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EFFICIENT COMPUTATIONAL METHODS FOR FLEXIBLE MULTIBODY DYNAMIC SYSTEMS WITH AERODYNAMIC INTERACTIONS

Henrik Hesse* **and Rafael Palacios**

Imperial College London, London SW7 2AZ, United Kingdom; h.hesse09@imperial.ac.uk.

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Geometrically-nonlinear beam theories are key in the development of highly-optimised, next-generation aircraft with higher-aspect-ratio wings [1]. To understand the static and dynamic characteristics of such vehicles, one needs to couple composite beam formulations with appropriate aerodynamic models with arbitrary kinematics. This requires efficient computational methods starting with the flexible multibody dynamic description to reduce the numerical burden of solving the coupled geometrically-nonlinear equations of motion (EoM). Only then are such higher fidelity tools attractive (and applicable) in the preliminary design of more efficient aircraft and large offshore wind turbines.

To address this, we have coupled a displacement-based, geometrically-nonlinear flexible-body dynamics formulation [2], as proposed by Géradin and Cardona [3], with a three-dimensional (3-D) unsteady aerodynamics solver [4]. Both ingredients in the coupling are geometrically nonlinear and can be used to assess the effect of wing bending at trim on the vehicle lift distribution its impact on the vehicle dynamic stability characteristics. This is illustrated in Figure 1 which shows the trim deformations of a UAV with increasing wing flexibility. However, even for extremely flexible configurations, the dynamic response is mostly driven by the large static deformations at trim [2].

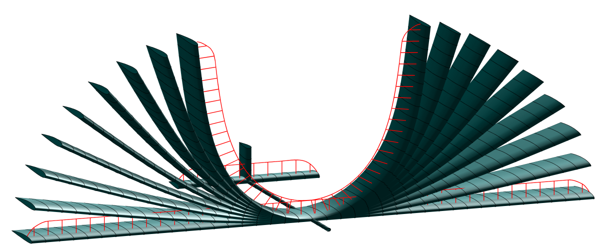

Figure 1: Trim deformations of a flexible aircraft with constant weight but increasingly flexible wings.

Hence, this work proposes a novel model reduction approach starting with a linearisation of the structural degrees of freedom (DoF) in the nonlinear flight dynamic response of flexible aircraft with geometrically nonlinear trim deformations. Note that this linearisation is consistent, such that the overall motions of the vehicle are allowed to be arbitrarily large and the inertial couplings between the large rigid-body dynamics and small structural deformations are preserved. As a result, the structural DoF of the coupled (nonlinear) system can be projected onto the vibration modes of the unconstrained vehicle. This allows the modal coefficients to be written in constant tensor form with up to cubic terms in the nonlinear flight dynamics, which are sparse and can be pre-computed.

Such a modal description significantly improves the numerical efficiency of the flexible-body EoM, but also provides a generic platform for coupling with time-domain unsteady aerodynamics models of different fidelities. In such a framework the inputs to the aerodynamics model are the transient elastic deformations (around a geometrically-nonlinear static equilibrium) and the aerodynamic inputs including atmospheric disturbances and control surface inputs. In this work we demonstrate the proposed model reduction approach using a linearized 3-D unsteady vortex lattice method [4]. This provides a medium-fidelity description of the nonlinear flight dynamics of very flexible aircraft with model orders of $\mathcal{O}(10^4)$ of the underlying linear aeroelastic system. We address this large system size using a modified balancing method to arrive at robust small-order representations of order $\mathcal{O}(10)$ even for possibly unstable plants. Numerical examples finally demonstrate this approach for a complete stick-to-stress description of flexible manoeuvring aircraft for load alleviation in nonuniform gust events. The focus has been on robust control methodologies which require a low-order representation of the full vehicle description, including geometrically-nonlinear effects, unsteady 3D aerodynamics and wing-mounted actuators and sensors.

The approach will be demonstrated here for large aeroelastic systems, but applies equally to multibody systems with nonholomonic constraints, as demonstrated for large wind turbines with tower dynamics and possible base motions [5].

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