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ADVANCEMENTS OF CFD-CSM COUPLING BY MEANS OF MULTIBODY SIMULATION

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Abstract

Previous work revealed that cross-sectional deformation of an aircraft wing at transonic speeds might have a considerable influence on shock prediction and, thus, on wave drag. CFD-CSM coupling based on standard FEM was, so far, not able to predict this camber deformation accurately over the whole chord, i.e. including leading edge and trailing edge devices. The objective of this work is to overcome this restriction through the use of an enhanced structural representation in the form of a multi-body model. The coupling of these models to CFD meshes is discussed. Finally, an improved representation of the cambering can be shown.

Wings of commercial aircraft consist of a main structure fixed to the fuselage and equipped with different types of movable surfaces in order to manoeuvre the flying aircraft and to support its take-off and landing performance. The safe operation of these devices must be ensured. For this purpose, static multi-body simulations are used in an industrial environment. This work presents an advanced process which enables coupling of these multi-body models directly to high-fidelity CFD. Results are presented and assessed regarding design of wing and movable surfaces.

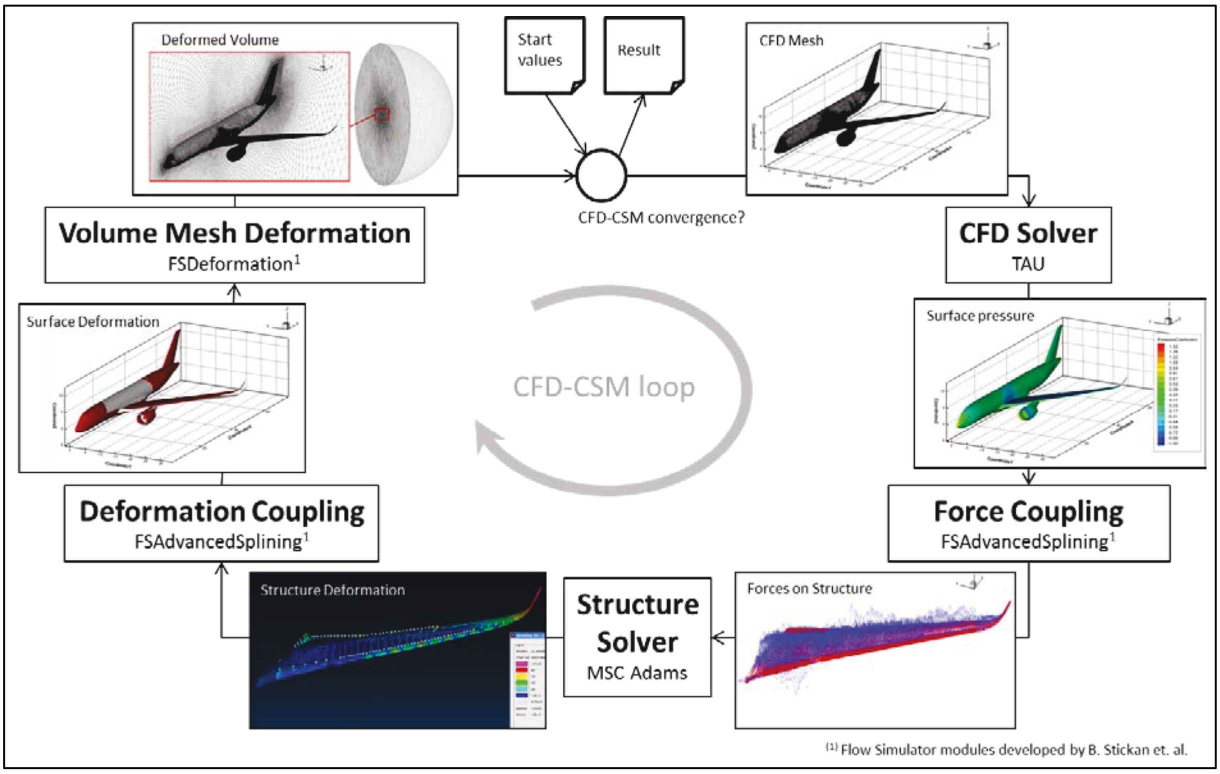

FIGURE 1. CFD-MBS process

1. INTRODUCTION

The design of an aircraft including a fixed wing and movable surfaces is a multidisciplinary exercise. Fluid-Structure Interaction (FSI) is taken into account for aircraft design since the first powered and controlled flights by the Wright brothers, who applied wing warping to attain roll control [15]. Numerical analysis of aeroelastic effects was, however, restricted until the 1980s due to limited compute power. This is when parallel computation became feasible, accompanied by the rapid development of domain decomposition methods [13, 36, 37]. Basic work was done in the 1990s towards maturity of parallel flow computation of large industrial applications, such as complete aircraft [24]. After the turn of the millennium enormous progress was achieved in the CFD solver [26], parallel computation [6], mesh generation [8, 12, 34], mesh deformation [3, 21, 22], force and displacement transfer [16, 17, 19, 21, 22]. Today, high-fidelity CFD-CSM coupling is considered as a reliable means showing significant improvement in the prediction of aerodynamic characteristics and structural behavior compared to mono-disciplinary approaches [7, 17, 21, 42]. Although application is up until now commonly restricted to the design point, the range of applications of high-fidelity CFD-CSM for aircraft design is growing [7, 27]. To continue this trend, several obstacles have still to be overcome.

The present work is targeting at applications for steady cruise design or manoeuvering conditions. Hence, the static interaction between aerodynamics and structures is in the foreground. In recent investigation by Bleecke, CFD-CSM coupling based on a structural model of Finite Elements (FE) revealed deficiencies to capture the cross-sectional deformation of an aircraft wing accurately over the whole chord, i.e. including leading- and trailing edge devices [1]. Furthermore, this effect, also referred to as cambering, was shown to have a considerable influence on the shock prediction and, thus, the wave drag. Corresponding observations are also described in [25, 44]. It is the objective of this work to advance the CFD-CSM coupling towards more realistic prediction of the chord-wise deformation, particularly on the upper shell.

A multi body representation of the structure is chosen to overcome the aforementioned model restrictions at the leading and trailing edge of the wing. As opposed to classical Multi Body Simulation (MBS), which is concerned with kinematic analysis of interconnected rigid bodies, a representation of flexible bodies is required here. This extension dates back to the 1990s when Wallrapp [45] and Shabana [40] provided a theoretical basis for flexible MBS. Soon this started to be widely used for aerospace applications, such as landing gears [28], tilt rotor [33] high-lift systems [18, 23, 47], foldable wing tip [9] and complete aircraft [29, 31, 32, 41]. These investigations were, however, usually restricted to simple aerodynamic methods and a small number of coupling nodes. Some examples of high-fidelity CFD-MBS coupling are more recent. Examples are found for wind turbines [20], tidal current turbines [5] or combat aircraft [39].

Multi body simulation is characterized as a “versatile gluing tool” which “allows an efficient representation of the combination of elastic motion and arbitrary rotations” by Cavagna [10]. This is exploited here to assemble a multi body model of the complete aircraft wing based on finite element models of the subcomponents, i.e. main structure of the wing and movable surfaces.

2. MODEL AND METHODS

The present work is based on the work of Bleecke, Stickan et. al. [1, 2]. A brief review of process and methods is given. Emphasis is put on the integration of flexible MBS.

A partitioned approach, i.e. a separate solution of the single field problems of aerodynamics and structure, was found to be advantageous over a monolithic approach, especially for industrial applications where sophisticated models and solvers are already used independently. With this approach the benefit of customized solvers can be exploited, models can be developed independently, existing models can be reused and changes can be rapidly implemented. In return, care must be taken to adequately couple the different problems.

2.1. Structure

State-of-the-art CFD-CSM commonly relies on a structural representation using finite elements. Depending on the application (steady or unsteady) and required accuracy and performance, different approaches are used:

- Reduced flexibility matrix [16]
- Modal approach [38, 41]
- Pure finite element approach [2, 17]

Recent investigation by Bleecke or Keye [1, 25] has proven mature and accurate results based on high-fidelity CFD-CSM compared to flight test. Large industrial FE models are, however, often lacking completeness or generality. The FE model of Bleecke was missing high-lift devices, whereas Keye had to use two different models for the configurations at cruise and landing. In both cases, the incomplete physical modelling of aerodynamic surfaces is mentioned as the cause for inaccurate coupling, i.e. these models were not capable of representing the chord-wise deformation with sufficient accuracy. This prediction is, however, particularly important in the transonic regime, where shock prediction shows sensitivity to deformations of a few millimetres, especially on the upper shell. For this purpose, a structural model is desired capable of representing the relatively small elastic deformation of the components, i.e. the main wing and movable surfaces. Moreover, their interconnections must be represented correctly allowing relatively large rigid body motion of the components with respect to each other.

MBS is offering the above stated capabilities among other advantages:

- The straight-forward modelling based on Commertial Off-The-Shelf (COTS) construction kit for joints and contacts including nonlinearities, such as friction or backlash.
- Co-simulation offers the possibility to incorporate sub-systems such as control- or drive systems.
- The complete multi body model usually copes with far less degrees of freedom than a comparable FE model.

2.1.1. Elastic Multi-Body Model

Flexible body representation in MBS is ranging from simple mass-spring models [30, 31] over beam models [9, 30, 31, 32, 41, 47] to detailed finite element models [10, 39, 41]. The latter can be directly coupled, which is, however, rarely done [10, 39]. In most cases Component Mode Synthesis (CMS) is performed [4, 33, 47]. “The CMS approach (...) is a consolidated technique to capture the dynamics of large complex deformable subsystems in reduced order, yet extremely efficient models." [10]

Since the present work requires detailed structural representation of the complete cross section, standard finite element models are used. In the industrial environment these are usually available for subcomponents and can be reused. Modelling efforts are, hence, restricted to the assembly of these flexible bodies, i.e. it is focused on the definition of their connection. Component mode synthesis of the flexible bodies is performed in order to limit the size of the model.

The coupling of multi-body systems and finite element models is realized in commercial software, such as SIMPACK or MSC Adams. The latter is used in this work in combination with MSC Nastran taking care of component mode synthesis of the flexible bodies. This procedure is using the Craig-Bampton method [11, 46] which allows the selection of interface degrees of freedom for which additional static modes are generated. This yields a more accurate structural behavior and exact loads transfer at these points compared to a free-free modal analysis. It was, therefore, found to be a particularly suitable and efficient means to incorporate small linear-elastic flexible body deformation into multi body systems.

For each flexible body, a component mode synthesis is performed as a pre-process generating the modal matrix Φ which is in turn used to express the physical coordinated u in terms of the generalized coordinate.

(1) $u = \hat{\Phi} q$

Furthermore, the generalized mass matrix $\hat{M}$ and the generalized stiffness matrix $\hat{K}$ are computed.

(2) $\hat{M} = \hat{\Phi}^T M \hat{\Phi}$

(3) $\hat{K} = \hat{\Phi}^T K \hat{\Phi}$

Likewise, the nodal forces which are applied on the flexible body and represented by the physical load vector F are transformed to the modal load vector f.

(4) $f = \Phi^T F.$

Finally, the equation of motion in modal form

(5) $\hat{M}\ddot{q} + \hat{K}q = f$

is solved for each flexible body. Furthermore, the kinematic equations of motion in Lagrangian formulation are solved by Adams. This includes nonlinear equations. More comprehensive theoretical background is given in [47].

For the given objective a structural model is needed which is as complete as possible with regard to the coupling surfaces and eventually allows large deflection of movable surfaces. FIGURE 2 shows the complete model of the complete aircraft wing composed of 28 Flexible bodies:

- Main structure of the wing and winglet (blue)
- 19 Control Surfaces as labelled in FIGURE 2
- 8 connectors or actuators

Additionally, rigid parts, different kinds of joints, springs and constraints are used. In total around 400 moving parts are implemented.

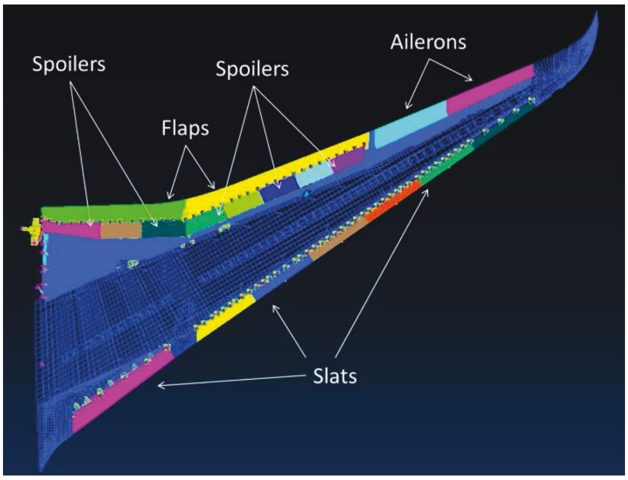

FIGURE 2. Multi body model of the left wing

2.2. Aerodynamics

High-fidelity CFD is considered accurate and reliable at design conditions. Closer to the edge of the flight envelope, however, the prediction of flow characteristics remains challenging [8].

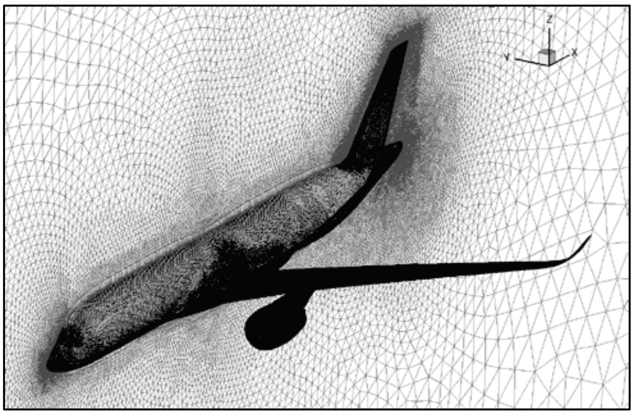

FIGURE 3. CFD mesh

Here the Reynolds-averaged Navier-Stokes (RANS) equations are solved on a finite-volume grid using TAU [26]. An unstructured mesh of the complete aircraft without horizontal tail plane as shown in FIGURE 3 (38M elements for a half model) is used. The Spalart-Allmaras turbulence model is used. Initial flight conditions, i.e. the boundary conditions for the flow computation, are set as in [1].

2.3. Coupling

As the structural and the aerodynamic problem are solved independently and on a different spatial discretization, care must be taken for their coupling.

The major steps of a coupling scheme are:

- Transfer of forces from the aerodynamic solution to structure

- Transfer of displacements from the structure solution to the aerodynamic surface

The Advanced Splining Method [2] was developed for the transfer of forces and displacements between different grids. A major advantage is its flexibility to combine different coupling techniques in one coupling matrix. This is important for industrial applications where a complete aircraft model is assembled from components of very different fidelity. It allows the use of surface, beam and rigid body splines at the same time. Furthermore, superior computation rate and reduced memory demand through “on-the-fly” generation of the spline matrix was demonstrated with respect to conventional software. An essential feature is the geometric subdivision in coupling zones in order to ensure correct allocation of forces and displacements with respect to the components. The correct allocation of structural nodes (depicted as spheres) to the CFD surface (shaded) can be verified as in FIGURE 4. It shows also that the movable surfaces are cut-out correctly (cf. FIGURE 2). Additional features like blending and relaxation techniques for smooth transition between components and domains are available as well.

In order to achieve precise coupling in chord-wise direction as well, the coupling method needs to cope with a large number of surface points. About 500000 nodes are available on the structure surface grid, i.e. an increase by an order of magnitude compared to [1]. The use of radial basis function (RBF) interpolation was shown to be highly efficient, especially if the deformations are smooth as for the application of span-wise wing deformation [2]. If steps in the deformation are expected, e.g. due to movable surface deflection, the subdivision of the wing in coupling zones facilitates the use of RBF interpolation [22]. Another advantage is that RBF interpolation copes with scatted data, i.e. there is no need for connectivity information.

Finally, an updated aerodynamic surface mesh is obtained.

2.4. Aerodynamic mesh adaptation

The aerodynamic volume mesh needs to account for the surface mesh updated in the previous step. Two kinds of changes are distinguished:

- Relatively small elastic deformation of the structure
- Possibly large rigid body motion due to the deflection of movable surfaces.

The latter is particularly demanding, since configuration changes and, thus, wholes or gaps occur. For the present work it is, however, sufficient to propagate small deflections into the volume mesh. This can be achieved by different strategies:

- The generation of a new mesh facilitates any change of the mesh, i.e. also configuration changes can be easily realized. On the other hand, numerical noise due to a changing mesh topology and a comparably high computational effort make is unsuitable for the present application.
- Mesh deformation methods are widely used, either based on structural analogy or on interpolation methods [3]. The latter is used for this work due to its proven efficiency when relatively small and smooth deformations present, such as the bending of a conventional aircraft wing.
- The Chimera method is very useful of large rigid body motion is to be realized. It allows configuration changes without topology change or the need to re-mesh. Due to its computational effort it is not used here, but future applications in combination with mesh deformation are envisaged [27].
- Other methods, such as the transpiration method [14, 43] or the advancing front technique [21] are possible but not considered here.

Mesh deformation requires caution to preserve the quality of the mesh, i.e. to avoid overlaps, holes and sudden changes in cell volumes or shape. For RANS meshes particular care must be taken to preserve the cells of the boundary layer. The FlowSimulator module FSDeformation provides mature and efficient mesh deformation based on RBF interpolation under the aforementioned precautions. A reduction of base points is needed, since the large number of surface grid nodes which are input to the mesh deformation leads to unsatisfying computational performance. As a side-effect the remaining/unused nodes are used for an error correction. Further details and test cases can be found in [3].

2.5. CFD-CSM Equilibrium

The static aeroelastic equilibrium is determined by an iterative process (FIGURE 1) exploiting the methods described above. It terminates if the convergence criterion is reached, i. e. in this case the maximum difference of nodal displacements between two consecutive iterations.

The FlowSimulator, dedicated for parallel simulation of multidisciplinary problems, is used as a framework [35].

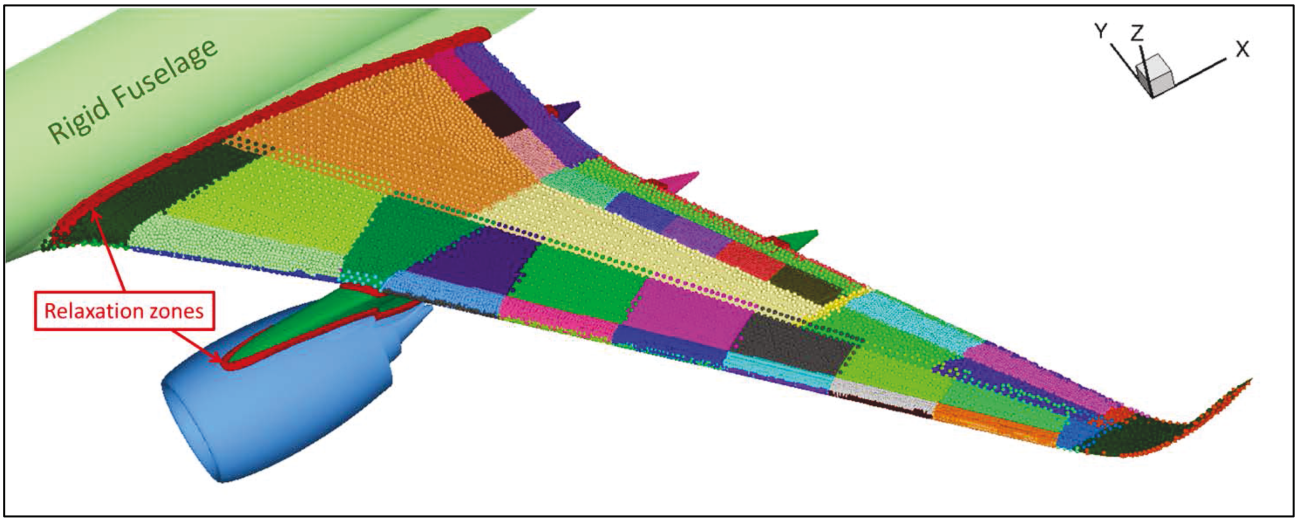

FIGURE 4. Coupling zones

3. APPLICATION FIELDS

3.1. Wing Design

The highly accurate prediction of the deformation state of an aircraft in cruise configuration is crucial for the prediction of aerodynamic performance [21]. The industry standard for numerical flight shape prediction is, however, lacking complete physical representation of wetted surfaces and can, therefore, not resolve effects like cambering.

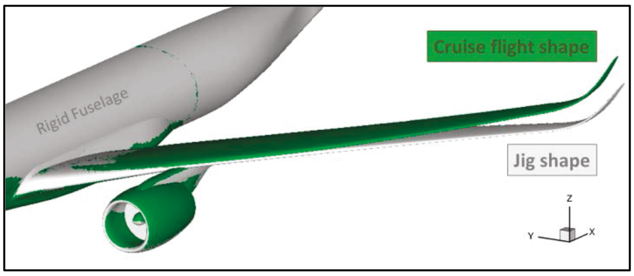

FIGURE 5. Aerodynamic surface shapes

3.2. Movable Surface Design

Movable surfaces, such as high-lift devices and control surfaces, are essential for the operation of commercial aircraft. According to certification specification EASA CS 25.683(b) "It must be shown by analysis and, where necessary, by tests that in the presence of deflections of the aeroplane structure due to the separate application of pitch, roll and yaw limit manoeuvre loads, the control system, when loaded to obtain these limit loads and operated within its operational range of deflections can be exercised about all control axes and remain free from jamming, excessive friction, disconnection and any form of permanent damage." [48]

In order to demonstrate compliance, the overall structural deformation of the aircraft in limit manoeuvre loads conditions needs to be determined as accurately as possible. Multi-body simulation with highly-accurate elastic structural representation is already used to simulate the behavior of control surfaces in flight (Ailerons Virtual Functioning Test). So far fluid-structure interaction (FSI) was, however, restricted to simplified structural models and aerodynamic loads were determined in a complex pre-process:

1.) Rigid aerodynamic database in table form is generated using CFD and wind tunnel test.
2.) Quasi-static flexibilization of aerodynamic data is using a beam-stick type structural model of the complete aircraft.
3.) Application of these quasi-flexible aerodynamic loads to multi body model.

An objective of this work is to facilitate a full-flexible aeroelastic solution through direct CFD-CSM coupling.

4. RESULTS AND DISCUSSION

In the following, results at the 1g steady level flight condition are presented. The target lift coefficient C_L=0.47 (referring to the complete aircraft) is achieved at typical cruise flight conditions (M = 0.85 and h = 39000ft). The flight shape at these conditions, determined by means of the CFD-MBS coupling, is depicted in FIGURE 5 with respect to the unloaded and weightless jig shape.

The absolute bending (dz) and twist (ry) over the wing span is shown in FIGURE 6. A good overall agreement of the deformation predicted by the coupling scheme using a multi-body model (CFD-MBS) and the prediction based on a finite element model (CFD-FEM) is observed. The differences at the wing root stem from a slightly different clamping of the structural model.

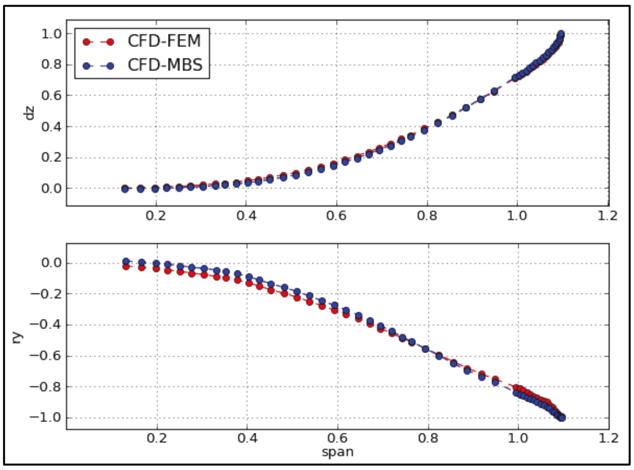

FIGURE 6. Absolute bending and twist deformation

In FIGURE 7 the chord-wise deformation is presented as relative displacements in z-direction (Δz). This means, that the absolute bending and twist (as depicted in FIGURE 6) is subtracted. It reflects the deformation of leading- and trailing edge movables and the transition between the wing and movable surfaces in detail. The largest deflections are observed at the trailing edge devices (right hand side of FIGURE 7). According to [1] this will have a considerable effect on aerodynamics.

The results reveal also steps at the transition between fixed wing and movable surfaces. Especially at the leading edge flaps this is presumably caused by forces due to interior aerodynamics. These forces stem from low-pressure, also referred to as cavity pressure, which develops in the interspace between the fixed wing and the movable surface, especially at the slats.

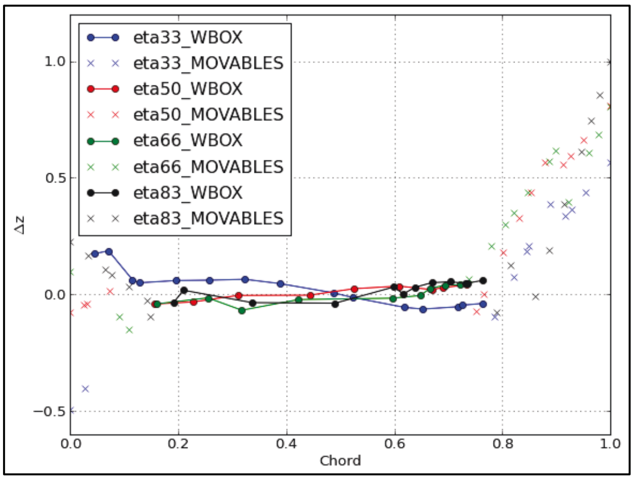

FIGURE 7. Relative deformation of the upper surface

5. CONCLUSION

This work describes how flexible multi body simulation can be coupled to high-fidelity CFD meshes giving rise to an unprecedented level of detail in the prediction of the static aeroelastic equilibrium of an aircraft wing. The cambering as well as steps between the fixed wing and movable surfaces can be resolved. This enables the quantification of these effects on aerodynamic characteristics which will be subject to future work.

The advantages of flexible multi body simulation to represent large and possibly also transient deflection of movable surfaces are stated. In order to exploit these capabilities in a coupled scheme enhanced methods on the aerodynamic side, especially in mesh adaptation, are required.

6. ACKNOWLEDGEMENT

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