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TOWARDS COMPUTATIONAL EFFICIENT FULLY COUPLED AEROELASTIC SIMULATIONS OF TURBOMACHINERY BLADES WITH TRACE AND CALCULIX

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Abstract. In the industrial design of turbomachinery blades their aeroelastic behaviour is most commonly investigated by methods, that use linearization or rely on unidirectional coupling. To circumvent the limitations of those methods a new fully coupled simulation in the time domain with the structural solver CalculiX and the turbomachinery CFD solver TRACE is currently developed and presented in this paper. The coupling library preCICE is chosen to couple the mentioned elaborated single physics solvers due to its focus on high performance computing applications. Within this work the preCICE adapter for CalculiX has recently been enabled to work with a special CalculiX method, that allows to investigate dedicated eigenforms of the blades or other structural objects. It is furthermore shown that the use of this CalculiX method can lead to a massive speedup for use cases, where the structural dynamics response can be well described by a piece-wise linear approximation within each increment. On the other hand a completely new preCICE adapter for TRACE has been developed and is introduced here. The preCICE-coupled system of CalculiX and TRACE is successfully validated against a TRACE-internal coupling approach by investigating a simple testcase with a NACA profile blade that shows good agreement.

1 INTRODUCTION

Turbomachinery blades tend to get more and more complex with respect to their materials and geometries while being optimized towards their stability limits. Thus, the aeroelastic evaluation of those components is crucial for the safety of an engine. It is necessary to investigate

the occurring phenomena as e.g. Flutter induced Limit Cycle Oscillations in a multidisciplinary fashion, taking the interactions between both physical fields, the aero- and structure dynamics into account.[1] Current simulation methods for industrial applications most commonly use simplifications, i.e. they use to some extend linearization of the aerodynamic forces, assume a fixed structural frequency and mode shape and usually facilitate only unidirectional coupling strategies.[2, 3, 4, 5] Those currently established methods in industry may not be sufficiently accurate for special design tasks, where the aerolastic behaviour of the blades need to be understood exactly and cannot be covered by the underlying theoretic simplification approaches of those methods. To guarantee a safe operation we need to raise the potential to become more accurate and therefore in this work a bidirectional coupling approach was chosen to pair the high-fidelity single physics solvers currently used at MTU Aero Engines AG, TRACE and CalculiX, in the time domain. Other bidirectionally coupled FSI simulations in the time domain are often not developed with optimization towards computational resources in mind or tend to focus on one of the physical fields in the multidisciplinary problem.[6] The coupling library preCICE was chosen for this project, as its focus on High Performance Computing allows to follow the approach to develop a fully coupled time domain simulation method with both solvers on an equal footing, that is the most accurate with respect to modeling of the underlying physics and can due to the use of preCICE be optimized towards computational performance. For this purpose a new preCICE-adapter was developed within TRACE and the respective adapter on the CalculiX side was enhanced to now also work with CalculiX's Modal Dynamic Analysis Mode. This newly formed simulation environment for aeroelastic time domain simulations is presented in this paper and validated against an existing and comparable method. Results of both methods for a single passage testcase with a Naca-profiled blade are compared with respect to several parameters.
First, the involved software is introduced with its underlying physics and numerical methods as well as the developments on the interfaces in between. Afterwards follows a detailed description of the testcase and obtained results. Finally the conclusions are drawn and an outlook to future work is given.

2 FSI MODELING

The fluid side of our FSI solver is captured by the TRACE (Turbomachinery Research Aerodynamic Computational Environment) CFD code [7] developed at DLRs Institute of Propulsion Technology and MTU Aero Engines AG. TRACE is a dedicated solver for the simulation of complex flows in turbomachinery and established in industrial design environments for the design and optimization of turbomachinery components. For the structural mechanics, the Open Source Software CalculiX [8] is used, which is developed at MTU Aero Engines AG and therefore has a special background in turbomachinery applications too. PreCICE was chosen as the interface between these two solvers, both of which are very sophisticated in their field. PreCICE is an Open Source coupling library for partitioned multi-physics simulations, mainly developed by the Chair of Scientific Computing at the Technical University of Munich and the Institute for Parallel and Distributed Systems at the University of Stuttgart.[9]

2.1 Fluid - TRACE

In TRACE, the unsteady Reynolds-averaged Navier-Stokes equations are discretized using the finite-volume method. The $k - \omega$ model by Wilcox is used for turbulence modeling.[10] We consider a moving fluid mesh because the wet surface will change due to deformation of the solid. The resulting equation in Arbitrary Lagrangian-Eulerian formulation is spatially discretized on a structured grid by a second order Fromm scheme with a Van Albada limiter.[11] For time discretization we use a second order Euler-Backward scheme with predictor corrector solution method. On the inflow and outflow boundary 2D frequency domain boundary conditions are used.[12, 13] For the moving mesh, a Laplace equation is solved by a GMRES solver that is initialised each time with the deformation of the last time step. For TRACE, a new preCICE adapter was developed within this work.

2.2 Solid - CalculiX

On the solid side of our FSI application, the equations of motion of the structure are solved by a Finite Element method in CalculiX. On one hand we use CalculiX' Dynamic Analysis Mode[8], where the response of a structure subject to dynamic loading is calculated by direct integration of the discretized equations of motion. For this method the preCICE adapter was already developed. On the other hand we use CalculiX' Modal Dynamic Analysis Mode[8], where the response of a structure subject to dynamic loading is calculated as a linear combination of the lowest modes of the structure. A precomputed number of modes, eigenfrequencies and the mass matrix are recovered to exactly calculate the response to the loading, which is assumed to be linear within each increment. Especially in the design environment of turbomachinery blades one often uses this feature to evaluate the blades stability under certain flow conditions that exite special structural frequencies. The existing adapter for CalculiX was enhanced within the scope of this paper to now also work with the latter method.

2.3 Interface - preCICE

On the interface, the so called wet surface, where both computational domains meet each other, the governing equations of both fields coincide through their boundary conditions. The deformation of the solid determines the domain of the fluid mesh, whereas the aerodynamic work acting on the blade correspond to the external forces in the structural equations. To take these interactions into account, it is necessary for the new FSI environment, that TRACE and CalculiX can communicate those boundaries to each other. Starting with the purely software concerning parts as the exchange of the physical data between the solvers, furthermore preCICE comes with elaborated interpolation methods to make matching mesh discretizations at the wet surface redundant. Finally preCICE is in charge of time stepping and can therefore ensure, that despite the solvers have different time increments, the data is exchanged at the same physical timesteps. With the configuration of preCICE one can handle the coupling scheme, whether the solvers are executed in parallel or in serial and whether the FSI system within each time step is solved in an explicit or implicit manner, with acceleration methods for the implicit variant if needed. However, not all of these features have yet been made available in our FSI application.

In order to integrate the preCICE library into the solvers(called participants in this context), its API is from the participants perspective minimal-invasively integrated into the routines of each code within so-called adapters, which are explained in more detail in the following. A scheme of both solvers coupled with preCICE is depicted in Figure 1.

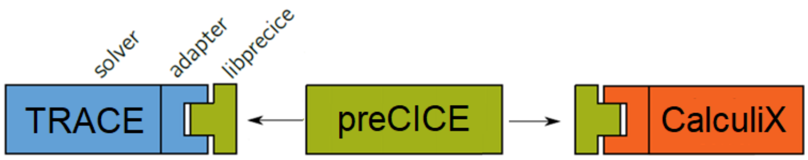

Figure 1: Connection between preCICE and both solvers.

2.4 TRACE-preCICE adapter development

TRACE is written in C and so the newly developed adapter utilizes preCICEs C-API to integrate the library into the code. Previous work where TRACE was able to call CalculiX as a subroutine internally [6] served as a base for the new developments, as parts of the existing interface routines could be reused to incorporate the needed functions for the data communication. As a fluid participant, TRACE on one hand must be able to calculate and deliver the aerodynamic forces acting on the blade. The user can choose if he wants to consistently communicate the pressure or to communicate the nodal forces in a conservative manner. The pressure value in each cell is multiplied by the face area of the cell to obtain a normal force value for conservative interpolation. On the other hand the displacements and velocities coming from CalculiX need to be processed to and considered by the mesh solver within TRACE.

2.5 CalculiX-preCICE adapter enhancement

The CalculiX-adapter was enhanced here in this work to now also handle the Modal Dynamic Analysis mode in CalculiX. Therefore the already existing adapter needed some small changes, but especially the already given adapter routines were included in the respective CalculiX C routine for the Modal Dynamic Analysis mode. The adapter enables CalculiX to read the pressure or forces coming from TRACE, or, as preCICE creates a plug and play environment, any other fluid solver. Those external forces are then applied as loading to the structural object, whose stresses are calculated by CalculiX. The resulting deformation on the other hand is read out by the adapter and further processed to the fluid solver.

To sum up, within this work we created the basic features for a new simulation environment, where TRACE and CalculiX are bidirectionally coupled via preCICE for aeroelastic time domain simulations in the field of turbomachinery design. Namely, a new preCICE adapter for TRACE and the enhancement of the preCICE adapter for CalculiX.

3 APPLICATION AND RESULTS

The newly developed FSI application with TRACE and CalculiX coupled by preCICE has been validated against a TRACE internal coupling interface, that starts CalculiX as a subroutine within TRACE. In this internal subroutine application the coupling related features as communication, interpolation, mapping and coupling schemes are implemented directly in the TRACE code. The participants can only compute their solutions in a serial manner one after another in this subroutine variant in contrast to the preCICE variant, where the solvers can be executed in parallel. Furthermore preCICE comes with more elaborated acceleration methods, thus in a long-term prespective we hope to benefit from the new coupling environment using preCICE in terms of stability and computational performance. Nevertheless right now, we have developed the basic features for our new preCICE-driven coupling environment as shown above and now compare both environments against each other. The comparison was carried out by calculating the exact same test case with both applications.

3.1 Testcase

A NACA 3506 profiled blade is computed in an unsteady single passage setup. The basic setup is depicted here in Figure 2 and Figure 3.

Re	$\sim 1.1 \times 10^6$
Mach	0.644
incidence	50°
cells	~ 12000

Fluid (TRACE) ↓

Young's modulus	210000 N/mm^2
density	7800 kg/m^3
# elements	4740
element type	C3D20R

Structure (CalculiX) →

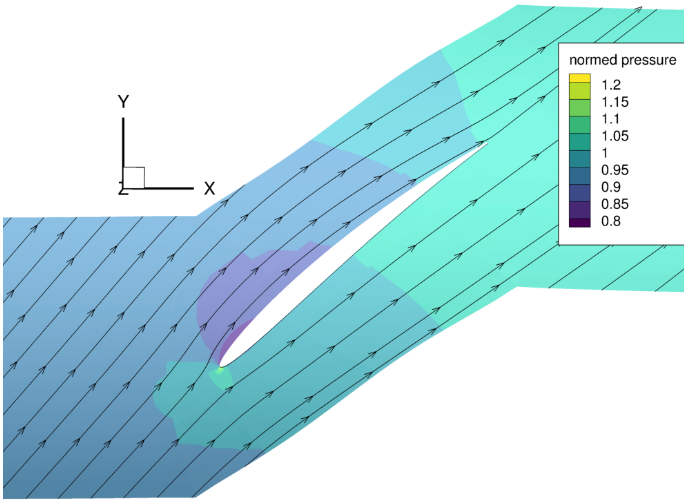

Figure 2: The steady flow solution around the blade.

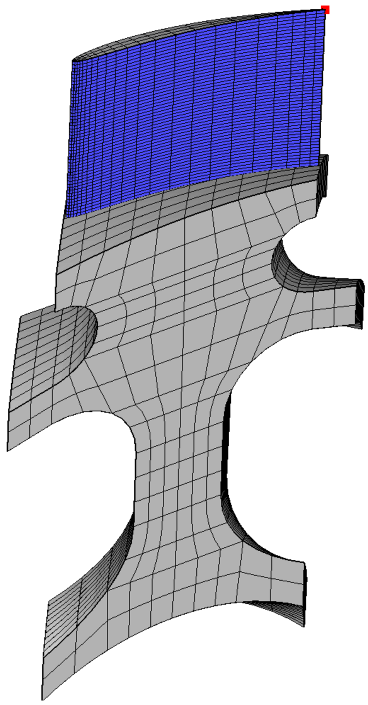

Figure 3: CalculiX-Mesh with blade surface mesh in blue/black.

The structured fluid mesh for the unsteady time domain RANS calculations consists of 12000 cells with nonreflecting 2D frequency boundary conditions at the inflow and outflow. The flow is characterized by a Reynolds number of about 1.1 million, a Mach number of 0.644 and an incident flow angle of 50° w.r.t. the x-axis. The structural model consists of 4740 twenty-node brick elements. As material for the blade we chose steel with a Young's modulus of 210000 N/mm^2 and a density of 7800 kg/m^3. With CalculiX we carried out both types of simulations, on one hand in Dynamic Analysis mode, and in comparison to that and for validation purposes of the enhanced CalculiX adapter, simulations in Modal Dynamic Analysis mode on the other hand. In Figure 3 you can see our analysis point at the corner tip of the blades trailing edge depicted in red. For preCICE we chose serial explicit coupling with a nearest neighbor mapping. Pressure is exchanged from TRACE to CalculiX and displacements and velocities are transferred from CalculiX to TRACE. The simulation runs with 128 timesteps per period and a frequency of 2237.37 Hz in TRACE leading to a timestep-width of about 3.5e-6 s. The chosen frequency corresponds to the frequency of the first bending mode of the blade. The steady flow solution from which the unsteady simulations start is shown in Figure 2.

3.2 Results

3.2.1 Longtime simulation

For both methods we carried out a simulation of 10000 timesteps, corresponding to 78 periods. The displacements in x direction of the corner tip of the blades trailing edge are plotted over time in Figure 4. The preCICE variant in orange with a dashed line and the subroutine variant with a dark solid line. It shows, that the results of the newly developed FSI application are in good agreement with the TRACE internal subroutine variant. It can be seen that even after many cycles both simulations show nearly exact agreement. For this simulation we used CalculiX' Modal Dynamic Analysis mode with two precomputed eigenmodes and therefore see a very uniform oscillation.

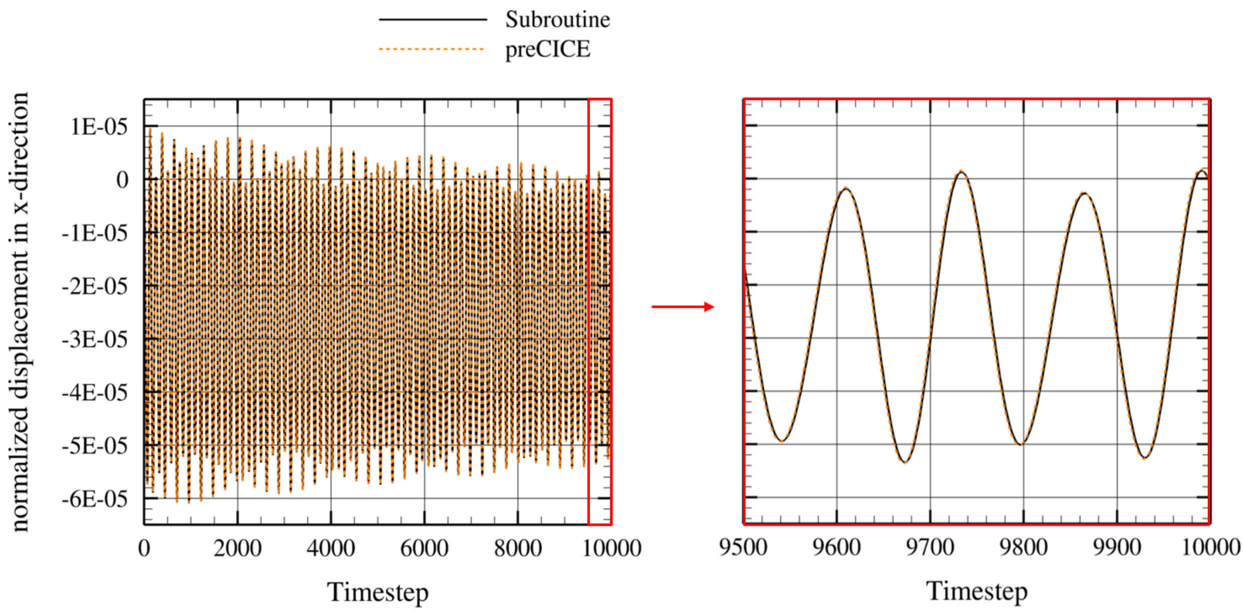

Figure 4: Displacement in x-direction over time for the corner tip trailing edge. Simulation with Modal Dynamic Analysis mode and two precomputed eigenmodes.

3.2.2 Simulation with CalculiX' Dynamic Analysis

In Figure 5 the result of simulations with both FSI applications using the Dynamic Analysis mode on CalculiX side can be seen. The simulation was carried out for 500 Timesteps. One observes a more realistic, perturbed oscillation of the blades tip. The match is very good between both methods, again the orange dashed line corresponds to the new preCICE and the solid dark one to the subroutine variant. Thus the new FSI environment is successfully validated for this type of simulations, which is the method of choice when nonlinear phenomena occur in both physical fields.

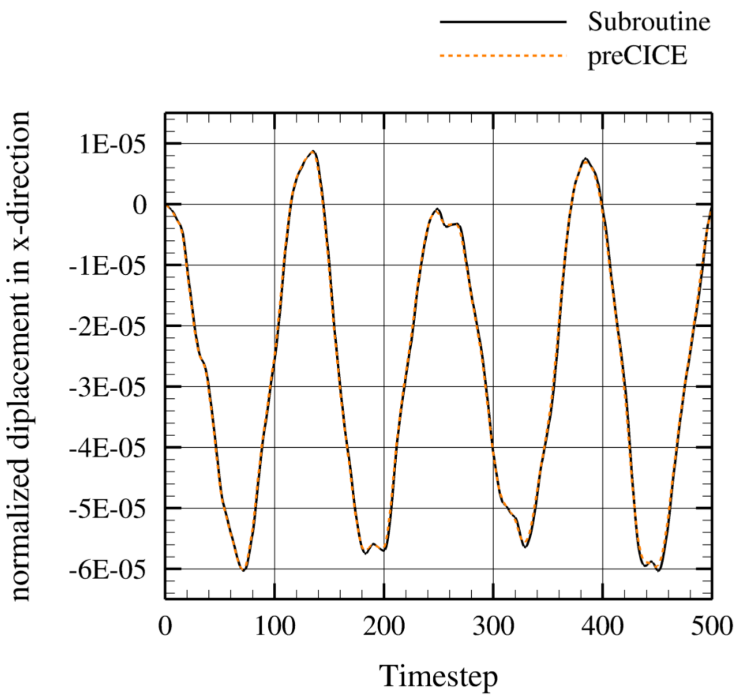

Figure 5: Displacement in x-direction over time for the corner tip trailing edge. Simulation with Dynamic Analysis mode.

3.2.3 Comparison of simulations with both CalculiX methods

Finally we validated the enhancement of the CalculiX adapter, by comparing a simulation that uses the Dynamic Analysis mode with one, that utilizes the Modal Dynamic Analysis mode. To achieve sufficiently accurate agreement of the resulting structural movement with both methods, we chose to precompute the first 150 structural eigenmodes for the latter one. The results are shown in Figure 6, where the dark solid line corresponds to the Dynamic Analysis and the dashed orange one to the Modal Dynamic Analysis. In this case both simulations were carried out with the newly developed preCICE coupling interface. Despite the fact that both CalculiX methods deliver qualitatively similar results for this use case, the total computation time of the simulation that utilized the modal dynamic analysis mode that was newly enabled with respect to preCICE was more than seven times faster.

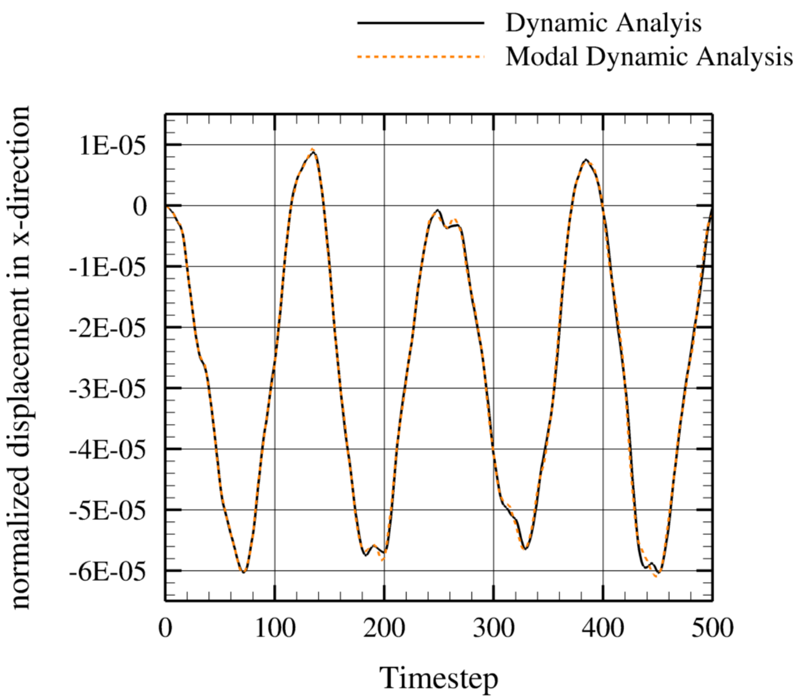

Figure 6: Displacement in x-direction over time for the corner tip trailing edge. Simulation with preCICE and Modal Dynamic Analysis mode vs. Dynamic Analysis mode.

3.2.4 Further parameter studies and results

For validation purposes further parameter studies were carried out. For some of those the values described above as basic setup were changed when investigating their influence on the simulation results. The following results could be observed from the studies. Both methods lead to very similar, in some cases nearly equal, results, regardless of how many time steps were simulated. For different incident flow angles the results match as far as there occured no further flow phenomena as e.g. flow detachment. The simulation also showed promising results when the test was carried out for smaller values of Young's modulus down to 210 N/mm^2, to ensure a strong aeroelastic coupling between fluid and structure, even if such a material for a turbomachinery blade is far from reality. Using a finer fluid mesh for both methods confirmed the good agreement. Furthermore the newly developed FSI application was successfully compared to another TRACE internal time domain coupling method called Modal FSI Module[1], where the motion of the structure is approximated by the superposition of precomputed natural mode shapes.

For many different comparisons with the enhanced CalculiX adapter we observed good agreement between the results of simulations that facilitate CalculiX' Dynamic Analysis mode and those results from simulations carried out with the newly available Modal Dynamic Analysis Mode.

4 CONCLUSIONS AND OUTLOOK

The results shown in this paper and the comprehensive parametric studies that were carried out so far show good agreement between simulations with the newly implemented preCICE interface between TRACE and CalculiX and those facilitating the proprietary subroutine interface. The comparison showed, that the preCICE approach is competitive in terms of the features that have been developed so far. Mentionable here are the great untapped potentials that the preCICE approach still has with respect to massively parallel simulations, optimized for respective cluster architectures for both solvers as well as preCICEs advanced acceleration methods for implicit coupling.
Furthermore we could show, that the enhancement of preCICEs CalculiX adapter with respect to the Modal Dynamic Analysis mode of CalculiX raises great opportunities to improve the computational efficiency of coupled simulations that use CalculiX as structure solver. In particular when the structural response to aerodynamic loads can in every increment be prescribed by a linear combination of the lowest modes of the structure, with the now usable solver mode one can easily investigate dedicated eigenmodes of the structure.
Overall we conclude that from a current point of view the new multidisciplinary simulation environment with preCICE, TRACE and CalculiX is a promising base for computational efficient fully coupled calculations in the time domain, that can be competitive in the area of high-fidelity methods for aeroelastic turbomachinery design.

4.1 Outlook

In the next phase of our project we look forward to further enhance the new preCICE interface between TRACE and CalculiX. In a first step we will enable all preCICE features to work within the new interface. In particular we need to include new functions in the respective adapters to allow implicit coupling with preCICEs outstanding acceleration methods. Moreover our focus lays on the computational efficiency, which is crucial for large real life engine test cases. The existing computing cluster infrastructure is specialized towards CPU numbers and memory per core with respect to the needs of the single physics solvers. In the upcoming future this HPC environment should be investigated in terms of its suitability for large massively parallel preCICE-coupled multiphysics simulations in aeroelastic turbomachinery design.

4.2 Acknowledgments

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