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Semi-analytical static aeroelastic analysis and response of flexible subsonic wings

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ABSTRACT

A semi-analytical model for the combined static aeroelastic analysis and response of flexible subsonic wings is presented. Based on a general variational formulation, the proposed aeroelastic models allow any arbitrary distribution of the flexible wing's physical properties and provide with a continuous solution of the wing's displacement along the span, as suitable for parametric optimisation studies within preliminary wing design. Numerical results which provide sound insights on the behaviour of a flexible wing in subsonic flow are obtained and critically discussed for all aeroelastic models, with respect to the most relevant aerodynamic and structural parameters as well as the computational efficiency. Different degrees of fidelity are considered for the aerodynamic modelling and the formulated modified strip theory is shown to be an excellent compromise between the lower complexity of standard strip theory and the higher accuracy of lifting line theory. The modified strip theory is hence suggested as a general and effective steady aerodynamic tool for the multidisciplinary design and optimisation of flexible wings in the subsonic regime.

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1. Introduction

Particularly at the preliminary stage, aircraft's multidisciplinary design and optimisation (MDO) [1] requires comprehensive, robust and efficient tools to be effectively managed by smart optimisation strategies and algorithms [2]. This is especially true for the optimal design of a flexible wing, where, assuming suitable parametric distributions for its aero-structural properties [3], all relevant aeroelastic issues and behaviours [4–6] must be analysed within an appropriately large design variables space [7,8] and fast reliable semi-analytical calculations of the aerodynamic load [9–33] are hence highly sought.

By relying on model reduction approaches [34,35], Euler–Bernoulli beam [36] and strip theory [37] or aerodynamic panel methods [38,39] are often coupled as the simplest yet adequate idealisation of the wing structure and airload, respectively [40]. Such fluid–structure interaction (FSI) [41] models are computationally convenient and offer precious theoretical insights on the fundamental behaviour of flexible wings [42,43]. Finite element methods (FEM) [44] and computational fluid dynamics (CFD) [45] have also increasingly been combined to form higher-fidelity aeroelastic tools of enhanced accuracy [46–48]. However, these are computationally expensive [49] and their correct coupling is still challenging [50,51], requiring special mathematical formulations and modelling treatments [52,53] to ensure that the correct physics are consistently reproduced in the demanding numerical simulations [54], especially concerning the boundary/interface conditions

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[55,56]. Correction-based approaches have then suitably been proposed in order to retain significant accuracy of nonlinear CFD at the low computational costs of linear potential-flow aerodynamics [57–60].

A computationally efficient semi-analytical model for the combined stability analysis and static response of flexible subsonic wings is hence hereby presented. A slender beam [61] being employed for the wing structure, several degrees of fidelity are considered for the aerodynamic modelling in order to account for the three-dimensional flow effects in different ways [62] and a new formulation of modified strip theory [20,25] is presented based on lifting line theory [9]. The proposed aeroelastic model accounts for both moderate sweep angle [63] and the presence of ailerons [64], so that the wing's response to steady aileron manoeuvres may also be analysed and control reversal investigated. The principle of virtual works (PVW) [65] is used to derive the linear system of differential equilibrium equations and the Ritz's method then employed to solve them within a linear modal approach [66], where polynomial mode shapes are suitably assumed for the wing displacement [67]. The resulting aeroelastic model allows any arbitrary distribution of the flexible wing's physical properties and provides with a continuous solution of the wing's displacement along the span (without the need of pre-defining monitoring points at all locations of interest), as appropriate for parametric optimisation studies within preliminary wing design. Considering a flat trapezoidal wing, numerical results for both divergence and reversal speeds as well as the static aeroelastic response are obtained for different sweep angles and critically compared for all formulated aeroelastic models, showing their sensitivity to relevant aerodynamic and structural parameters such as the wing's aspect ratio and stiffness ratio, respectively, as well as highlighting their computational efficiency. Exact analytical solutions are also explicitly derived in special cases, whenever possible.

2. Aeroelastic problem formulation

According to the typical closely-spaced rigid diaphragm assumption [68], the slender wing is reasonably considered spanwise flexible only and a stripwise approach is suitably employed. The wing's elastic axis (EA, where all applied loads are reacted [36]) is drawn by the locus of the shear centre of each chordwise section and modelled as a Rayleigh beam [61] with distributed Young modulus $E(y)$, shear modulus $G(y)$, second area moment of inertia $I(y)$ and torsion factor $J(y)$; axial pre-tension $T(y)$ is also considered for generality [65]. The spanwise y axis of the reference system is then aligned with the EA, with $y_R = 0$ and $y_T = l$ for the wing root and tip, respectively, whereas the chordwise x axis is orthogonal to the EA and directed towards the wing's trailing edge, with $x_{EA}(y) \equiv 0$ fixed for convenience. The structural mass $m(y)$ is then distributed on the wing's inertial axis $x_{CG}(y)$, which is drawn by the locus of the centre of gravity (CG, where the gravity load is applied [36]) of each chordwise section.

With $z(y)$ and $\vartheta(y)$ the vertical (positive upwards) and torsional (positive clockwise) displacements of the EA, respectively, the static aeroelastic equilibrium of the wing is the solution of the linear system of coupled ordinary differential equations (ODEs) for both wing bending and wing torsion [66]:

$$(EIz'')'' - (Tz')' = \Delta L - mg + Q_z, \qquad (GJ\vartheta')' = -\Delta M - x_{CG}mg + Q_\vartheta, \tag{1}$$

with g the gravity acceleration. $Q_z(y)$ and $Q_\vartheta(y)$ are applied loads due to a vertical k_z, rotational $k_{z'}$ and torsional k_ϑ spring at the location (x_S, y_S) and a concentrated mass M_C at the location (x_I, y_I), namely [65]:

$$Q_z = k_{z'}(z - x_S\vartheta)'\delta'_S - k_z(z - x_S\vartheta)\delta_S - M_C g\delta_I, \qquad Q_\vartheta = x_S k_{z'}(z - x_S\vartheta)'\delta'_S + [k_\vartheta\vartheta - x_S k_z(z - x_S\vartheta)]\delta_S - x_I M_C g\delta_I, \tag{2}$$

where $\delta_S = \delta(y - y_S)$ and $\delta_I = \delta(y - y_I)$ are Dirac delta functions [54]. $\Delta L(y)$ and $\Delta M(y)$ are the aerodynamic force (positive upwards) and pitching moment (positive clockwise) distributions, respectively, the wing's total lift L, pitching moment M_p and rolling moment M_r being then given by [37]:

$$L = \int_0^l \Delta L dy, \qquad M_p = \int_0^l \Delta M dy, \qquad M_r = \int_0^l \Delta L y dy, \tag{3}$$

respectively. The two equilibrium equations are finally completed by the appropriate boundary conditions for clamped-free beam [65]:

$$Tz'(l) - (EIz'')'(l) = 0, \qquad EIz''(l) = 0, \qquad z(0) = 0, \qquad z'(0) = 0, \qquad GJ\vartheta'(l) = 0, \qquad \vartheta(0) = 0. \tag{4}$$

3. Aerodynamic models

The steady subsonic flow being reasonably considered as inviscid, four models are investigated and compared for calculating the aerodynamic load: standard strip theory (SST) [29], tuned strip theory (TST) [23], lifting line theory (LLT) [9] and the newly formulated modified strip theory (MST). In all cases, both aerodynamic force and moment of each chordwise section act at its aerodynamic centre (AC, where the aerodynamic load is applied [38]), whereas the fluid–structure interaction is enforced at its control point (CP, where the non-penetration boundary condition for the aerodynamic flow is imposed [38]). In particular, according to thin aerofoil theory for incompressible flow, the AC position $x_{AC}(y)$ and the CP position $x_{CP}(y)$ fall at the first and last quarters of the wing section chord $c(y)$, respectively. With $\alpha(y)$ and $\alpha_r(y)$ the total and reference angles of attack of the airflow, respectively, each wing section has its own camber and is characterised by its own zero-lift

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