Multibody Simulation of Low Frequency Aeroelastic Wing Loads

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SUMMARY

Aircraft wings are frequently fitted with outboard equipment, either with external fuel tanks to augment the mission range, research or military aircraft with various sensors for scientific or reconnaissance missions, and of course combat aircraft with missiles or bombs. These external devices not only influence the aerodynamics of the wing, they also change considerably the structural behavior of the wing and the flight mechanics. The release of such equipment leads to peak loads on the wings which can be rather high, especially if the aircraft is in a special flight condition, e.g. a high-g turn.

To enable a realistic assessment of the aeroelastic phenomena of aircraft, a simultaneous application of computational fluid dynamics (CFD), computational structural mechanics and flight mechanics has thus to be performed. The combination of CFD and elastic multibody simulation with its large number of interfaces to other disciplines systems is well suited for the simulation of a range of aircraft applications, especially for aircraft ground dynamics and store separation.

The article presents methods to couple aerodynamics, structural mechanics and flight mechanics in the time domain based on multibody dynamics in a virtual design environment. The applied programs and the coupling methods are presented. Advantages and limits of using multibody simulation as compared to the direct use of FEA methods for the representation of structural dynamics are discussed.

1.0 INTRODUCTION

1.1. Multi-Disciplinary Simulation in Aeronautics

The interconnection between the aerodynamic forces, structural deformations caused by these forces and the resulting feedback on the aerodynamic conditions, in combination with the impact of the overall dynamic behavior of the aircraft is a key element in lightweight aircraft design. Although the main aerodynamic forces will generally depend on the attitude of the aircraft and on control inputs by the pilot, aerodynamic effects due to airframe deformation may have a decisive influence on the system which has to be accounted for.

This article presents methods to couple aerodynamics, structural mechanics and flight mechanics based on multibody dynamics in a virtual design environment. Possible fields of application are widespread; for this work, we will concentrate on the needs and requirements of the following applications:

- simulation of the free-flying, manoeuvring large transport aircraft,
- simulation of the highly manoeuvrable fighter aircraft,
- ground dynamics analysis of large transports, and
- dynamic behavior and performance of new concepts and configurations.

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Examples for questions and problems to be solved by these analyses and simulations range from manoeuvre, gust or ground loads, store separation over flight control system design and other aspects of aeroservoelasticity, handling qualities, resonance and vibration problems to dynamic behavior and performance studies. The presented methods of coupling Computational Fluid Dynamics (CFD), Finite Element Analysis (FEA) and Multibody Simulation (MBS) in the time domain, however, limit the applicability to steady, quasi-steady and low-frequency unsteady aeroelastic effects; high frequency aeroelastic phenomena such as flutter will not be adequately represented by the approaches discussed here.

1.2. Finite Element and Multibody Simulation for Fluid-Structure Coupling

The coupling of fluid and structure has become a well developed topic in the finite element world. Consequently, in most applications finite element codes are used for the purpose of fluid-structure coupling. There are, however, a number of reasons to use applications with multibody codes in addition. MBS codes are generally used for the simulation of complex dynamic systems with large, non-linear motions. Examples are road and wheel/rail vehicles, aircraft and machines. In these simulations aerodynamic forces have often been used based on simple assumptions. In many applications, e.g. for automotive, trains, and, of course, aircraft on the ground and in the air, a detailed calculation of the aerodynamic forces is becoming more and more important. For this reason an interface of an MBS program (the MBS code SIMPACK [1] is used in the presented work) to CFD codes is essential.

Another field where a simulation using MBS methods is effective is the coupled aeroelastic simulation of the flying aircraft, i.e. when fluid-structure coupling interacts with flight mechanics and flight control. For this case multibody simulation with its large number of interfaces to other disciplines can be an integrating platform for the multidisciplinary simulation. Such an approach is used in the DLR for the aeroelastic simulation of an aircraft flying at high angles of attack based on the experience gained in the projects AMANDA and AeroSUM [2], [3].

2.0 APPROACHES TO AEROELASTIC COUPLING

Aeroelastic problems can be approached in two ways. First, structural elasticity and aerodynamics can be regarded as a combined mathematical system, as it is the case in classical flutter calculation [4]. Such approaches are performed as a rule in the frequency domain and are valid for small variations of the flow speed. For time simulation (close coupling) those approaches have to be transformed into the time domain by approximation functions (e.g. minimum state method, [5]). Another approach for a close coupling of structure and aerodynamics is the modal representation of aerodynamic effects as presented in Section of this article.

A different coupling method suited for time simulation is the subsequent, separate but coupled calculation of structural deformations and aerodynamics, often called co-simulation. With this so-called loose coupling aerodynamic and structural models can be of different complexity, depending on the requirements, i.e. the structural deformation can be linear or non-linear, the aerodynamics can range from linear models to highly complex CFD models, see Section of this article.

An interesting aspect of the presented methods is the possibility to be part of a chain of couplings of varying model complexity. Using methods of varying complexity on both the structure and the aerodynamics side a thorough design chain can be established from pre-design to high fidelity analysis, Figure 1, [6]. The example given in Section 4 depicts that philosophy.

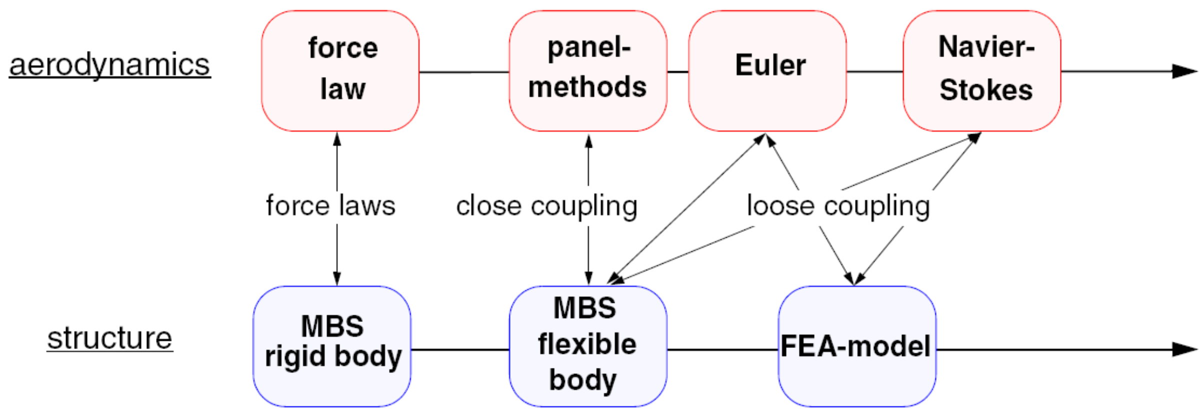

Figure 1: Aerodynamics/structure interaction of varying complexity

2.1. Spatial Coupling of MBS and CFD Models

Since CFD grids and structure grids usually do not match and are often even of vastly differing complexity, an interpolation between the grids is necessary (see e.g. the application example in Section 4.1, Figure 6). This problem is independent from the question whether the model is regarded inthe time domain or in the frequency domain, and whether close coupling or loose coupling techniques are used. Such interpolation routines have to transform forces on grids from CFD to the structure and the deflection of grid points from the structure to CFD. The transformation has to be such that the work (i.e. the forces multiplied with the respective deflections) comes out to be the same both on the structure and on the aerodynamics grids in order that no energy is dissipated or added to the system. For this reason the transformation matrix for transforming the forces $F_{struc} = T * F_{aero}$ is determined such that the transposed of the transformation matrix can be used for interpolation of the deflections $d_{aero} = T^T * d_{struc}$. A boundary condition for the calculation of T is usually that deflections have to be smooth over the surface and must not distort the net. A number of interpolation algorithms exist [8]. They might differ considerably in the interpolation results depending on the application, so a careful choice of the algorithms used is necessary.

For the work presented in this article the coupling library MpCCI (Mesh-based parallel Code Coupling Interface) developed at the Fraunhofer Institute for Algorithms and Scientific Computing (SCAI) [7] has been used. For the interpolation a neighborhood search and different standard interpolation algorithms (e.g. trilinear splines) are implemented in MpCCI. These interpolations have been used for the first proof-of-concept couplings between SIMPACK and the CFD code. For further applications, e.g. the coupling with slender wings, additional interpolation routines, based on finite interpolation elements and radial basis functions have been introduced as user-defined interpolations [9].

2.2. Close Coupling: Modal Aeroelasticity

The Principle of Modal Aeroelasticity in MBS:

For a free-flying airplane, three main sources of aerodynamic forces can be identified:

- rigid body aerodynamics, i.e. the aerodynamic forces acting on the aircraft in its undeformed reference configuration;
- aerodynamic force increments deriving from deflections of the aircraft structure;
- aircraft control forces due to deflections of control surfaces (primary or secondary controls, lift dumping devices, etc.).

For a wide range of applications, the resulting aerodynamic forces and their distribution on the aircraft structure can be found by superposing these airloads linearly, as indicated in Figure 2.

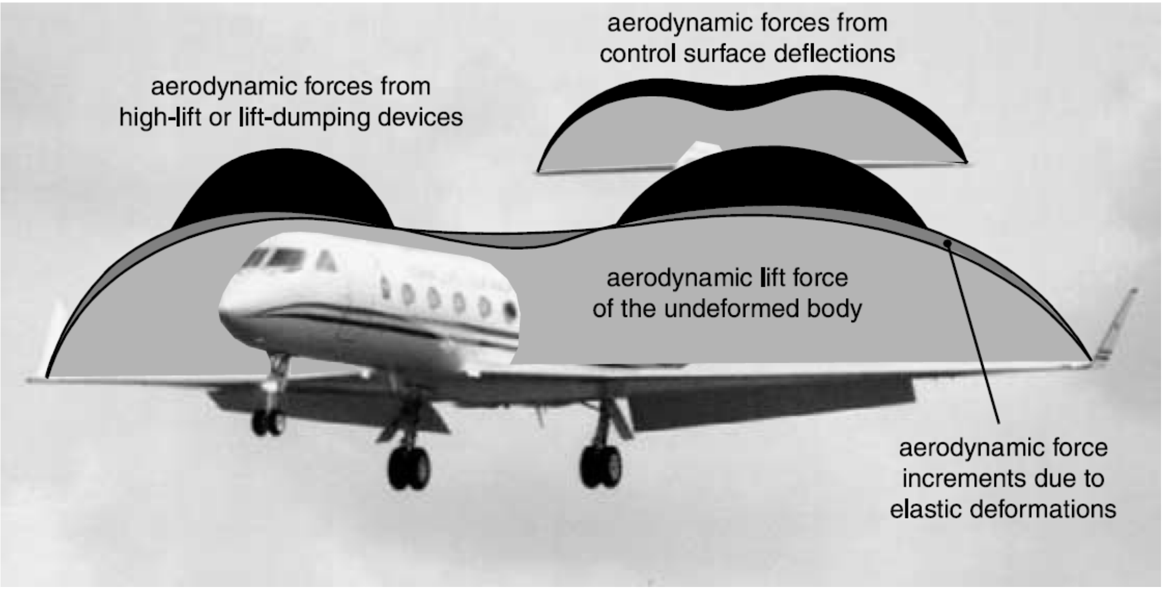

Figure 2: Superposition of aerodynamic effects

Elastic deformation and aerodynamic forces deriving from body deflection are closely connected. The deformability of a body of a multibody system is reduced to a limited number of deformation forms, the base functions of the Ritz approach. The actual body deformation, depending on the state of the system, its boundary conditions and applied and constrained forces, is found by a linear superposition of these basic, independent deformation modes. An elastic coordinate represents a time-dependent weighting factor which determines the contribution of its corresponding mode to the overall deformation.

It should be noticed that aeroelastic effects on an elastic MBS body can only derive from these modes of deformation, i.e. they are “linked” to the base functions, eigen- and static modes of the deformable body, which are selected in the process of generating the modal coefficient matrices. Computing the aerodynamic effects of a body deflection given by each base function which is used for elastic body representation and superposing them according to the deformation state automatically delivers the corresponding aerodynamic state of forces on the body, and vice versa. Accordingly, this approach may be termed “modal aeroelasticity”.

This approach of linking normalized aerodynamic modes to other quantities affecting the aircraft's dynamic behavior is not necessarily limited to elastic deformations. Rigid body and control deflection modes, i.e. generalized rotations or displacements of the rigid airframe body and its control surfaces, can be added to deliver the rigid body aerodynamics and aircraft control forces.

Naturally, a superposition of linearized aerodynamic effects represents a considerable simplification of the actual aerodynamics of the aeroplane. Several assumptions have to be valid for this method to deliver good results: the general principle of modal representation of elastic bodies in MBS must be valid, the overall aerodynamic conditions are of (quasi-)steady nature, any time lag between cause (e.g. structural deformation) and effect (e.g. resulting airloads) may be neglected, and aerodynamic forces on the aircraft stand in a basically linear relation to the state of the system (attitude, control surface deflection), respectively they may be linearized in sections around given working points. Finally, although the effects of an aerodynamic mode, even if it derives from a local displacement or control input, may have impact on the overall air load distribution, it is required that the various aerodynamic modes are decoupled, i.e. every aerodynamic mode is independent (qualitatively and quantitatively) from the state of another aerodynamic mode.

Fortunately, these assumptions hold for a wide range of applications, allowing to compute the elastic, aerodynamic and, consequently, aeroelastic properties of a MBS body prior to the actual multibody simulation. Thus, when modelling an aircraft for a "multidisciplinary" multibody simulation, the basic structure (mainly bodies and connections) is set up in the MBS environment.

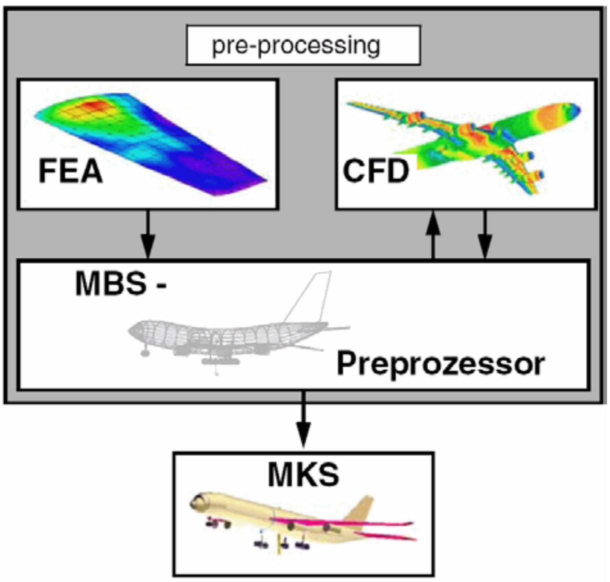

Figure 3: Structure of modal aeroelasticity

The aeroelastic model data is not a decoupled, "stand-alone" solution but is dependent on the results of the FEA analysis. The main quantities the aerodynamic analysis of the aircraft has to deliver are the rigid body derivatives of the aircraft attitudes, control inputs and manoeuvres (to account for the aircraft overall motion), and the corresponding aerodynamic loads on the deformable structure (to be further processed to yield the aeroelastic matrices). Thus, the equation of motion of the single, flexible body can be enhanced by the modal aeroelastic matrices of the rigid body motion, control surface deflection and elastic deformations.

The CFD reference cases should correspond to the MBS scenario. A landing sequence, for example, may use a CFD analysis file of the aircraft at approach angle-of-attack and an analysis file of the aircraft in derotated attitude. For MBS simulation, the aerodynamic properties are then interpolated between these sampling points or switched by root functions. Additional sampling points can be used to improve accuracy. The influence of ground effect and adjustment factors which allow to account for losses of control effectiveness at larger flap deflection angles may be included as well.

Summarizing, the method of modal aeroelasticity has three major advantages:

- The necessary FEA and CFD analyses can be computed in a preprocessing step to the MBS evaluation. For a "frozen" design step, i.e. the basic structural and aerodynamic properties of the aircraft remain constant, the MBS input data from FEA and CFD can be used for dynamic simulations without the need for time-consuming recomputations of the MBS input files.
- The MBS input data can be derived from existing FEA and CFD reference models. Most of the process can be automated; the set-up process is straightforward and assisted by various tools, e.g. for setting up the analysis process or interpolation of the CFD and FEA discretisations. Only little user input and no deeper knowledge in computational fluid dynamics is required to run the preprocessing routines.
- The principle of aeroelastic modes allows for a very efficient time integration of the multibody simulation. It includes aerodynamic effects on deformable aircraft structures in MBS in a robust computation process and with only little penalties in respect to computation times.

It has nevertheless to be kept in mind that the approach can be applied only to applications where the prerequisites of approximately linear aerodynamic conditions around a given working point and of widely decoupled influence factors hold.

2.3. Loose Coupling: Co-Simulation of CFD and MBS

In Section an approach based on modal representation of the aerodynamic forces has been presented for aeroelastic simulation in the time domain. There is another common approach for the coupling of fluid and structure, based on a co-simulation of a CFD tool, often Euler or Navier-Stokes calculations, and a structural solver, here the MBS code. Using this method, both engineering disciplines use the tool optimized for their special purpose and models, and aerodynamic models of much larger complexity are applicable than in the close coupling. During simulation the CFD tool solves for the forces and moments on a structure which are passed to the MBS code. The MBS code then calculates a new aircraft position, attitude and deflection of the elastic body based on the aerodynamic forces, which are then, in turn, passed back to the CFD tool for a new aerodynamic calculation. Figure 4 shows the principle of such a coupled calculation.

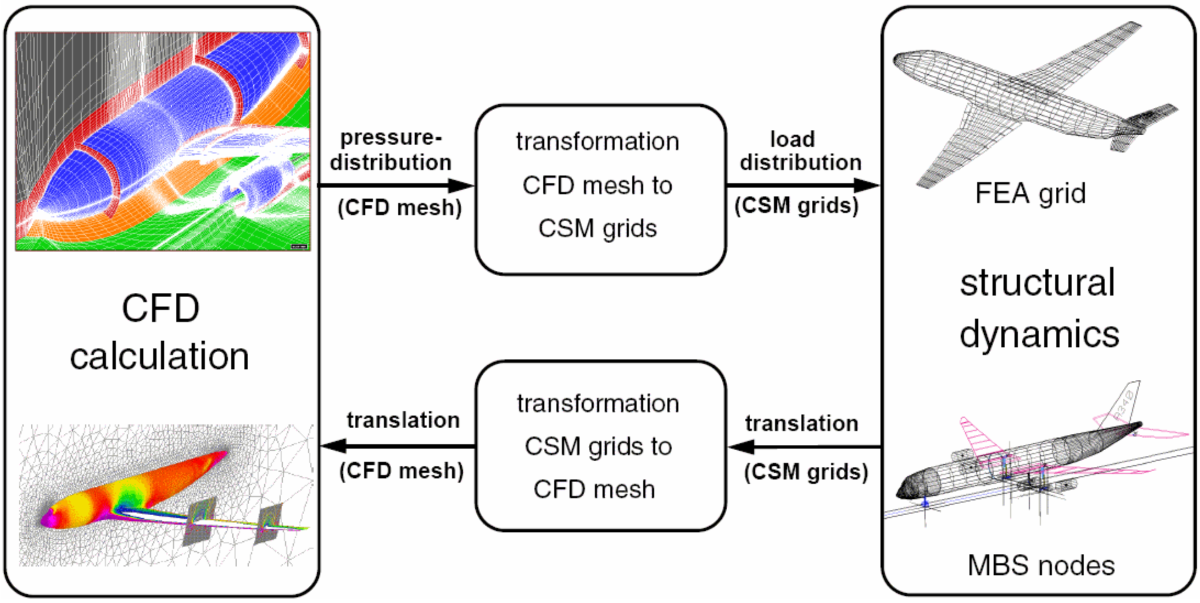

Figure 4: Loose coupling of fluid and structure

Such a procedure poses a number of obstacles - first, the data handling is non-trivial, as commonly large models and amounts of data are used in CFD calculations, often on distributed computers and with considerable calculation times. Second, as indicated in Fig. , the spatial discretization of aerodynamic and structural model is, as a rule, different, so interpolation algorithms between the respective grid systems have to be used (see Section 3.1). Third, to allow the programs to make use of their respective optimized solvers, the data exchange is usually performed at discrete time points. This has a large influence on the numerical stability of the coupled solution.

In a full aeroelastic simulation of CFD and MBS several codes are involved. In the work presented here, SIMPACK and the CFD-code FLOWer have been used. FLOWer, a tool developed at DLR [10], [11], solves the Reynolds- averaged, three-dimensional, complete Navier-Stokes or Euler equations. It is a finite volume method on structured multi-block grids. For the spatial discretization a central scheme with artificial dissipation is used. The time integration is based on a multi-step, explicit Runge-Kutta scheme.

For turbulence modeling, algebraic as well as different transport-equation turbulence models are available. A convergence acceleration for stationary cases is reached using local time-stepping, implicit residual smoothing, and multi-grid techniques. For a further drastic reduction of response time, FLOWer has been parallelized. For an efficient simulation of instationary flows an implicit dual time-stepping method has been implemented in FLOWer [12]. Contrary to the explicit basic scheme it allows the selection of a time step in accordance to the instationary, physical problem, without stability restrictions.

For the simulation of rigid body motion all six degrees of freedom are supported by FLOWer. A relative motion of bodies is possible by the Chimera technique (overlapping grids). Thus, a motion of, e.g., ailerons or the elevator is possible. For the use in aeroelastic simulations FLOWer has been expanded to deformable meshes. The grid is deformed starting from the deformation of the surface of a wing or aircraft using algebraic algorithms. The deformation of the grid becomes smaller as the distance of the grid points from the surface increases and becomes zero at the boundary. Alternatively, a grid generator can be used which reads in a deformed surface geometry and generates a deformed mesh with identical topology to the undeformed mesh. The deformed mesh is than read by FLOWer at the beginning of a new time step. For the communication between SIMPACK and FLOWer and the interpolation between the different grids the coupling library MpCCI is used (see above).

Further tools are needed for the pre-processing of the models. The structural elasticity in the SIMPACK model is represented using the modal approach. The original FE model has been set up in NASTRAN and transferred to SIMPACK in a pre-processing step via FEMBS. The CFD-grid is also generated in a pre-processing step and read by FLOWer. The grid deformation tool used in the example is implemented as part of FLOWer. For the whole work flow of the co-simulation see Figure 5.

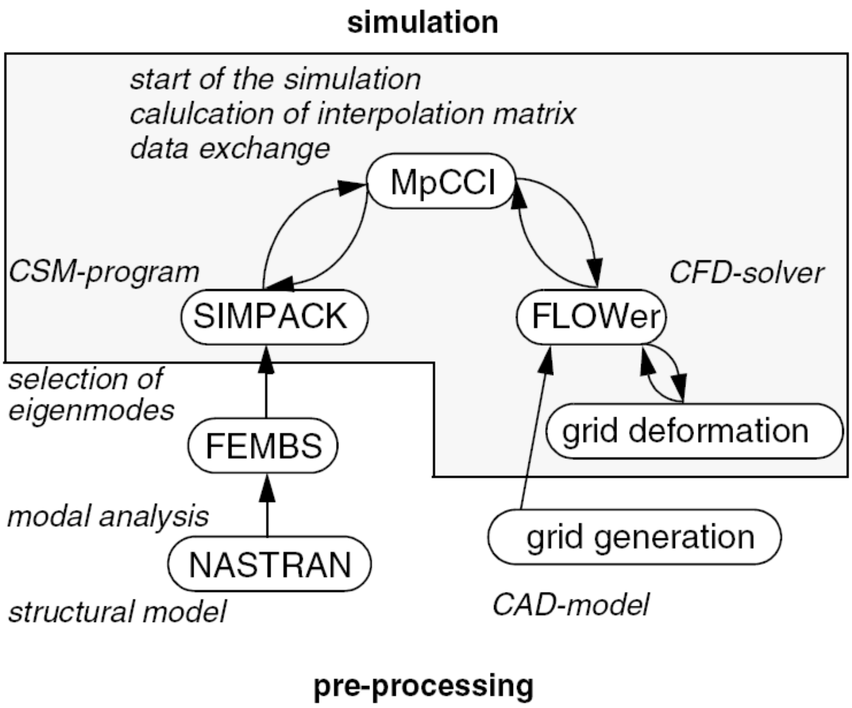

Figure 5: Work flow for co-simulation of MBS and CFD

Time Discrete Coupling:

Aeroelastic cases can be divided into stationary and instationary problems. For a completely stationary coupling, the CFD code and the structure code are called alternately, each one computing a stationary solution in its domain and passing the result to the other domain. If the system is well behaved, the solution converges to a stationary state within a limited number of iterations [8]. Convergence, however, cannot be guaranteed [14]. Coupled time simulations require the codes to calculate instationary solutions. Usually each discipline uses its own optimized solvers, communicating at discrete time points. Most often, explicit coupling schemes are employed, communication is performed forward in time, not using old results. A first order coupling scheme is still state-of-the-art, being sufficient for many applications [15]. However, numerical stability decreases for systems with low damping, and small step sizes are required for phenomena with higher frequencies, leading to extremely high computation times when using CFD Euler or even Navier-Stokes codes. 2nd order coupling schemes increase the stability realm and allow larger step sizes, but only implicit coupling schemes involving iterations can solve the stability problem. Why then are they employed so rarely? The main reason is probably a practical one: ''classical'' co-simulation with a 1st order coupling scheme can be used with many commercial software packages without altering the data structures and without the necessity to include coupling routines in the code. Only a few lines of an external ''wrapper'' are often needed to include file-based simulation tools (e.g. NASTRAN) in a co-simulation. In SIMPACK, access to the solver was available, so alternative coupling schemes could be employed.

3.0 EXAMPLES

3.1. Model of a Transport Aircraft Wing

The following section will present applications for the coupling methods discussed above, i.e. for a close coupling case, a loose coupling case and a trim calcuation, an application which is important for the simulation of free-flying aircraft.

All examples use the same model, a wing model which was built and tested (although those tests had other goals) in a wind tunnel in Göttingen, Germany, in the AMP project [16], [17]. It is a wing of large aspect ratio as it is typical for a transport aircraft. For such a wing a NASTRAN structure has been available. The model is a beam with additional points at the wing leading edge and the trailing edge, Figure 6, top. The four lowest natural frequencies have been selected for the modal representation, thus the wing deflection is described by four elastic states, i.e. one torsion and three bending modes.

The wing has an asymmetric profile which delivers lift at zero angle of attack; the resulting zero-lift angle is approximately -1.8 deg. The CFD mesh consists of approx. 10000 cells, Figure 6, bottom. This is a relatively coarse grid used for demonstration calculations, for verification purposes a finer grid is available. The transformation from structure to CFD grid has been performed by standard MpCCI interpolation routines.

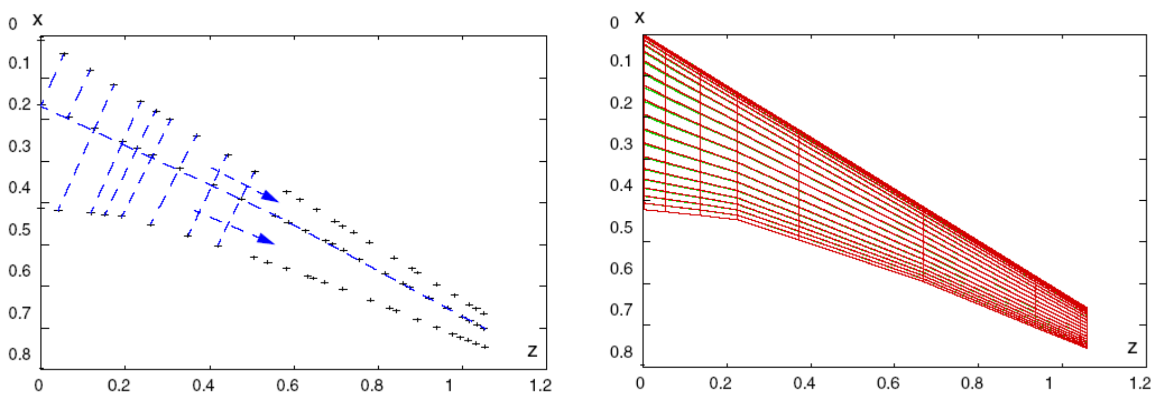

Figure 6: Model of transport aircraft wing

Loose Coupling

Subject of the co-simulation calculations was an instationary simulation of the elastic wing motion from the undeflected to the steady state deflected position. The wing motion was simulated for an angle of attack of zero degrees, at a flow speed of Ma = 0.78, with an instationary Euler CFD-calculation. A step size of 0.01 s was used for communication between CFD and MBS code. In the simulation a final vertical displacement of the wing tip of approximately 3.6 cm is reached. Figure 7, right, full line, shows the vertical diplacement at the tip of the wing as a function of time. Figure 7, left, shows the deflected wing in SIMPACK and the corresponding pressure distribution in FLOWer.

Close Coupling

The co-simulation setup for the example described in Section 4.2 has been used as a pre-processing for the modal aerodynamics of the close coupling. Instead of a free motion, each elastic state z_e has been changed by a small reference deflection for which a CFD calculation has been performed, all other states being at zero deflection, respectively. In addition, a calculation with an undeflected wing has been made. From the results, modal aerodynamic matrices have been generated. The resulting data describe the aeroelastic motion of the wing around the working point of the CFD simulation. Figure 7, right, dotted line, gives the simulation result for an instationary pure MBS simulation into the steady state position and the comparison with the coupled CFD calculation, Section 4.2. It can be seen that for small deflections the differences of the results are comparatively small (for this case in the range of 10%), which is sufficiently accurate for many applications, especially in the pre-design phase, given other model uncertainties. In any case, the close coupling only needs a fraction of the computation time of the full-scale co-simulation, most of the time being used for the pre-processing CFD calculations.

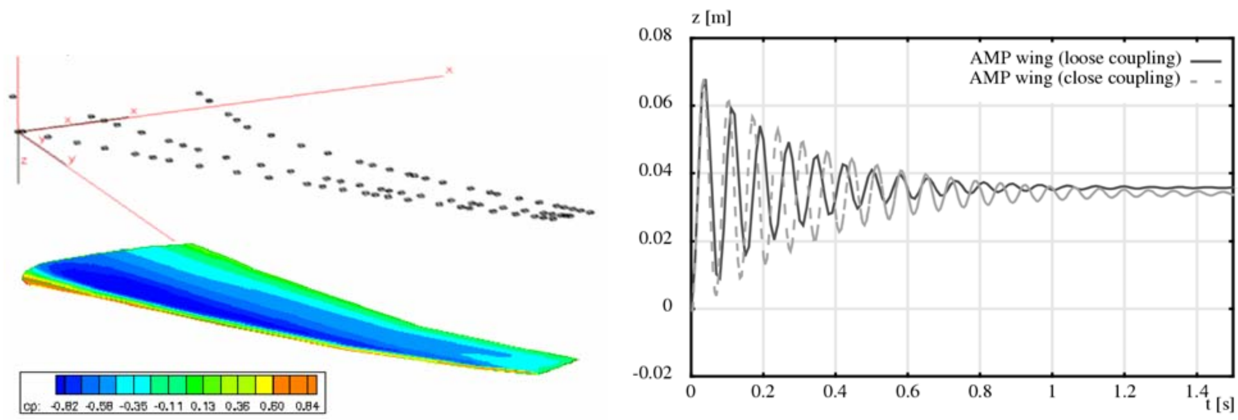

Figure 7: Simulation results for coupled calculations

4.0 OUTLOOK

In this article methods for the coupling of CFD and MBS have been presented. An example has been given for the application of loose coupling (co-simulation) and close coupling (model aerodynamics). It should be noted that total aircraft applications have also been realized. A glider plane in flight was presented in [18], and work on aeroelastic effects on ground dynamics continues in the Flexible Aircraft project [19]. An elastic aircraft at high angles of attack is the aim of the DLR SikMa project.

The fluid-structure coupling using MBS and CFD is well suited to supplement the often used couplings of FEA and CFD. The advantages are especially the simple simulation of unsteady dynamics beyond the pure fluid-structure coupling, e.g. including flight mechanics or for ground vehicles.

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DISCUSSION EDITING

Paper No. 11: Multibody Simulation of Low Frequency Aeroelastic Wing Loads

Authors: Dr.-Ing. Wolf R. Krüger, Dipl.-Ing. Martin Spieck

Speaker: W. Krüger

Discussor: Wolfgang Luber

Question: How far are we nowadays from analysing an emergency jettison sequence (drop of all stores within less of 2 seconds) with a multibody simulation and a time discrete coupling technique?

Why do you use only 13 elastic modes on the transporter aircraft and 20 elastic modes on the fighter aircraft?

Speaker's Reply: The first question (emergency jettison) I cannot directly answer. The complete simulation would have to be modular, and it would depend on the availability of the modules describing aerodynamics and the models describing the stores. If everything is there, the basis for a coupled simulation is prepared.

Answering the second question, the choice of 20 modes for the generic fighter is only based on the quality of the available model and has been somewhat arbitrary. There is no special physical background for the decision.

Discussor: Mahmood Khalid

Question: 1. Did you actually carry out a validation of your results against measured data?
2. You showed the study of an aircraft configuration under landing condition. How do you reconcile the use of panel methods near C_{Lmax} conditions where aircraft surfaces may support regions of separated flows?

Speaker's Reply: 1. We had a chance to compare our results with flight test data from the aircraft manufacturer. This gives us confidence in the results cannot regarded as an in-depth study.
2. The choice of panel methods for the simulation of the landing is a practical one – despite their limitations panel methods are state-of-the-art for these investigations and within the required range of accuracy. Euler and/or Navier Stokes methods can, of course, deliver aerodynamic forces with greater accuracy, but they also require extensive validation and take too much model preparation and computation time for the questions aimed at with multibody simulation, namely system dynamics and realistic ground loads (please remember that the aerodynamic design is not the goal of these studies).

Discussor: Osman Basoglu

Question: How do you include turbulence in a panel method? A panel method uses potential flow theory and it is inviscid hence at landing or manoeuvring conditions I think that these simple methods may not work because of high angles of attack which cannot be modelled by a panel method.

Speaker's Reply: I agree that panel methods are limited in their range of application and that close investigation of those limits in necessary beforehand. However, we hope that there are sufficiently exact for our main goal, the simulation of realistic ground loads.
In fact, turbulence was not the term I should have used. I was referring to the ability of modern panel methods to simulate unsteady flow and (leading edge) separation. As an example, such a time-exact simulation of the leading edge wake can be used to investigate coupled aerodynamic / flight mechanic motion as, e.g. the phenomenon of "wing rock".