Coupling StarCD with structural Codes for doing FSI Simulations

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Summary:

There is an increasing need for multidisciplinary simulations in various research and engineering fields. Fluid-structure interaction, magneto-hydro dynamics, thermal coupling, plasma computations or coupled manufacturing processes define only a subset of recent multi-physics activities. There is a common feeling in the community that in most cases not a single (proprietary) simulation system can provide all necessary features but that coupling the best codes of each discipline will enable more flexibility and simulation quality to the end user.
The MpCCI interface has been accepted as a 'de-facto' standard for simulation code coupling. MpCCI is developed at Fraunhofer Institute for Algorithms and Scientific Computing (SCAI).
This article will describe the MpCCI concepts and some coupled applications.

Keywords:

Multi-Physics Simulation, Fluid-Structure-Interaction, Thermal Coupling, Magneto-Hydro-Dynamics, Simulation Coupling, Code Coupling Interface, MpCCI

1 MpCCI - The Standard for Simulation Code Coupling

1.1 Overview

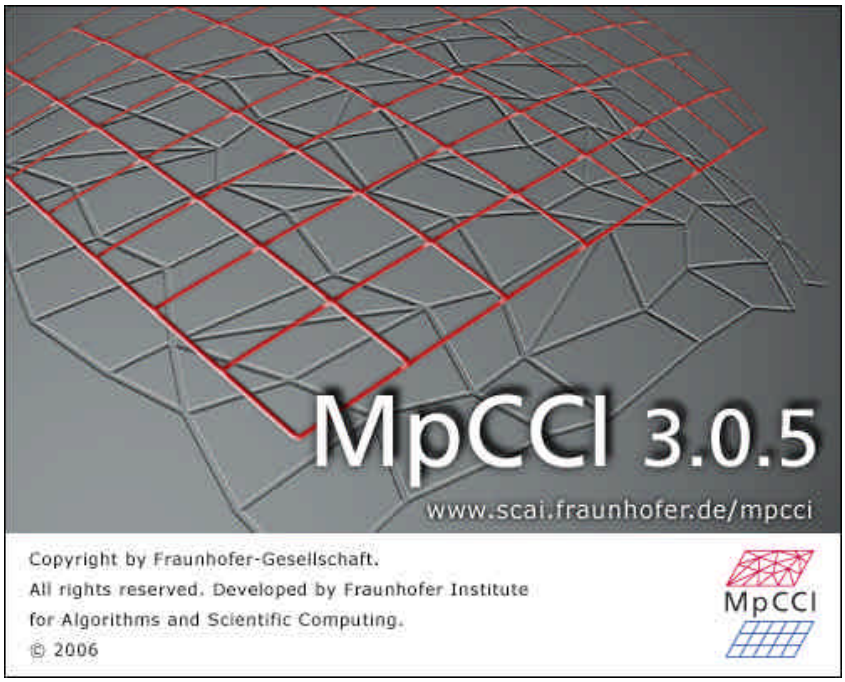
Structural analysis studies the behavior of solid structures under a number of different loading conditions, focusing on stress, contact, plasticity, large, and small deformations - basically upon the behavior of the structure itself. CFD (computational fluid dynamics) studies the behavior and effects of fluids moving around and through structures. The two disciplines meet at the surfaces of the solid structure, and each may provide loads and boundaries for the other. Most of the action takes place at the high end because of the extreme nonlinearity of CFD (its need to work with nonlinear structural codes) as recalculation takes place at each time step (or even within time steps), and because the kinds of problems that are likely to require FSI analysis are very complex and usually involve nonlinear structural behavior.

MpCCI (Mesh-based parallel Code Coupling Interface) has been developed at the Fraunhofer Institute SCAI in order to provide an application independent interface for the coupling of different simulation codes. MpCCI is a software environment which enables the exchange of data between the meshes of two or more simulation codes in the coupling region. Since the meshes belonging to different simulation codes are not compatible in general, MpCCI performs an interpolation. In case of parallel codes MpCCI keeps track on the distribution of the domains onto different processes.
MpCCI allows the exchange of nearly any kind of data between the coupled codes; e.g. energy and momentum sources, material properties, mesh definitions, or global quantities. The details of the data exchange are hidden behind the concise interface of MpCCI.

1.2 Supported Codes

The current version 3.0.5 of the MpCCI simulation coupling environment supports

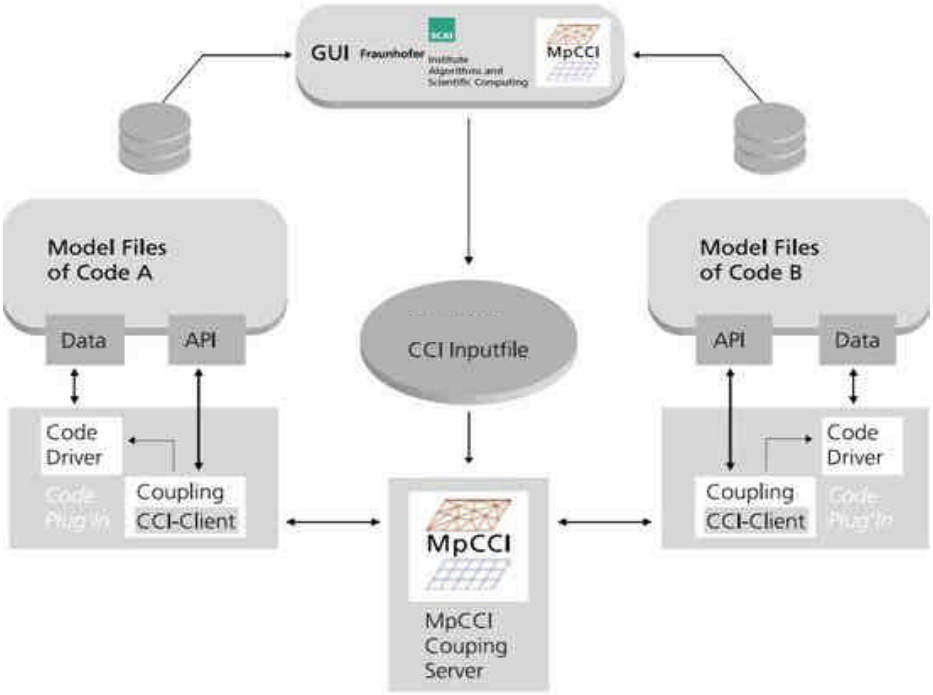
- ABAQUS
- Ansys
- Fluent
- Flux3D
- ICEPAK
- MSC.Marc
- Permas
- StarCD
- RadTherm



To ensure best compatibility between MpCCI and the codes listed above Fraunhofer SCAI has established long term cooperations with most of the corresponding software vendors. Joint development plans, combined marketing activities and cooperative support for end users ensure solution quality and success in application.
Distribution of MpCCI software is mostly handled through Fraunhofer SCAI itself. In 2004 CDAJ started the distribution and the technical supports of MpCCI in Japan, Korea and China. The importance of the multi-physics simulations coupling between CFD and CSM is recently rising up because of the diversification of the analytical contents and the demand for the high accuracy. CDAJ's customers are various companies and universities in the automotive, electric, chemical, atomic energy, architecture, aerospace and heavy industries. In these industrial fields, the coupling simulations play important roles for solving problems of the complex multi-physics and MpCCI would be a powerful tool for these simulations.

1.3 MpCCI Architecture

MpCCI 3.0 enables a direct communication between the coupled codes by providing adapters for a growing number of commercial codes. These code-adapters make use of the already existing application programming interfaces (APIs) of the simulation tools. This technique allows for an easy installation of MpCCI at the end users site without changing the standard installation of the simulation codes.



The MpCCI 3.0 environment consists of several components:

- MpCCI Code Adapter allows adapting MpCCI to commercial codes through their standard code APIs without any changes in the source of the simulation code.
- The MpCCI-User-Interface provides a comfortable way to define the coupling setup and to start the simulation - independent of the codes involved in the coupled application.
- The MpCCI Coupling Server is the "heart" of the MpCCI system. Environment handling, communication between the codes, neighborhood computation, and interpolation are part of this kernel.

1.4 Code Adaptation

Within the MpCCI 3.0 system the code adapters establish a direct connection between the MpCCI Coupling Server and the codes themselves. They make use of the APIs of the commercial codes and thus (in most cases) need no modified versions of these codes. A code adapter is a library which will be linked to the code either statically or dynamically. Any code adapter consists of two modules - the Coupling Manager and the Code Driver. Additionally for each code there are code specific scripts to scan the model input data, to start the codes and finally to stop the codes properly.

1.4.1 Standardized Quantities

One major advantage of having compatible code adapters for all codes supported by MpCCI is the standardization of coupling parameters and procedures independent from the used code pairing. MpCCI provides unified quantity definitions for

- Globals: time, iteration, residuals
- Mass source and sink: production species
- Momentum sources: e.g. Lorentz forces
- Energy sources: e.g. joule heat
- Material properties: e.g. electrical conductivity
- Boundary condition values: e.g. temperature or pressure
- Boundary condition gradients: e.g. heat flux density

- Grid data: nodal positions or displacements
- And chemical components: e.g. for reaction kinetics

The current version of MpCCI needs consistent unit definitions for all quantities – better support for unit translation is planned for follow up versions. Based on these unified quantity definitions MpCCI provides a growing set of predefined coupling procedures.

1.4.2 Grid Morphing

In fluid-structure-interaction (FSI) a major requirement to the fluid codes is an efficient support for changing fluid domain boundaries. As not all CFD codes provide an automatic mesh deformation tool MpCCI has an internal mesh morphing tool which may support the code adapter of such CFD codes. The MpCCI Grid Morpher is an external program running as an additional process besides the application. The grid-morpher fully supports parallel runs of e.g. StarCD 3.x.
Through various control parameters the user may control how and which regions of the CFD mesh shall be morphed. The grid-morpher does not change the mesh topology – it does not provide a remshing of the CFD domain.

1.5 User Interface

MpCCI has been designed as a neutral interface between various commercial and in-house simulation codes. While the user interfaces of the coupled codes differ, MpCCI itself provides a unique and code-independent way to specify all coupling relevant parameters. The MPCCI GUI allows to set-up and start the coupled application on a computing network.
The GUI guides the application engineers through few configuration steps to specify all required coupling parameters:

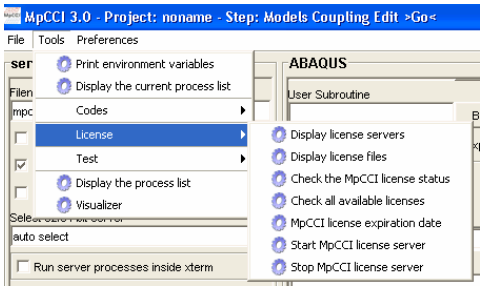
(1) The user has to select the codes and to specify the input files containing the model data.
(2) The next step is to select those element groups in each of the coupled codes which define a coupling region where the coupling interaction takes place; any number of independent coupling regions can be specified during MpCCI setup.
(3) For each of these coupled components the quantities to be transferred have to be specified; quantities may be physical values like pressure or temperature.
(4) Additional coupling parameters like neighborhood search configuration, mesh quality checks, or output parameters can be set.
(5) Finally the job can be started on a network of computing resources. The MpCCI server has to be launched first. Then the coupled codes will be activated, either in command or in interactive mode.

1.5.1 Tools and Commands

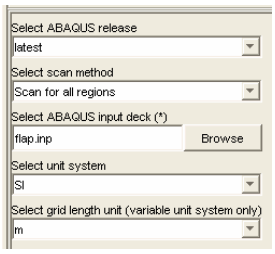
To ease practical use of MpCCI most of the commands in MpCCI 3.0.5 can be invoked from the GUI menu bar:

- information about the codes,
- license status and management,
- some test suites, and
- details about the environment

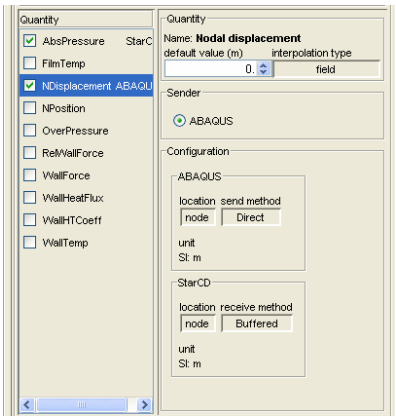
can now be accessed by a few simple clicks in the GUI.



1.5.2 Unit Systems and Coordinate Length Units



Within MpCCI 3.0.5 it is now possible to couple models with different grid length units in their coordinate systems and with different unit systems used. When reading the model files MpCCI 3.0.5 now checks for the metrics and unit system and shows the parameters in the model panel of the GUI. During coupling definition the GUI presents for each quantity the specified unit system.

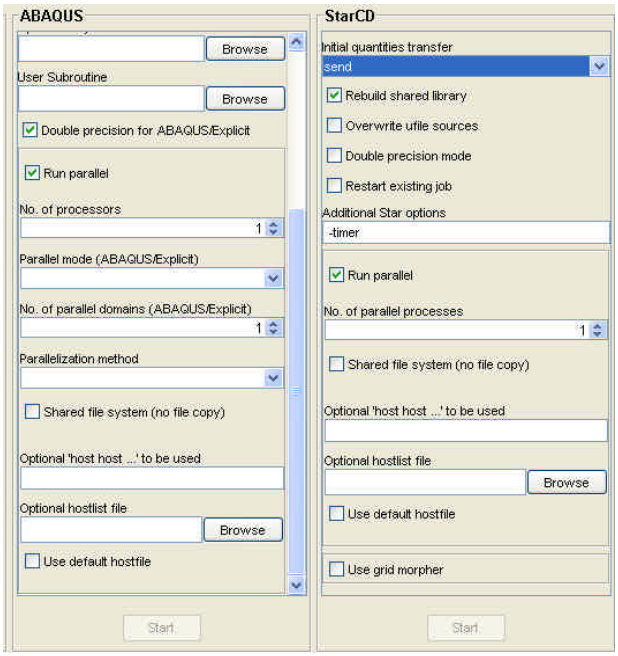


1.5.3 Running Codes in parallel

Most codes supported by MpCCI offer different ways to start them as parallel system:

- using some MPI for a message passing approach,
- using shared memory techniques, or
- spawning parallel threads.

MpCCI 3.0.5 GUI supports these different ways of parallelisms in the codes by adequate parameters in the GO-panel of its GUI. The parallel options of the codes have been integrated into the selection menus.



1.6 Coupling of incompatible Model Discretisations

1.6.1 Association and Data transfer

If the meshes are located in the same reference system, the coupling/neighbor computation can be set up. The method for associating meshes and the physical quantities to be transferred need to be chosen. The association method determines which entities are associated. There are two different association methods available:

- Point-Element (PE): A node of one mesh is associated with the element of the other mesh containing the node. The location of the node is given by the local coordinates.
- Element-Element (EE): Elements of one mesh are associated with all intersecting elements of the other. The intersection figure is used as associative link. It is used for element based data.

All physical quantities are assigned to an interpolation type characterizing the data transfer. There are two types of data transfer schemes:

- Flux: The data is treated as a flux, which means that it is transferred in a conservative way.
- Field: The data is treated as field data, where the transfer need not be conservative.

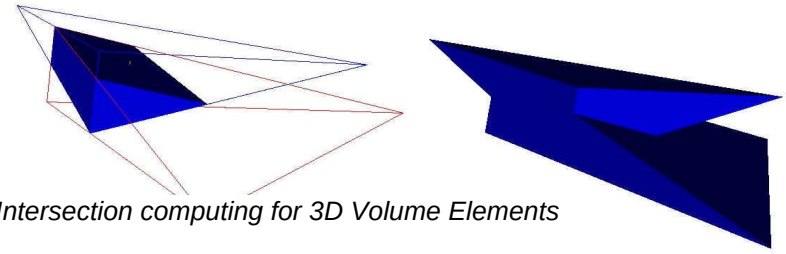
1.6.2 Improvements on Element-Element-Association

The Element-Element Association is based on intersections of elements. In a two step neighborhood search, intersecting elements are aligned. First for each element of one mesh, those elements of the other mesh are selected that are close. Then the candidates are tested for intersection. The results of the neighborhood search are pairs of intersecting elements together with the size of their overlap. For reducing the complexity of calculating and representing the intersection we split all elements into simplexes, neglecting the error due to warping effects.

Volume Coupling

With the EE-association, flux and field based data transfer is an interpolation over the size of intersection areas. As the problem of calculating intersections can be badly conditioned a robust algorithm must be used, that can handle problems resulting from floating point arithmetic. We have implemented two different algorithms. The current algorithm transforms intersecting elements to local (bary-centric) coordinates of an intersecting element. Then volumes of trapezoids are calculated and summed up. The weakness of this algorithm is the transformation to local coordinates for elements with bad aspect ratio. We have improved the concept so that even aspect ratios < 10e-6 do not lead to bad results.

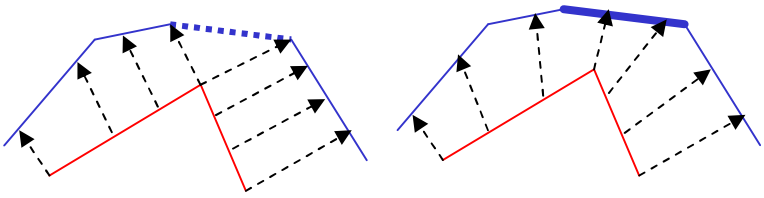
The second one is a topology aware clipping algorithm. Given two simplexes or other convex manifolds we choose one to be the clipping simplex. For each face (or edge in 2D) we determine the plane it lies in, and cut off the part of the other simplex lying beyond it. This is done successively for each face of the clipping simplex. Then the volume of the resulting intersection figure is calculated. No coordinate transformation is needed. The necessary Face-Face intersection tests can be reduced to two inner products and a simple sign comparison, so that the topology of the intersection figure can be determined in a robust and consistent way, without depending on the exact position of the intersection line. Tough this method is robust there is still an inaccuracy issue implied by almost coplanar intersecting faces. Calculating the position of the intersection lines is still badly conditioned. For almost coplanar faces the calculated position of the intersection line could differ significantly from the exact one. But as the faces are almost coplanar the error of the intersection volume stays small and thus the error of the data transfer.



Intersection computing for 3D Volume Elements

Surface Coupling

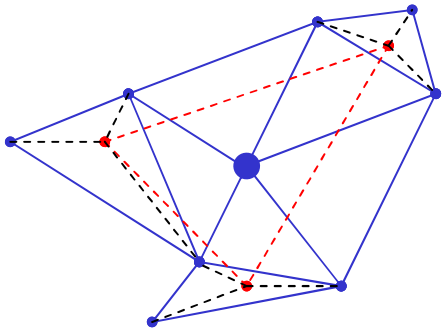
For EE based surface coupling a projection must be carried out as the surfaces do not necessarily share the same space. Hence MpCCI projects the elements of one mesh in an orthogonal way onto the other mesh. Then the intersection is calculated with the projection image instead of the mesh itself. The problem with this projection method is that it does neither define a bijective nor a steady mapping between the meshes. There are element parts of the target mesh that keeps unrecognized (left part of figure).The solution is to give up the strict orthogonal projection using a more complex one instead. Therefore unique projection directions are determined for all nodes. The projection directions for the rest of the mesh are interpolated such that a steady and bijective projection between the meshes is defined. As this projection is longer linear over one element, the intersection figure of a target face and the projection image of a source face become more difficult to handle. Therefore we calculate the intersection of edges and curved projected edges and linearize the part of the projected edges between the intersection points. Thus the presentation gets easier to handle and the projection keeps steady and bijective.



Left: orthogonal projection *Right: adapted interpolation*

1.6.3 Improved Point-Element based Flux Data Transfer (PE)

If coupling meshes are different there is no node-node correspondence. Thus for each node the physically corresponding point on the other mesh is searched for. The corresponding point is described by local coordinates related to the element containing the node.



The red nodes contribute to the data of all blue nodes (black lines) except the one in the centre.

The neighborhood search is performed in two steps: First a number of elements is computed, that are most likely to contain the nodes. In the second step the best match is chosen among the results. The best match is the element containing the node, or with surface coupling the one containing the closest point. The problem arises when trying to transfer data conservatively between a coarse source mesh and a fine target mesh. Nodes of a source mesh are transferring their data to the nodes of the associated element of the target mesh. The data is portioned by means of the local coordinates and distributed to the assigned target element nodes. The problem occurs when there are target nodes whose incident elements are not

associated with a source node. Then no data is transported to that so called orphaned nodes. One way to solve this problem is to do a post processing step including a relaxation. This method preserves the data to be transferred but it is expensive concerning time complexity. It also smoothes strong data contrasts. Therefore we introduce another transfer algorithm based on EE.

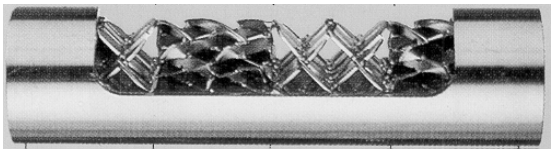
Node based Data transfer with EE
EE-Association is used for accurate and conservative Data transfer with element based data. This method can be adapted to node based data. The difference to the element based data is that the data can not be easily portioned by the intersection sizes to be then transported to the target mesh. Instead values are integrated over the intersection area of the source element. Then the data is transported to the intersecting area of the target element. There the data is portioned and distributed back to the nodes. As the association is bijective for volume and with the new EE-surface association for surfaces too, this method no longer results in orphaned nodes.

2 Application Areas

2.1 Fluid-Structure with Deformable Structures

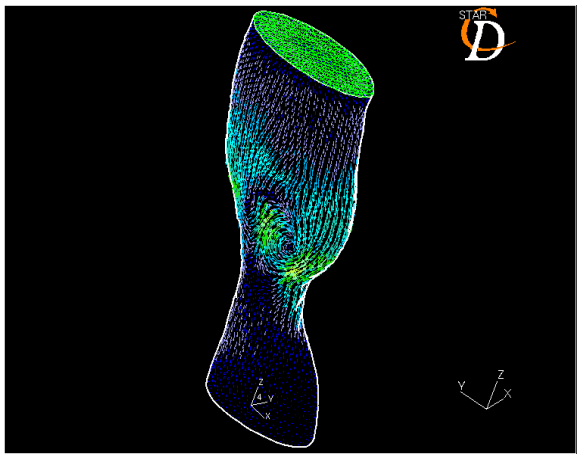
Typical FSI examples are defined by the dynamic effects over a deformable structure which is located in a fluid or air stream. Flexible flaps or valves may deform due to the normal and viscous fluid forces of the moving fluid or air stream. Or the structure might deform due to external loads – and the fluid domain has to follow these deformations.
In the following few examples will highlight different aspects of FSI with deformable structures.

2.1.1 Static Mixers



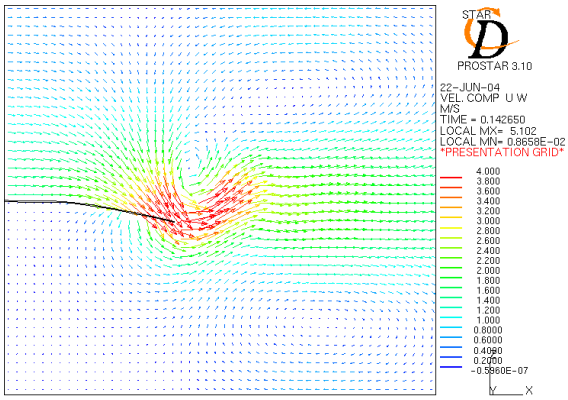
Static or dynamic mixers as used in the chemical industry deform due to high pressure loads. Such a mixer is the Sulzer SMX as shown in figure on right. It is designed for the mixing of liquids of high viscosity where the flow is laminar. The complex structures of the blades generate layers which drive the process of mixing. Special versions of the mixer are designed for applications (e.g. polymer melts blending) featuring a pressure drop across the structure of the mixer of up to 100 bar or higher. The mechanical forces and stresses in the structure caused by the flow are given by the pressure drop of each of the blades. The resulting total force is transferred from the mixer structure to the outer pipe e.g. at one end of the mixer. This application was done with a coupled StarCD-Permas environment at Sulzer Innotec in Switzerland [wintergerste2005].

2.1.2 Biomechanical Applications (JAERI)



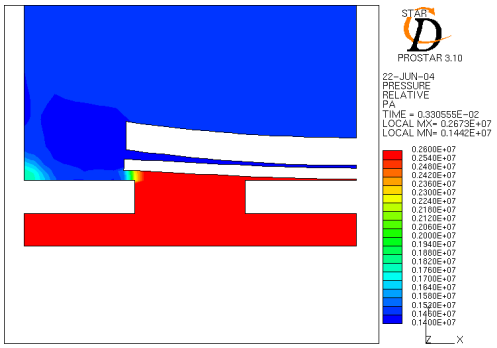
Computational biomechanics of vascular system, diseases, and thrombosis has been often concerned with the local hemodynamics conditions of blood flow that are computed by various of CFD (Computational Fluid Dynamics) methods, since it is well known that unusual hemodynamics condition may cause an abnormal biological response. Meanwhile, since pulse blood flow in arteries causes wall stresses to oscillate and non-uniform, biologists become recently more and more interesting in computational analyses of arterial wall stresses by CSD (Computational Structure Dynamics) methods to predict patient disease risks, like plaque rupture endothelial injury, etc., or to help plan surgery operation. Herein wall elasticity has to be taken into account which is neglected on many situations as the secondary importance feature generally. Consequently, it is necessary to analyze hemodynamics conditions of blood flow by CFD and stress distribution on arterial wall by CSD simultaneously from view of clinical request [guo2002]. In the figure the velocity distribution on carotid artery is shown.

2.1.3 Piezo Elements



In the electric industries, the piezoelectric actuators are used as pump, speaker and fan. The piezoelectric device oscillates by alternately changing axial strains caused by A.C. voltage loading. In order to analyze such phenomena, only the piezoelectric/structural analyses have been used usually. In these cases, one of the key components, the fluid force, is simplified as an easy damping model. However MpCCI enables the coupling analysis between CSM and CFD now and the more realistic behavior can be solved by defining the exact fluid forces on the device.

2.1.4 Compressor Valves



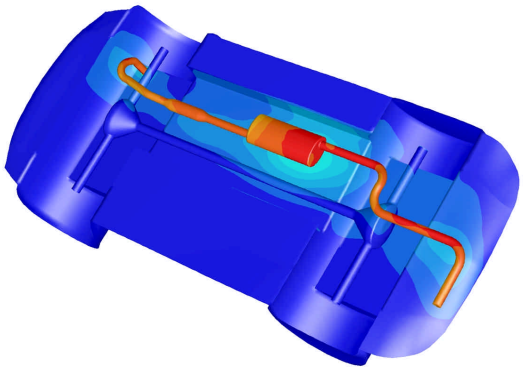
Another example is the valve in the compressor used in the various fields. These valves are opened by the gas compressed by the piston motion and exhaust the gas (see figure, pressure field around the valve). This is solved as FSI case because the valve is deformed by the pressure force of the compressed gas. The analysis results of the pressure and deformation of valve are compared with the experimental data. The coupling analysis via MpCCI is going to be useful for the design of the compressor.

2.2 Thermal Coupling and Radiation

2.2.1 Automotive Manifolds

An important issue for numerical analysis in automotive industry is to provide solutions for the thermal management of cars. A fully coupled (two-way) temperature-stress analysis was used to simultaneously solve for both displacement and temperature fields for problems in which both the stress and temperature are dependent upon each other. The transfer of temperature fields and heat transfer coefficients in an engine exhaust manifold may illustrate the importance of thermal coupling in the transient heating due to the flow of the internal hot exhaust gas stream [vosbeek2006].

2.2.2 Thermal Management in Automotive Systems

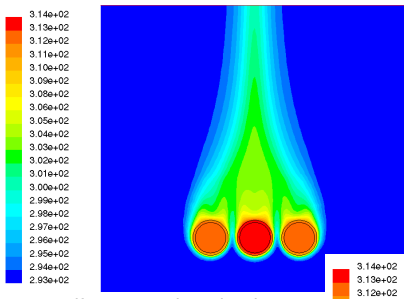


Calculation of underhood component temperatures of passenger cars requires the combination of even three different disciplines: structural analysis, fluid dynamics and radiation. For the simulation of thermal conduction and convective heat transfer a coupled fluid-structure environment is needed. With regard to the whole car geometry also radiation plays an important role in the overall heat management calculation. In areas with relevant fluid flows (e.g. engine compartment, gear box or exhaust system) convective heat transfer and radiation need to be calculated in a coupled environment. DaimlerChrysler starts to use a fully coupled 3-code environment based on StarCD, Permas and Posrad (radiation code from CD adapco) to solve thermal management applications [maihöfer2004] [weidmann2005].

2.3 Thermo-Electrical Coupling

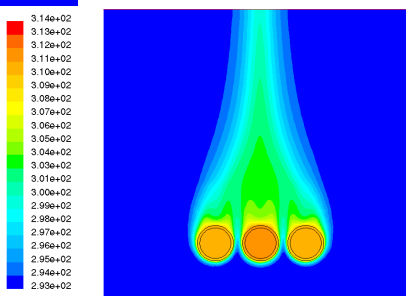
The prediction of heating and cooling processes is of eminent importance in the development of electrical devices. The flow of the alternating current induces heating due to losses by Ohms' law and the usual mechanism for cooling is free convection. The increasing tendency of miniaturization requires to fully utilizing the thermal potential of the materials involved. Heat dissipating surfaces are,

however, reduced in a way that can result in temperatures which may destroy the complete device or parts of it [zolfaghari2005].
The free convection is simulated by the CFD Software (e.g. StarCD). The electromagnetic quantities, governed by the Maxwell equations, are calculated using Finite Element Code ANSYS. It calculates Joulean heat in the conducting cables and sends it to the flow simulator as an energy source term. The conductivity depends on temperatures; it is, therefore, being calculated within CFD by means of a user defined function. The complete data transfer between the flow and the electromagnetic simulation is done by MpCCI.
The CFD simulation with StarCD leads to a stationary solution, ANSYS operates in frequency domain. The power loss density can be derived from the harmonic solution and the exchange of data between the two simulations codes is performed as soon as new results (power loss densities and conductivities) are available.
The cables are insulated by a non-conducting PVC layer. Skin and proximity effects lead to a non-uniform distribution of the current density resulting in a non-uniform temperature field. Skin- and proximity effects which are taken into account in the coupled simulation actually play an important role. If one neglects such effects and assumes a constant power loss density the heating behaves substantially different. The figure shows results from a simulation based on a constant power loss density. It is obvious, that the heating of the middle phase is definitely underestimated.



Non-uniform power loss density
(coupled solution

Constant power loss density



3 MpCCI Business Development

The first commercial version MpCCI 3.0.x was released in autumn 2004; MpCCI 3.0.4 was published in April 2005 and provided full size interfaces and graphical user interface.
Since that time the MpCCI solution for simulation code coupling was sold for more than 90 times (March 2006). Around 30 of them are for research and academic – more than 50 licenses are installed at industrial sites. Additionally more than 50 MpCCI installations are used for demonstration and teaching purposes at the headquarters and local offices of our CAE partners

The following numbers may act as a snapshot of the geographic distribution of MpCCI usage worldwide (March 2006):

- Germany: **25**
- Europe: **27**
- USA: **26**
- Japan, Korea, Asia: **12**

A more detailed statistics on the code distribution is given in the following list

- ABAQUS users: **55**
- ANSYS users: **12**
- FLUENT users: **58**
- Flux3d (prototype): **1**
- Icepak (prototype): **1**
- MSC.Marc (prototype) **2**
- Permas users: **2**
- StarCD users: **15**
- RadTherm users: **2**
- In-house Codes: **20**

(*Note: the total number is much bigger than 90 as each user need more than 1 code adapter*):

4 Conclusion

MpCCI 3.0.5 provides a lot of new features for the coupling of simulation codes. Together with MpCCI code adapters now a complete toolbox for multidisciplinary simulation is ready for use with standard commercial simulation codes. Various solutions demonstrate the applicability of this concept and the valuable outcome for the end users. A growing number of commercial codes are supported by MpCCI code adapters.

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