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COUPLING 0D/1D-3D NUMERICAL APPROACHES: AN FMI STANDARD-BASED CO-SIMULATION STRATEGY FOR MONITORING INDOOR AIR QUALITY

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Summary. The current work describes a co-simulation approach where the lumped modelling techniques are made collaborating with a 3D fluid dynamic approach. The idea is to encapsulate each corresponding solver within a dedicated *FMI* standard-based block (*FMU*). They are then deployed into a co-simulation platform, which orchestrates their mutual communication. The indoor environment air quality (*IAQ*) is taken into account as application field. The Fast Fluid Dynamic (*FFD*) approach is proposed for solving the air flow field, while the *Modelica* modelling language is used for describing the physics involved on the surroundings. After testing the robustness of the approach by a benchmark case, a typical application is described dealing with the air conditioning control.

1 INTRODUCTION

Nowadays, the numerical simulation is considered a powerful tool supporting designers to achieve optimized products and efficient controlling strategies. This is the case for the *IAQ* monitoring for buildings applications. Due to the large number of the available simulation techniques, an integrated approach is becoming essential in order to achieve accurate results efficiently.

The aim of the current work is to suggest a way for integrating some of the numerical techniques typically involved when analysing the *IAQ* behaviour within a closed room. Two categories of numerical approaches are here considered: 1) *0D/1D lumped modelling*: based on the *Modelica* language, it describes the physical phenomena dynamics by means of *DAE* systems [1]. 2) *3D detailed fluid dynamic modelling*: *CFD* is the standard tool when a detailed description of the flow fields is desired, but it is inapplicable when large computational resources and times are not available. The *FFD* approach is a good compromise: it provides more accurate results than standard lumped models, while demanding lower resources than standard *CFD*. The recent trend is going towards joining the two modelling approaches ([2, 3]). Lumped models handle the physics surrounding the closed environment, thus providing the dynamic boundary conditions to the fluid dynamic models. A two-way coupling is built up by making the detailed models give back information to lumped models. The standard coupling techniques do not apply common standard rules, thus requiring *ad-hoc* communication interfaces to be implemented.

The present work suggests a co-simulation approach able to make heterogeneous modelling techniques to communicate in a standardized and tool-independent way. The *FMI* (Functional Mock-up Interface) standard is adopted ([4]): it wraps the models providing a standardized interface to communicate with. Among the available approaches, the *Co-Simulation* interface is used. It encapsulates the numerical model together with its corresponding solver: the resulting *FMU* block can be managed as a black-box, being autonomous when performing time-integration between two successive time instants, no matter whether the internal solver handles *DAE*s or *PDE*s. By simply stimulating each single *FMU* unit at the specified communication points, the co-simulation orchestrator is able to handle different numerical problems without any overhead. This approach is natively adopted for making to interact only different lumped models. The here proposed idea is to extend the same approach to 3D detailed modelling.

The present paper is organized in the following way: in chapter 2 the built-up *FMI*-based co-simulation architecture is described; in chapter 3 a benchmark example is provided for testing the robustness of the co-simulation architecture. In chapter 4 the final conclusions are resumed by providing an application case.

2 CO-SIMULATION STRATEGY

In the present work the Modelica *Buildings* library models are taken as reference starting point ([2]). In particular the focus is on the models implementing the interaction between standard Modelica lumped models and the external FFD code developed from scratch in C language ([5]). The interaction between these two entities is made acausal, and it is realized by implementing a dedicated middleware function layer. The usage of these models is limited to the *Modelica* environment: the addition of any further component needs an *ad-hoc* interface implementation whose applicability is restricted within the same framework. A more adaptable usage of the same models being desired, an *FMI*-based co-simulation approach has been chosen in the present work.

Modelica implements the acausal approach, whereas the *FMI* standard implements the I/O logic. The main effort has been devoted to subdivide the original referenced models into sub-units able to exchange information as I/O data flow without affecting the results. The following classification of the involved units is identified:

- *lumped models*: they include the 0D/1D dynamic models based on governing *DAE* systems. Their encapsulation into *FMU*s is normally accomplished by the adopted implementation tool, no overhead being required;
- *3D FFD model*: the *FFD* solver is encapsulated within a dedicated *FMU* unit without modifying its peculiarities. [5] implemented one of the first reliable and relevant version of the *FFD* technique applied to the indoor environments. It handles the standard Navier-Stokes equations by solving progressively their 3 sub-components: the one containing the non-linear convective term is dealt with by the Semi-Lagrangian approach, the one containing the diffusive term is handled by a standard implicit Laplacian solver, and the one including the pressure gradient is treated according to the standard *PIMPLE* approach. Not being affected by the *CFL* condition, the solving procedure results to be always stable and robust.

Once these *FMU* units are available, the last step is to integrate them within an *FMI*-based co-simulation platform. Several platforms are available: in the present work *DYMOLA* is adopted ([6]) due to its robustness and to its performance features. The effectiveness of the resulting coupling is increased by the efficiency of the unit models themselves: lumped models are typically employed when real-time results are required, and the *FFD* is many times quicker than *CFD*, running faster than real-time with acceptable accuracy. All these features make the resulting co-simulation model extremely versatile and ready-to-use, enabling for example to support the control strategies of *HVAC* devices ([2]) and the real-time environment monitoring.

3 BENCHMARK CASE

As benchmark of the above-described co-simulation framework, the case from [7] is considered, which has already been used in [5] for *FFD* validation purposes. It deals with the thermal exchange phenomena arising within a room where a heated box is placed and each boundary wall has a fixed temperature value. Both natural and forced convection phenomena are present. The domain description together with the mesh size and the supplied boundary conditions are detailed within the referenced works. In Figure 1 results are compared with *CFD* and *FFD* references. Results from the here implemented co-simulation approach agree well with the *CFD* results, the main differences being due to the absence of any turbulence and wall treatment within the *FFD* approach. On the other side, the few differences between the *FFD* from [5] and the *FFD* from the here implemented co-simulation are ascribable to the different distribution of mesh elements. On the other side, the great simulation speed improvement of the *FFD* vs the *CFD* is confirmed even when the *FFD* is embedded within the co-simulation approach, being *1.2* times faster than real-time when running on a single-core.

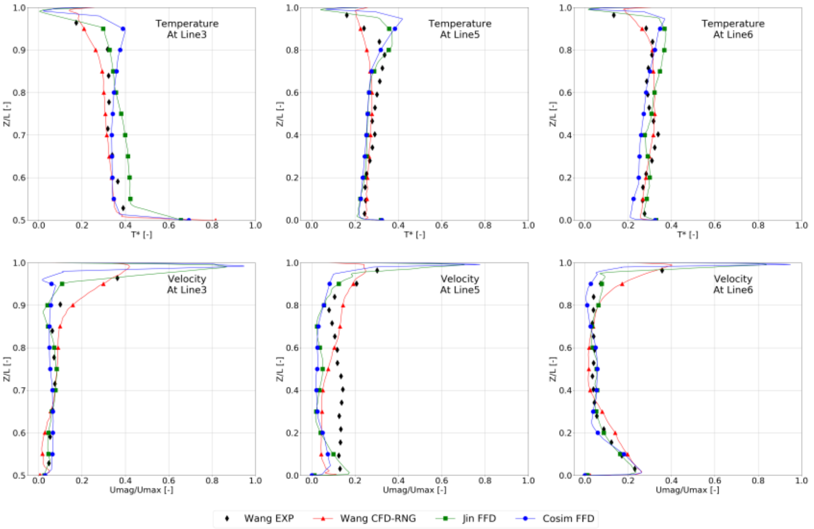

Figure 1 – Experiment [7] vs CFD [7] vs FFD [5] vs Co-Simulation approaches: temperature (top) and velocity (bottom) vertical profiles at points 3, 5 and 6 according to setup from [7].

4 CONCLUSIONS

The present work proposes a co-simulation framework where numerical simulation approaches are involved handling different kinds of governing equations. *DAE*-based lumped models and *PDE*-based *FFD* model are encapsulated within corresponding *FMI*-based units and they are made to cooperate without needing any further overhead. The main strength of this approach is represented by the way a co-simulation model can be built once each single *FMU* unit is available. Even without a deep knowledge about the physics and the numerical aspects involved within each unit, the final user can easily represent the IAQ of closed rooms by interfacing the lumped modelling with the 3D *FFD* simulation approach quickly and reliably. Just as an application example, in Figure 2 a co-simulation model is depicted where an *HVAC* device acts on the air temperature within the same domain used for the benchmark described in §3. Once the single *FMU* units are made available, their mutual interaction is as easy as connecting their I/O ports graphically.

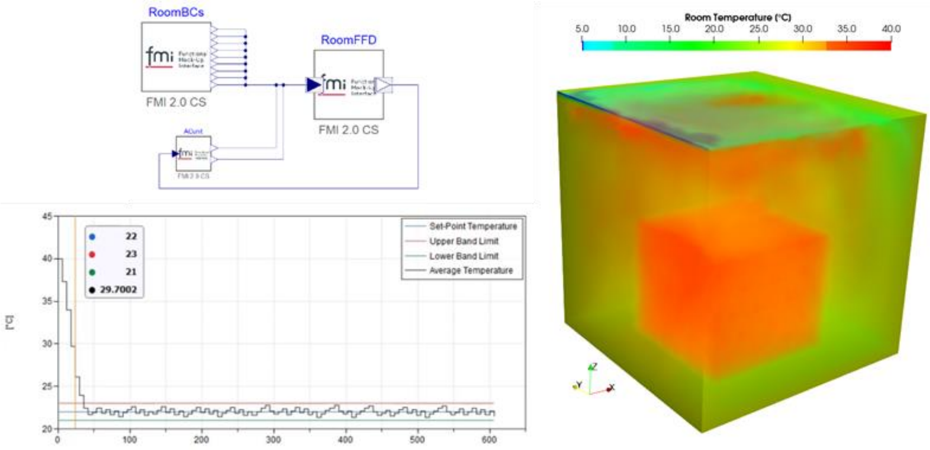

Figure 2 - HVAC control for indoor applications: FMI co-simulation model (top left); room average temperature time history (bottom left); snapshot of the 3D thermal field within the controlled domain (right).

The approach described in the current work can be considered as the first stage of a more structured road map. In particular, three improving steps have been identified, that is: the parallelization of the *FFD* solver both by standard *CPU*-based and *GPU*-based approaches; the integration of the on-field sensor data within the numerical co-simulation framework; the deployment of the co-simulation framework within the *HVAC* control unit devices, enabling the control strategies to fit better the actual indoor air quality situation.

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