARW feasible in terms of weight penalties, these wings are designed to be very flexible.

The total drag coefficient can be defined [1] as

$$C_D = C_{D_0} + C_{D_i} + C_{D_w} = C_{D_0} + \frac{C_L^2}{\pi e AR} + C_{D_w}\,, \tag{1}$$

where C_D, C_{D_0}, C_{D_i}, C_{D_w} are the coefficients of total drag, profile drag, induced drag and wave drag, respectively; C_L is the lift coefficient; e the span efficiency factor and AR the wing aspect-ratio.

Nevertheless, this challenge warrants further investigation due to large deformations under normal operating loads leading to a geometrical nonlinear behavior and aeroelastic problems [2,3]. These large deformations can change the natural frequencies of the wing which can produce noticeable changes in its aeroelastic behavior [4].

In order to better understand the physical behavior of the wing without building an expensive full scale demonstrator, a reduced scale model provides a feasible alternative. Experimental testing of aeroelastically scaled models is a common approach in new flight vehicle development programs [5]. In this work, the scaled model is intended to closely reproduce the aeroelastic response of the full scale model at operating conditions.

Aeroelastic scaling requires adequate consideration to aerodynamic and structural physics. Aerodynamic similitude is achieved analytically by geometrically scaling the aerodynamic shape when Mach and Reynolds number are consistent. Flight conditions such as airspeed and altitude are selected for matching scaled parameters like Froude number and density ratio, for example. The Froude number is a dimensionless parameter defined as the ratio between inertial and gravitational forces [6]:

$$Fr = \frac{V}{\sqrt{b a_g}}\,, \tag{2}$$

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Nomenclature

AR	Wing aspect-ratio	n	Load factor
a_g	Acceleration of gravity	n_F	Force ratio
b	Reference wing span	n_f	Frequency ratio
C_D	Total drag coefficient	n_g	Length ratio
C_{D_0}	Profile drag coefficient	n_m	Mass ratio
C_{D_i}	Induced drag coefficient	n_v	Velocity ratio
C_{D_w}	Wave drag coefficient	n_ρ	Air density ratio
C_L	Lift coefficient	L	Total lift
e	Span efficiency factor	$[Q]$	Aerodynamic coefficient matrix
F	Force	S	Wing area
Fr	Froude number	u	Static deflection
f	Natural frequency	V	Air speed
g	Damping factor	W	Aircraft weight
$[K]$	Stiffness matrix	x	System degrees of freedom
k	Reduced frequency	α	Angle of attack
M	Mass	ρ	Air density
$[M]$	Mass matrix	ϕ	Natural mode shape

where b is the reference wing span, V the airspeed and a_g the gravity acceleration. The density ratio, n_ρ, is the ratio between the air density at which the scaled model will operates (ρ_s) and the air density at which the full model operates (ρ_f) [7]:

$$n_\rho = \frac{\rho_s}{\rho_f} \,. \tag{3}$$

Structural similitude is not realistically achievable by geometrically scaling the structural components and corresponding analytical scaling requirements will generally specify that a geometrically scaled structure should be made from materials that have non-physical properties. There is also a high probability that the manufacturing techniques used for the full scale design cannot be duplicated at a smaller scale. The only feasible option is to redesign the internal structure using available materials and optimize it such that its scaled mass and stiffness properties are consistent with the full scale aircraft [8]. The ladder structure is one of several scaled model configurations recommended by Bisplinghoff et al. [7].

In the classical approach, aeroelastic scaling is achieved by selecting a discrete subset of modal degrees of freedom that capture the relevant global properties of the full model, and optimizing the scaled aircraft such that the non-dimensional modal masses and stiffness coefficients match the full scale aircraft [7].

The most common practice for classical aeroelastic scaling is to use a truncated number of the vibration mode shapes from the target full scale model as the modal degrees of freedom for the scaled model optimization [9]. However, there is a drawback. The truncation may omit information that becomes important when geometric nonlinearities are significant (it can be considered analogous to omitting certain flexibility in the model (*e.g.*, axial and shear)). Classical scaling methods have worked in practice for traditional applications, but the validity of the modeling assumptions needs verification for cases where geometric nonlinearities become important.

Few papers can be found in the literature regarding nonlinear aeroelastic scaling [10–13]. Just recently this topic has become a focus of study in order to investigate the High Altitude Long Endurance (HALE) aircraft, which are characterized by their high aspect-ratio wings and high structural flexibility, either by using a Joined-Wing configuration [10,11,13] or a conventional configuration [12].

Bond et al. [11] developed a nonlinear aeroelastic scaling methodology similar to the one presented by French and Eastep [5]. This methodology directly matches the first three natural frequencies and corresponding mode shapes, and the first buckling eigenvalue. From the results retrieved, the authors reported a good matching for the aeroelastic frequencies and damping.

Wan and Cesnik [12] devised scaling parameters to incorporate geometric nonlinearities (through nonlinear stiffness matrix) and pre-stress to be applied to unsteady aeroelastic system. The main observations drawn by the authors were the following: similar scaling laws are also applicable to scale down structures presenting geometric nonlinearities; the Froude number should not be disregarded when considering high aspect-ratio wings; matching the Reynolds number (when Reynolds number is low) may result in an additional challenge to other scaling factors.

Simultaneously, Ricciardi et al. [13] proposed a new aeroelastic scaling methodology capable of incorporating geometric nonlinearities in the scaling process. With optimization efficiency in mind Equivalent Static Loads (ESL) were included in their methodology. From the comparison of theirs scaling methodology with a classic scaling methodology, the authors verified that the deflections and aeroelastic frequencies results were improved, although with a loss of accuracy in terms of flutter speed.

In this work, a new nonlinear scaling methodology similar to the one proposed by Ricciardi et al. [13] is presented. The main difference is in what concern to the way the scaling is performed: the stiffness and mass distributions are achieved separately in two optimization loops in the new approach; while in Ricciardi et al. method just one optimization procedure is carried out. The application case is a high aspect-ratio regional transport aircraft wing, which has a much lower aspect-ratio than those of the HALE aircraft of the previously reported nonlinear aeroelastic scaling works. Thus, this wing has a lower flexibility and smaller deformations than the aforementioned HALE aircraft. Despite this fact, geometric nonlinearities effects are clearly visible even for a 1 g load. Important considerations such as engine mass and pylon, besides fuel (no sloshing effect was modeled in the aeroelastic analyses) were taken into account in this work.

2. Theoretical background

Due to the complex nature of the problem, a simplified physics model was chosen: the small disturbance, linear potential partial differential equations (PDE) [14] as stated in Eq. (4).

$$[M]\{\ddot{x}\} + [K]\{x\} = \frac{\rho V^2}{2}[Q]\{x\} \,, \tag{4}$$

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