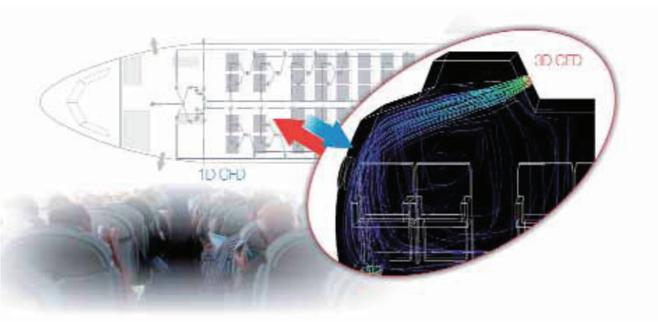
Coupling ID and 3D CFD The Challenges and Rewards of Co-Simulation

It is now well known that 3D CFD simulations can give detailed information about fluid and flow properties in complex 3D domains and that, on the other hand, 1D CFD simulations can give important information at system levels, i.e. about the performances of an entire system of internal flows. The drawbacks of the two simulation methods are that the former requires high computational costs while the latter cannot capture complex local 3D features of the flow. Therefore, the two simulations methods are to be seen as complementary, indeed a coupling of the two methods can use the strongest points of the two methods while minimizing the drawbacks. In particular, with a multi-scale modelling approach (achieved by coupling 1D and 3D codes) it is possible to simulate large and complex domains by modelling the complex parts with a 3D approach and the rest of the system with a 1D approach. This methodology can provide detailed information only where needed while providing system level information in the rest of the domain; this minimizes the computational costs. Moreover, the multi-scale approach avoids the need of imposing approximated boundary conditions to the 3D simulation which would badly affect the reliability of the simulation itself.

EnginSoft has a long and important experience both in 1D and 3D simulation modelling (with ANYS Fluent, ANSYS CFX and Flowmaster) and is active in multi-scale simulations. There are different methodology for coupling 1D and 3D codes. The coupling methodologies can be divided in *manual* or *automatic* depending on the method of data transfer between the two codes, or in *one-way* or *two-way* depending whether both systems mutually influence each other or not. Manual one-way coupling between 1D and 3D CFD codes is a standard practice in EnginSoft. Usually the complex components in the systems (such as valves, orifices, heat exchangers, vessels) are modelled in 3D with ANSYS CFX or ANSYS Fluent. The characterization of these components allows the definition of an equivalent 1D component used inside the 1D model of Flowmaster. Using this simple approach all the detailed information gained with the 3D simulations are embedded and used inside the 1D system model. EnginSoft is also actively investigating automatic one-way and two-way coupling methodologies between Flowmaster and ANSYS Fluent and ANSYS CFX.



The coupling possibility is not limited to CFD field but can extend to multi-physics. An example of multi-physics one-way coupling is the simulation of vibrations in piping systems (e.g. compressed gas systems, blow-down systems); this simulation is performed by modelling the pressure wave propagation inside the piping system with Flowmaster and passing the forces exerted by the internal flow to ANSYS for a mechanical analysis. EnginSoft has performed several vibration analyses for different customer using this one-way multi-physics approach with a semi-automatic procedure. Another example of multi-physics two-way coupling is the simulation of thermal deformation of solid structures and the fluid flow though them. In this case both systems influence each other so that the coupling needs to be two-way and automatic. EnginSoft has developed a fully-automatic interface between Flowmaster and a thermo-mechanical code for such a simulation. Finally, in this framework it is worth mentioning that Flowmaster can be directly coupled with mode-FRONTIER allowing multi-objective optimizations. EnginSoft is active in this field with different optimization projects involving 1D CFD and Flowmaster.

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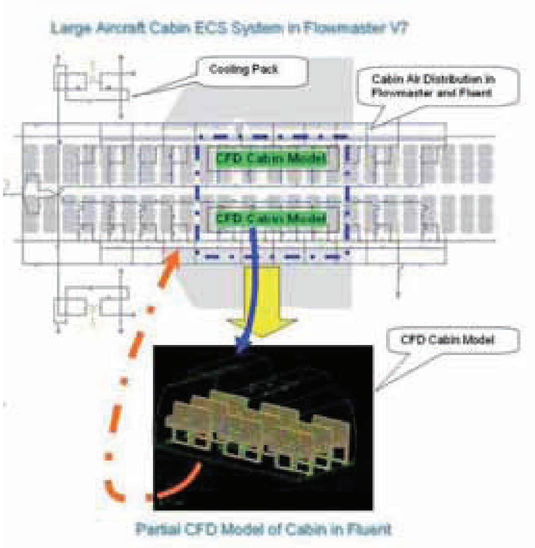
Vincent Soumoy of EURO/CFD and David Kelsall of Flowmaster Ltd, both members of the NAFEMS CFD Working Group, provide an overview of the recent NAFEMS UK seminar on coupling 1D and 3D.

The benefits of coupling 1D and 3D CFD codes have long since been recognised. Automotive and aerospace companies have used 1D codes to gain a better understanding of system performance (such as fuels systems), whilst 3D codes are used to analyse detailed behaviour within and around key components. With that in mind, the NAFEMS CFD Working Group recently arranged a seminar at the Heritage Motor Centre in Gaydon to understand the benefits of such links and assess the current state of the art. Approximately 40 interested parties from across the NAFEMS membership attended to hear a number of interesting and thought-provoking presentations from various speakers.

Darren Morrison started the technical presentations by sharing an interesting view on the subject from the perspective of a large aerospace company (AIRBUS). Validation is seen as



Large aircraft system co-simulation

desperately important, so that much of their work is to prove that any couplings are producing realistic and reasonably accurate predictions. In designing fuel systems, much of the analysis is done with 1D codes – for reasons of computational economy – but sometimes the passages and fluid interactions are so complex that only a 3D treatment is felt appropriate. Hitherto results have been passed manually from 1D to 3D analyses. There is a desire for such couplings to be automatic – but without compromising the integrity of the analysis.

Representing a vendor's perspective, Domonik Sholz from ANSYS Germany called for participating codes to develop a common infrastructure so that they could support a wide range of multi-physics applications. Using the example of tracer transport in a pipe network, he showed how co-simulation between ANSYS CFX and LMS AMESim gave excellent agreement with experiment, for flows in- and around- pipe junctions. The inter-code coupling was partially enabled by ANSYS CFD codes (CFX and Fluent) providing direct links to several 1D Codes (including AMESim, Flowmaster and GTPower). Further examples included:

- a vehicle thermal management model simultaneously running Fluent, GTPower and Flowmaster which gives temperature results to within 2% of experimental observations;
- an exhaust gas recycle (EGR) featuring CFX and GTPower.

LMS International's R&D Manager Roberto d'Ippolito then demonstrated an exciting application of 1D-3D coupling: optimization. 3D CFD on its own is currently too computationally intensive to be used in conjunction with optimization analyses for large industrial systems. 1D codes can be used to approximate the essential features of 3D CFD predictions so that meaningful optimization analyses can be performed in conjunction with CFD analyses. Using the example of a water jacket for a 5-cylinder in-line turbo-diesel, d'Ippolito demonstrated a practical methodology to optimise the design of the cooling holes of the head gasket. This is a multi objective optimization problem with a need to maximize the minimum velocity through the holes and to minimize the related pressure losses between the cylinder head and crank-case in the context of a complicated flow topology. Even with 1D analyses simplifying the fluid dynamic calculations, about 250 CPU-days of CFD computations where used to optimise the configuration.

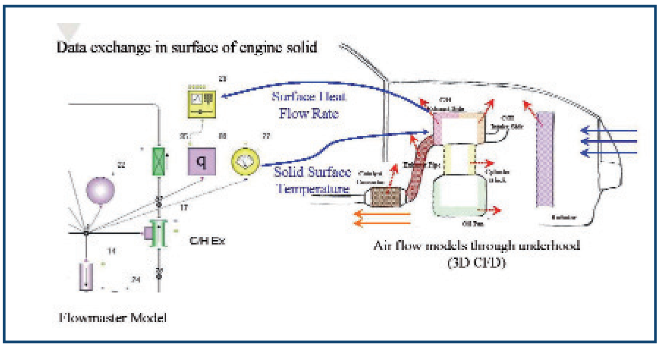
Picking up on some of the concepts raised by ANSYS's Sholz, Sreenadh Jonnavithula from CD-adapco discussed the motivations for coupling 1D and 3D CFD drawing on experience gained within CD-adapco. (In fact, these struck a chord with most participants in the meeting.) He showed how couplings to SPT Group's multiphase flow code OLGA, Gamma Technologies' GT-Power and Ricardo's WAVE have been implemented in CD-adapco's newest CFD code, STAR-CCM+. Jonnavithula used automotive and oil industry case studies to demonstrate the generic coupling capabilities of STAR-CCM+ together with specific interfaces to 3rd party products, including:

- a coupling to OLGA to facilitate the design of an oil company slug-catcher (to capture a large plug or slug of liquid that might be projected from a multiphase oil pipeline);
- a coupling with GT-POWER to facilitate the design of auto engine intake and exhaust systems, with GT-POWER modelling exhaust pipes and ducts, whilst STAR-CCM+ simulated detailed flows within the manifolds.

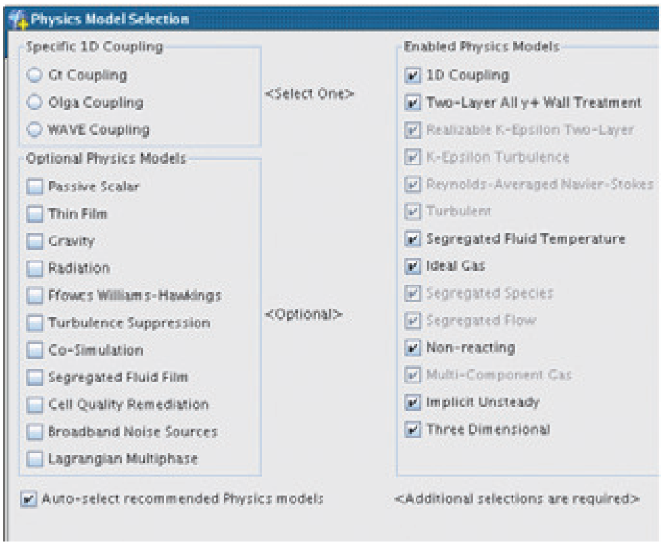
As a complete contrast to the bespoke couplings offered by ANSYS and CD-Adapco, Pascal Bayrasy of the Fraunhofer Institute for Algorithms and Scientific Computing (Fraunhofer SCAI) presented the neutral coupling interface server, MpCCI(Mesh-based parallel Code Coupling Interface).

MpCCI was originally developed as a multi-physics coupling application. It facilitates coupling and data exchange between, for example, a finite element (FE) stress analysis code and a CFD flow analysis codes for Fluid Structure Interaction (FSI) calculations and has recently been enhanced to allow 1D-3D couplings.

MpCCI addressed some of the challenges inherent in co-simulation - complex hardware environments and challenging software engineering requirements - by using adapters (developed for each software vendor) to establish a direct connection between the MpCCI Coupling Server and the 1D or 3D CFD code. Currently coupling adaptors exist for Abaqus, ANSYS, Fine/HEXA, Fine/TURBO, Flowmaster, Fluent, Flux, ICEPAK, MSC.Marc, Permas, STAR-CD and RadTherm amongst others. In principle, MpCCI offers the potential of even more complex couplings than bi-lateral ones between 1D and 3D CFD codes. Nevertheless Bayrasy demonstrated the attention to detail that



Full vehicle thermal management



The links with 1D software are fully integrated in the STAR-CCM+ user interface

has been necessary to ensure that MpCCI produces stable, convergent, conservative and consistent co-simulation solutions.
Flowmaster's David Kelsall then illustrated how a 1D code might be coupled to a 3D code (Fluent, STAR-CD or STAR-CCM+) using MpCCI as a coupling adaptor. Using the example of an aircraft environmental control system (ECS) to manage passenger cabin climate, Flowmaster was used to model the equipment and ducting within the ECS supply, whilst 3D CFD codes were used to model a partial section of the cabin (to minimize CFD run-times). MpCCI was used as a coupling adapter. The overall model allowed various what-if scenarios to be tested. Changes within the ECS supply network were shown to have a demonstrable effect on passenger comfort within the aircraft cabin. The example showed that realistic simulations are possible and provided further scope for development and optimization. The presentation discussed some of the challenges overcome in coupling 1D and 3D models and demonstrates that a methodical approach promotes convergence. With the MpCCI coupling adaptor it was a relatively straightforward exercise to swap the CFD codes between STAR-CD, Fluent and STAR-CCM+
The final session of the day was dedicated to different aspects of the 1D-3D coupling challenges.

Francesca Iudicello from the ESDU Fluid Mechanics Group reminded the meeting of the importance of using fully validated data and correlations, particularly when 3D calculations are approximated as 1D processes. ESDU has a rich history in developing methods for the design of internal flow systems for over 40 years, using validated experimental data and 1D analytical methods. Their methods now include the use of 3D CFD predictions to supplement and support experimental data. Iudicello emphasized the importance of understanding:

- the type of averaging to use for the flow parameters at the inlet and outlet boundaries;
- the sensitivity of the CFD solutions to the location, magnitude, profile and turbulence entity of the boundary conditions.

Much of ESDU's experience is now captured in CFD Best Practice Guidelines for modelling pressure loss and flow characteristics.
The final talk of the day came from David Burt of MMI engineering. He showed a multiply coupled problem featuring buoyancy driven flow in a complex ventilation system. It related to a nuclear facility where no contaminants could be allowed to escape from a process building. The modelling involved coupling a 3D CFD model (for the building space), a 1D model (for the ventilation system) and MATLAB to define some of the key components within the overall model. Much of the coupling was achieved manually, and whilst this gave acceptable results it limited the test scenarios, use cases and failure cases that could be assessed. Burt felt that an automatic coupling capability (between the computer applications) would have led to an improved understanding of the influence of each model on any of the others.

Concluding Remarks

The presentations of the day clearly demonstrated that there is a significant interest in the coupling of 1D-3D CFD.
The type of organisation undertaking coupled solution would seem to be capital intensive industries (such as automotive, aerospace, and oil) where significant gains may accrue from improved understanding of system interactions.
Developers and vendors are clearly responding to customer needs because many 3D CFD developers (e,g, ANSYS, CD-adapco) are developing bespoke coupling solutions for their own products, linked to specific 3rd party applications. However many users will be lucky if they happen to have the specific combination of 1D-3D applications that specific vendors already support – otherwise the development costs may be significant if a new coupling adaptor needs to be developed.
Fraunhofer-SCAI are pursuing a different strategy. They provide a neutral interface for simulation code coupling and already provide coupling adaptors to a wide range of FE, 3D and 1D CFD and other simulation tools.
During the day and in the questions time after the presentations there were a number of lively discussions, with some useful insight into the different perspectives of the vendors and users in a range of different industries.
There are clearly many issues still to be addressed before coupling and co-simulation become universally stages of the analysis process. But the current state of the art (and the competing offerings from developers and suppliers) would seem to suggest that this technology will develop and improve over the coming years. It is an area that NAFEMS will continue to monitor and make information available to members.
Thanks are recorded to members of the NAFEMS CFD working group who organised this event and especially to Jo Davenport (of NAFEMS) for organizing the venue and ensuring the day ran so smoothly and David Kelsall as technical champion.

Vincent Soumoy – EURO/CFD • David Kelsall – Flowmaster Ltd

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