

NUMERICAL VALIDATION OF A HIGH-ASPECT RATIO WING FLEXIBLE AIRCRAFT MODELLED IN AN ENHANCED LOW-FIDELITY FRAMEWORK

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ABSTRACT

The aviation industry has been continuously seeking forms to enhance the aircraft's aerodynamic efficiency, thereby reducing the environmental impacts associated with standard flights. Given these constraints, aircraft designers have focused on reducing the aircraft's weight while maximizing its lift-to-drag ratio by applying slender elongated wings, the so-called High-Aspect-Ratio Wings (HARWs). This type of airframe minimizes induced drag and hence fuel consumption. However, lightweight HARWs introduce substantial structural flexibility to the vehicle, defining the class of flexible aircraft. In this case, flexibility effects can no longer be treated as separate secondary phenomena but instead become integral to the aircraft's behaviour [1]. The low-frequency elastic modes may overlap with rigid-body flight dynamics, yielding unprecedented coupling effects.

Predicting these phenomena is even more challenging when flying in the transonic regime. In this case, viscous and compressibility effects drive shock formation and unsteady buffet effects. All together, these synergic effects demand simulation tools descriptive enough to capture their full complexity. The integration of Computational Fluid Dynamics (CFD) and Computational Structural Dynamics formulations allows the characterization of such phenomena. However, despite recent advances in computational performance, modern CFD/CSD solvers still require massive simulation time and are therefore unsuitable for preliminary design, multi-disciplinary optimization and real-time applications involving flexible aircraft.

To address this problem the TU Berlin - ModSiG (Modelling and Simulation Group) has created a numerical low-fidelity framework for simulation of flexible aircraft. The coupled aircraft dynamics is written on the basis of the linearized mean axes constraints [2], and the principle of modal superposition is applied. An unsteady strip theory formulation in the time-domain is used to calculate the incremental aerodynamic forces and moments [3]. As a result, this framework presents high computational performance and resemble higher complexity models well enough so that control design, testing and flying quality analyses are possible.

Therefore, this work describes the methodology behind the ModSiG framework, and the modification of the low-fidelity unsteady strip theory with data derived from higher-fidelity CFD simulations to sufficiently account for transonic dynamics. The derived model is numerically validated for the DLR-F25 virtual reference aircraft [4], see Fig. 1, through a comparative analysis of its longitudinal behavior against full CFD data in the time- and frequency-domains.



Figure 1: DLR reference aircraft F-25, retrieved from [5]; licensed under CC BY-NC-ND 3.0.

Results show a fairly good qualitative and quantitative agreement in both time and frequency domains, as shown exemplary in the next figures.

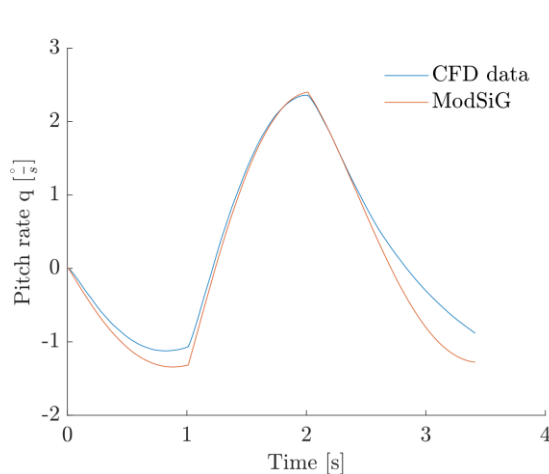


Figure 2: pitch response in the center of gravity due to a 1 Hz elevator doublet.

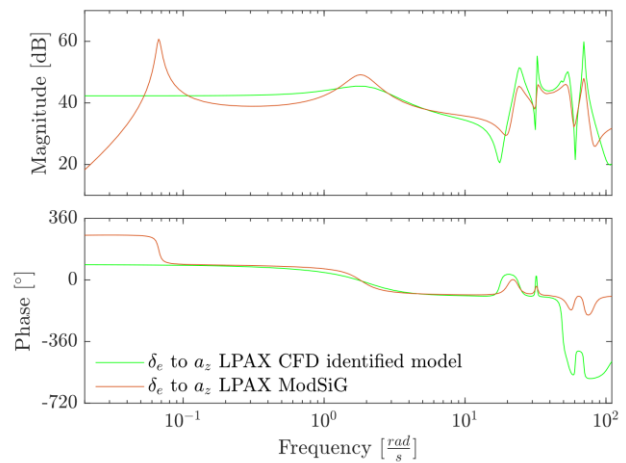


Figure 3: Bode diagram of the transfer functions from the elevator to a discrete point of the aircraft at the position of the last passenger derived from the ModSiG and CFD data.

Figure 2 displays the reaction of the pitch rate in the centre of gravity due to a 1 Hz elevator doublet. Figure 3 displays the Bode diagram of the transfer functions from the elevator to a discrete point of the aircraft at the position of the last passenger derived from the ModSiG and CFD data.

These results are reinforcing the framework's ability to capture complex transonic aeroelastic effects with high computational efficiency, enabling e.g. the real-time simulation of flexible aircraft into the transonic regime.

[1] Silva, G. C., Silvestre, F. J., Donadon, M. V., “Aeroelastic Analysis of a Smart SMA-Composite”. In: Proceedings of the International Forum on Aeroelasticity and Structural Dynamics (IFASD), 2024, The Hague, The Netherlands.

[2] Waszak, M. R., and Schmidt, D. K., “Flight Dynamics of Aeroelastic Vehicles,” AIAA, 1988. <https://doi.org/10.2514/3.45623>.

[3] Quesada, A. A. G., Gonzalez, P. J., Barbosa, G. C., Stavorinus, G., and Silvestre, F. J., “Influence of Nonlinear Aerodynamic Effects on High Aspect Ratio Aircraft Model,” International Forum on Aeroelasticity and Structural dynamics (IFASD), 2024.

[4] Wöhler, Sebastian und Häßy, Jannik und Kriewall, Vivian (2024) Establishing the DLR-F25 as a Research Baseline Aircraft for the Short-Medium Range Market in 2035. 34th Congress of the International Council of the Aeronautical Sciences, 2024-09-09 - 2024-09-13, Florence, Italy.

[5] DLR Institute of System Architectures in Aeronautics, <https://www.digital-hangar.de/media/>, accessed 15.01.2026