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Coupling of MBS and CFD: an Oscillating Aeroelastic Wing Model

Multi-body simulation has been shown to be a valuable software tool for virtual aircraft design. It is a standard approach for the analysis of landing gears, of aircraft on the ground, and for the design of high-lift systems. The medium level of complexity of typical multi-body models also makes it a suitable tool for the application of flight mechanics in combination with elastic deformations. The development of reliable aerodynamic models, in addition to the existing interface for complex elastic structures, has been a major activity in the DLR Institute of Aeroelasticity during the past several years. The coupling procedure of SIMPACK to CFD is shown in this article for the application of the Aeroelastic Model Programme (AMP) wind tunnel wing simulated with SIMPACK and the DLR TAU code.

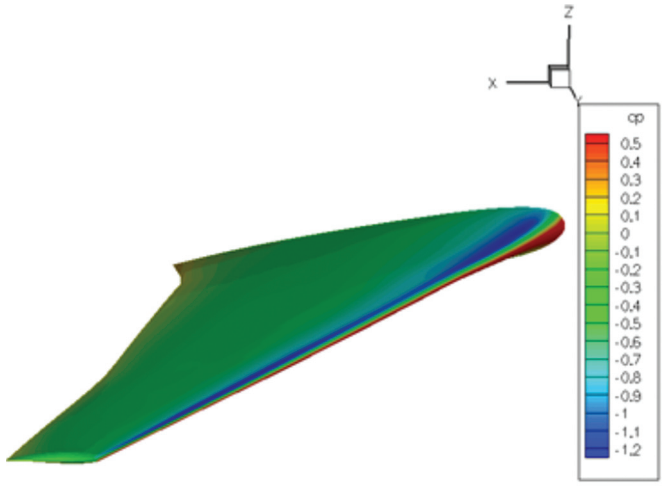

Fig. 1: CFD model of the AMP wing

AEROELASTIC SIMULATION USING SIMPACK AND CFD

Aeroelastic simulations in terms of pure fluid-structure interaction have reached a satisfactory level of maturity for both steady and unsteady problems. A step beyond this classical scope is the additional consideration of large motions superimposed by flight maneuvers. In DLR, such a coupling has been developed based on elastic multi-body systems coupled with CFD calculation. The intention of this article is to describe the model set-up used for the coupled calculations, as well as to describe the options to introduce MBS-generated motions into the CFD calculations. Results are given for the so-called AMP wind tunnel model for heave and pitch oscillations at a Mach number of 0.6. A more detailed illustration of the work as well as a list of references is given in [1].

GENERAL SET-UP

For the simulation of a complete elastic aircraft using MBS, the flight mechanics (FM)are represented as non-linear MBS joints. This approach is possible for transport aircraft, where the flight mechanics can be a 6-degree-of-freedom joint, but also for wind tunnel models with a reduced number of degrees of freedom or for helicopters, where the complex kinematics of the system (e.g. the rotor hub) can be introduced. The elastic members are included in modal form

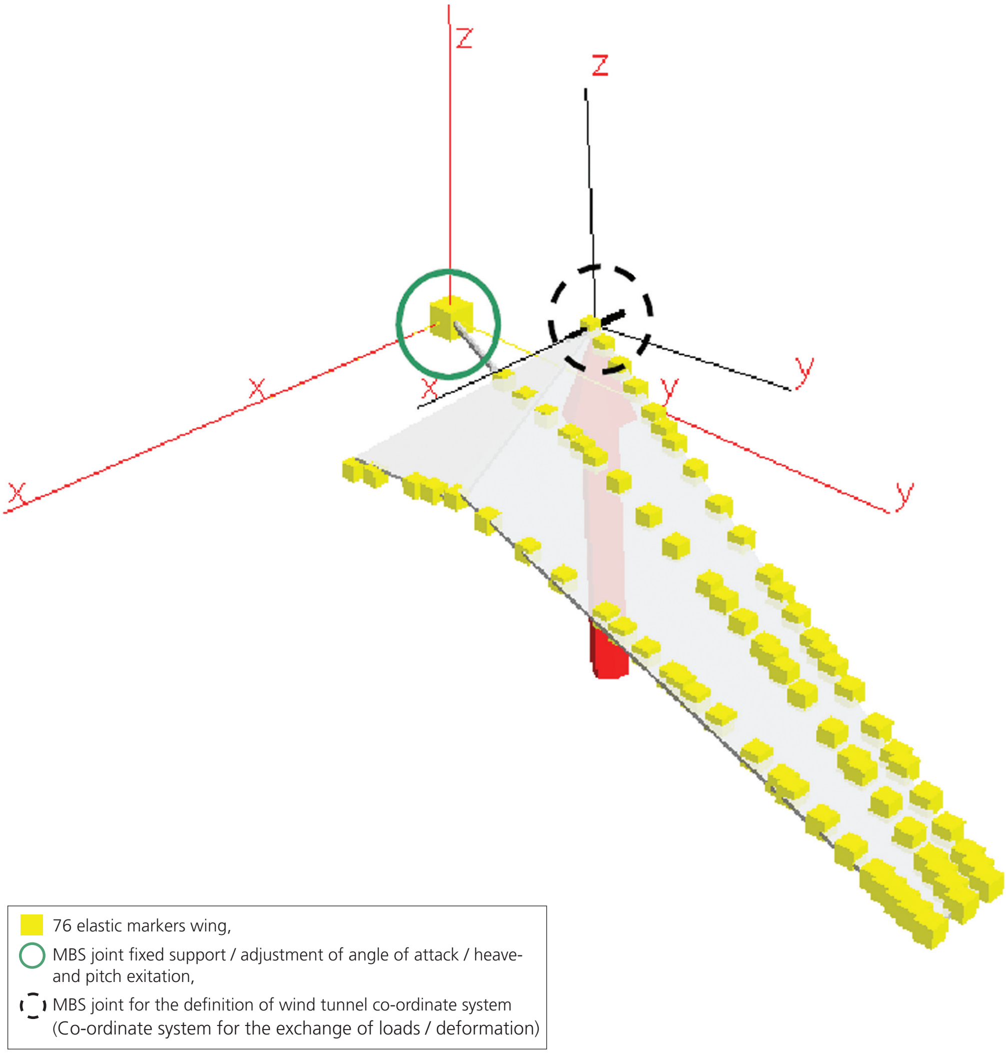

Fig. 2: MBS model of the AMP wing

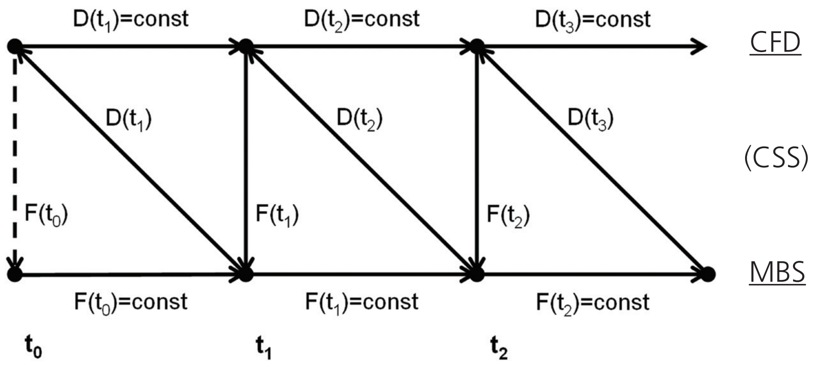

Fig. 3: Temporal coupling scheme

via the FEMBS interface, the equations of motion solved by the MBS tool. The CFD-based aerodynamics are calculated by a dedicated CFD solver and coupled to the MBS system via co-simulation.

CFD

The behavior of the flow around the wing is simulated with the TAU Code, a CFD tool developed by the DLR Institute of Aerodynamics and Flow Technology. The TAU Code solves the compressible, three-dimensional, time-accurate Reynolds-averaged Navier-Stokes (RANS) equations using a finite volume formulation. The TAU Code is based on an unstructured grid approach, capable of using hybrid grids.

> *"The data transfer is performed via the Python program and a socket connection using the SIMPACK IPC co-simulation interface."*

The TAU Code functionality is organized into modules. The following modules have been used for the process described in this paper: the Preprocessor module, which uses the information from the initial grid to create a dual-mesh; the Solver module, which performs the flow calculations on the dual-mesh and applies guided rigid body motions when specified; the Deformation module, which propagates the deformation of surface coordinates to the surrounding grid; and the Postprocessing module, which is used to convert TAU Code result files to formats readable by popular visualization tools.

The Solver module can be executed in Euler mode, or using Navier-Stokes (RANS) equations with 1-Equation or with 2-Equation turbulence modeling. The results shown in this paper are all based on the Euler mode. This is mainly done for reasons of computation time. The coupling procedure as such is identical for RANS calculations. For steady calculations, an explicit multistage Runge-Kutta time stepping scheme is used. For time-accurate computations, an implicit dual-time stepping approach is used. Fig. 1 shows the aerodynamic model of the AMP wing used in the work.

The TAU Code modules have been wrapped with Python interfaces, and can thus be used as library functions from within a Python script. To couple TAU to SIMPACK, the TAU Solver is called from a coupling script. The flight mechanic data calculated by SIMPACK is sent to the Motion module of the TAU Code, which builds the required transformation matrices used by the Solver module. The data transfer is performed via the Python program and a socket connection using the SIMPACK IPC co-simulation interface.

STRUCTURAL MODEL

The structural model of the wing has been set up in the FE code NASTRAN and has been subject to a modal analysis. The results have been exported to SIMPACK using the FEMBS Interface. The model used in SIMPACK consists of a wing model and model support represented by 76 markers on the elastic structure and 20 elastic modes. Fig. 2 shows the MBS representation of the structural model including the used reference frames and joints defined for prescribed motion.

SPATIAL AND TEMPORAL COUPLING

Due to the different discretizations of the CFD and the elastic MBS model, dedicated routines for spatial coupling have to be used. For time-marching simulation, a temporal coupling scheme has to be employed. Spatial coupling of SIMPACK to TAU is realized via the DLR inhouse development PyCSM. The approach makes use of node-based, conservative interpolation methods to map aerodynamic forces between structural and aerodynamic grids, and a non-conservative interpolation to map deformations.

CFD and MBS codes exchange their results (forces/deformation) at each simulated time step in co-simulation through a TCP/IP socket. The communication scheme is

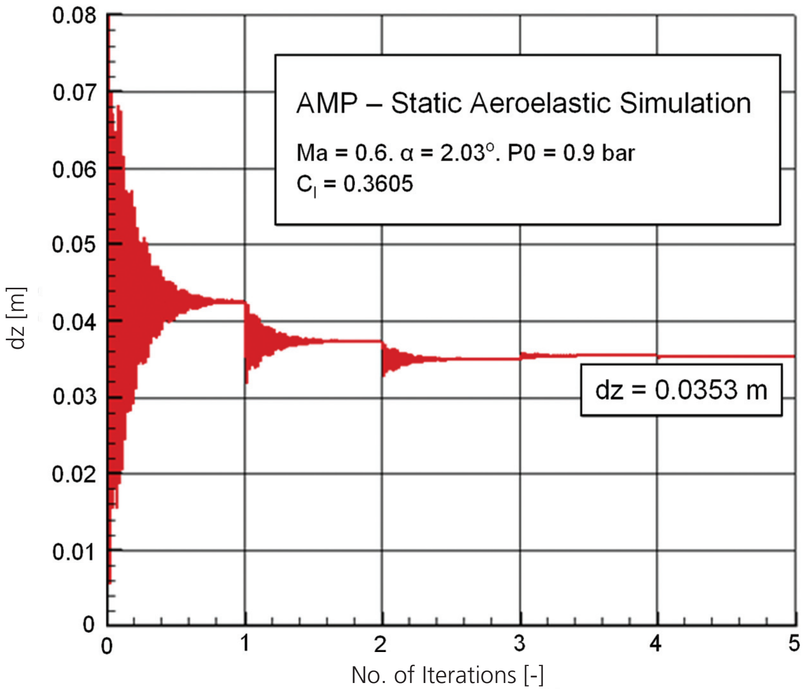

Fig. 4: Results of quasi-steady coupling

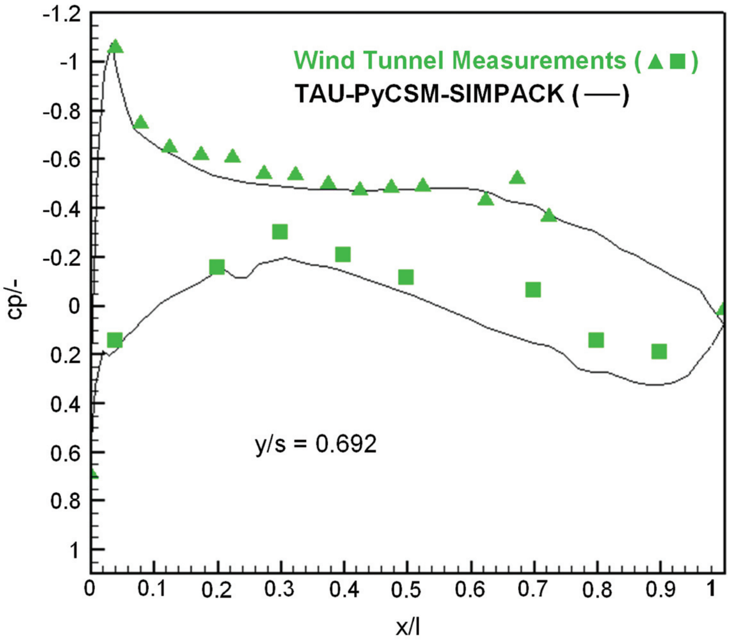

Fig. 5: Comparison of pressure distribution

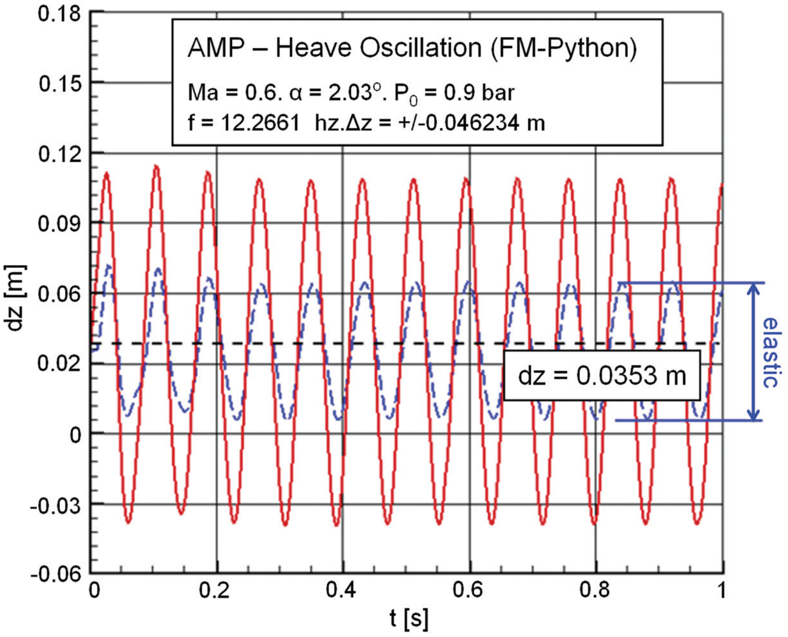

Fig. 6: Wing tip deflection for wing heave motion

the so-called 'Conventional Serial Staggered CSS', a first-order scheme, see Fig. 3. This approach allows TAU to run on a high performance computing cluster using highly parallel computation, if required.

SIMULATION RESULTS AND COMPARISON

The test cases used for comparison are simulations for a Mach number of 0.6, a pressure of 0.9 bar, and an angle of attack of 2.03°. Three different configurations are regarded, first a steady state solution, second a sinusoidal heave oscillation at the model support of f = 12.27 Hz and an amplitude of $\Delta z = \pm 0.0462$ m, and third a pitch oscillation at the same frequency with a pitch of $\Delta\alpha = \pm 0.5°$ around the same point. For the pitch and the heave case, the resulting motion of the wing tip will be a combination of rigid body motion of the excitation plus an elastic structural deformation.

STATE OF EQUILIBRIUM

The state of equilibrium for the deformed AMP-Wing is computed with two different approaches, both starting from the undeformed wing shape. First, a quasi-steady coupling procedure, taking five coupling steps into account (see Fig. 4), second, a transient simulation for the physical time t of 1.0 s using time-accurate unsteady aerodynamics and 500 co-simulation steps.

The resulting static deformation at the wing tip in the *z*-direction and the constrained force in the *z*-direction at the support are the same for both approaches with steady and unsteady aerodynamic forces. Values of 0.0353 m and 1853 N are obtained in the wind tunnel coordinate system. To validate the result, pressure distributions of the experiment have been compared to the results obtained with CFD/MBS. Numerical and experimental results correspond very well; see Fig. 5 for data at a location of 69.2 % wing span.

HEAVE AND PITCH OSCILLATIONS

Two different approaches have been investigated to find the response of the elastic AMP-Wing to the forced heave and pitch excitations at the model support. The first approach represents the rigid body motion due to heave excitation and the elastic wing deformation from aerodynamic loads together in the TAU Deformation module. The second approach uses the TAU Motion module to represent the heave or pitch, and the Deformation module to represent the elastic deformation only. In the latter approach, the Motion module is supplied with twelve flight mechanics (FM) parameters. The FM-parameters are comprised of three angles and angular rates, each in the body coordinate system and three translations and translational velocities each defined in the geodesic coordinate system. They are measured as MBS sensor data and communicated through a Python-shell to the TAU Motion module.

The oscillating deformation at the wing tip in the *z*-direction and the constrained force in the *z*-direction at the model support are the same for both approaches. This is true for the heave as well as for the pitch case. Fig. 6 shows the corresponding time histories of the wing tip deflection for the heave case. The red line represents the total deflection; the blue line the purely elastic part of deflection. Pitch oscillation data look very similar and are given in [1]. Unfortunately, no experimental results for direct comparison are currently available for these cases.

OUTLOOK

The work described has been a test case for the interface of SIMPACK to CFD aerodynamics, i.e. the TAU Code. This coupling is of great interest for aeronautical applications both in the area of fixed wing aircraft and for helicopters. The implemented approach forms the basis of an extensive application of MBS/CFD coupling pursued by the DLR Institute of Aeroelasticity.

REFERENCES

[1] Arnold J., Einarsson G., Krüger W. R. (2009): "Multibody simulation of an oscillating aeroelastic wing model." NAFEMS International Journal of CFD Case Studies, Volume 8, pp 5-18.