Modular programming approach to aircraft static aeroelasticity

Arthur Rizzi[1], Mengmeng Zhang[2], and Jesper Oppelstrup[1]
[1]KTH Royal Institute of Technology, Sweden [2]AirInnova AB, Sweden

Abstract
Prediction of aircraft wing shapes in steady load conditions is a classical FSI problem. CFD and CSM tools need to be combined to solve it. The paper describes the use of loosely-coupled computational modules for structural (computational structural mechanics, CSM) and aerodynamic (computational fluid dynamics, CFD) analysis in prediction of static aeroelastic effects. The models are used to predict the flight shape and determine speed limits for "divergence", i.e. run-away increasing deformations, and "control surface loss of authority", i.e. the (in)effectiveness of control surfaces in a deformed state.
The modularity allows a certain amount of plug-and-play of CFD and CSM modules which interact in the "Aero-Elastic Loop" by exchanging data in a common format, without one code knowing the characteristics of the other.
Figure 1 pictures the loosely coupled system of a CFD module and a CSM module exchanging data through a defined data set in the AeroElastic Loop. The process starts with the unloaded jig shape, for which the CFD module computes the aerodynamical forces. These are mapped to forces (and moments) understood by the CSM module which proceeds to compute the resulting displacement to the jig shape. These are mapped to deflections of the CFD geometry and the process can be iterated.

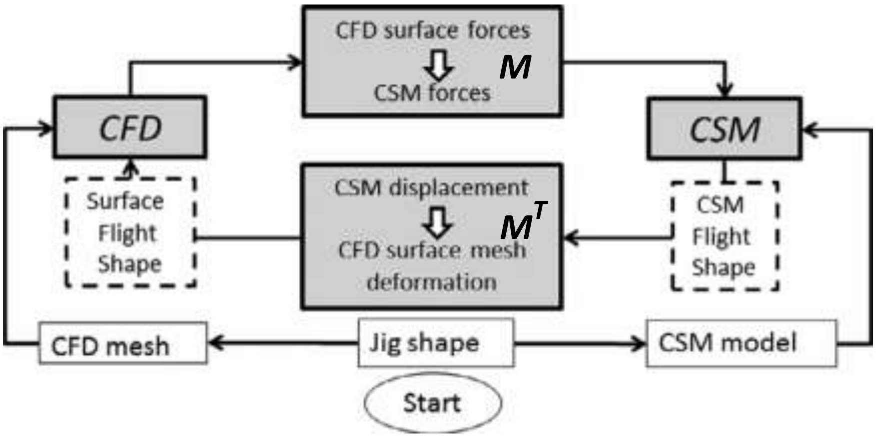

Figure 1: The Aero-Elastic Loop.

A simplistic algorithmic loop for computing the flight shape for a given jig shape and flight state results from running the AEL as the figure shows. The map of displacement is the adjoint to that of forces as required by energy conservation. This holds even if the CSM degrees of freedom include rotations although the aerodynamic forces are only point forces and no couples.
The classical models rely on linear potential flow models enhanced with localized vorticity in sheets (ref. 6) and "equivalent beam" finite element models for the structures (ref. 1). Results from a pilot system compare such computations with windtunnel experiments.
The fidelity of results can be increased by replacing the potential flow solvers by CFD and the beams by detailed FE models of the structure. Such plug-and-play precludes easy assembly of a linearized system matrix since most CFD modules do not provide relevant matrices.
The linearized problem is $(K - q\, M\, AIC\, M^T)dS = qb$ where q is the dynamic pressure, K the tangent stiffness matrix and dS the displacements of the structural model. The matrix AIC is the aeroelastic influence matrix of displacements on aerodynamic forces and not available as natural by-product of the CFD solution process. However, its effect on a given displacement dS vector is computed in the AEL, so the AEL can build relevant Krylov subspaces. Deformations for a linearized aero-elastic model and given *q* can be computed by iterative methods such as GMRES (ref 3). For the linearized problem divergence occurs when *q* is the smallest positive number (if any) to give

$$(K - q\, M\, AIC\, M^T)\, dS = 0, \text{ with } dS \text{ non-zero},$$

The eigenvalues *q* can be computed by the Arnoldi scheme requiring only AEL iterations (ref. 5).

References

[1] W. P. Rodden. *Theoretical and Computational Aeroelasticity*, 1st edition. Crest Publishing, 2012.
[2] E. H. Johnson, *MSC Developments in Aeroelasticity*, The MacNeal-Schwendler Corporation 815 Colorado Blvd., Los Angeles, California 90041
[3] Y. Saad and M. B. Schultz. GMRES: *A generalized minimal residual algorithm for solving nonsymmetric linear systems*. Siam Journal on Scientific and Statistical Computing, 7(3): 856–869, 1986.
[4] A. Dettmann. *Loosely Coupled, Modular Framework for Linear Static Aeroelastic Analyses*. Diploma thesis, KTH School of Engineering Sciences, 2019
[5] R. B. Lehoucq, D. C. Sorensen, and C. Yang. *ARPACK Users' Guide: Solution of Large-Scale Eigenvalue Problems with Implicitly Restarted Arnoldi Methods*. SIAM, 1998
[6] M. Drela. *Flight Vehicle Aerodynamics*. MIT Press, 2014