Coupled System-Level and Physical-Level Simulation

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ABSTRACT

Software tools for Mixed-Level Coupled Simulations have been developed. The system-level simulation uses the circuit theory approach, where each element of the system is modeled either through mathematical equation, or through coupling with physical-level 3D simulation. The physical-level simulation solves numerically partial differential equations for those elements. As a system-level simulator, SABER is used, and for the physical 3D simulation, CFD-ACE+ multi-physics solver from CFDRC is used. The coupling communication has been realized using CORBA and additional templates in MAST and C++. The respective SABER and CFD-ACE+ modules can be run on the same or separate computers. Application examples are presented in the paper for electronic packaging, microfluidic system, PCR control, and VCSEL array.

Keywords: mixed-level, mixed-mode, coupled 3D simulation, system-level and physical modeling

1 INTRODUCTION

The system-level simulator SABER makes it possible to model problems described by circuits built from lumped elements. The elements represent physical phenomena that can be expressed through mathematical equations based on "through" and "across" variables, and conservation laws.

Such reduced models may not exist for some physical devices. Those devices can be modeled using a numerical technique, such as the Finite Element Method, or the Finite Volume Method, which directly solve the partial differential equations describing the physical phenomena. Since those methods are much more time consuming, it could be useful to use circuit description for most of the system, and perform three-dimensional physical simulation only for few elements for which there are no lumped models available.

1.1 Objective

Develop a tool for mixed-level coupled simulation. The system-level simulation will use the circuit theory approach where each element of the system is modeled either through mathematical equation, or through physical-level 3D simulation. The physical-level simulation solves numerically partial differential equations for those elements. As a system-level simulator, we will use SABER, and for the physical 3D simulation, CFD-ACE+ multi-physics solver from CFDRC.

2 IMPLEMENTATION

For this type of simulation, we have developed new tools, which allow performing a coupled simulation between physical-level simulator and SABER. Both the simulators communicate through CORBA, which establishes the client-server relationships between them. Additional templates, written in MAST and C++, handle the communication with CFD-ACE+ and provide relevant physical simulation results from the 3D simulator to SABER (Figure 1).

The simulation requires creating 3D models for all physically modeled elements, and another model for SABER, describing system-level circuit. The latter model uses the special templates for parts simulated with 3D models. Communication through CORBA allows to run both simulators on a single computer or separate machines, and to exchange data automatically.

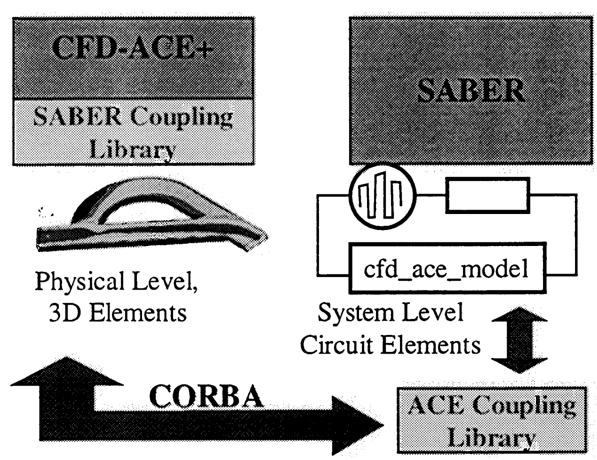

Figure 1: Communication model between the coupled simulators.

2.1 Coupled Simulators

The SABER Mixed-Signal Simulator provides analysis of the complete behavior of analog and mixed digital-analog signal systems, including electrical, mechanical, hydraulic and other technology subsystems, and their interactions.

The CFD-ACE+ [1] is the Multi-Physics Computational Environment, which includes: General Purpose Multi-

Disciplinary Physics Solver, Model Builders CFD-GEOM and CFD-Micromesh, and Visualization Tool CFD-VIEW. CFD-ACE+ analysis package provides the tools to specify, and iteratively solve, the equations that describe the physical processes for fluidic, thermal, mechanical, electrostatic, and magnetic problems. The physical models are solved on a 2D, cylindrical, or 3D multi-domain grid. The grid can be structured, unstructured, hybrid, or adaptive Cartesian. There is also a moving grid capability to track moving and deforming bodies and surfaces. The physical models are implemented in a highly modularized code architecture, which facilitates the addition of future physical models. The software has been used in a wide range of applications in Aerospace, Automotive, Bio-Medical and Chemical Engineering, Semiconductor Industry, MEMS design (pressure and acceleration sensors, micro-resonators, micro-pumps, micro-valves, micro-channels, micro-fluidics amplifiers, ink jet nozzles, chemical sensors), Optical Microdevices, VLSI Interconnects, and Electronics Packaging.

2.2 Communication

The communication between SABER and CFD-ACE+ is based on CORBA specification [2] for application interoperability. This approach makes the coupling independent of platform and operating system. Both simulators can be started on the same computer, or two different machines (Figure 1).

3 COUPLING ALGORITHM

The SABER program controls the coupled simulation. When SABER needs information about physical elements, a 3D simulation is triggered for the current solution point. If there is more than one element described through physical 3D models, each of them can be simulated on a separate computer. The computed results define not only values of variables for given element template, but also their derivatives. This information is used to formulate linearized equations for this element at the given operation point. The 3D simulation can be very time consuming, so those computations should be performed as rarely as possible. Therefore, some intermediate results required by SABER during the iteration process in steady-state simulation, for the element modeled in 3D could be computed from this linear model. The decision whether to perform full simulation or use approximation result depends on current estimation of accuracy.

The transient simulation uses the same approach for each time step as the steady-state solution. The coupling allows SABER to automatically select time step of the entire computation. The physical 3D simulator uses those time steps, but it also can limit maximum time step used by SABER. The time step repetition in CFD-ACE+ simulator is fully supported, so it can repeat computation with smaller time step if circuit simulation requires it. Both simulations use the same time stepping, but to speed up the computation some results from 3D simulation can be obtained not from full simulation but on the basis of earlier results.

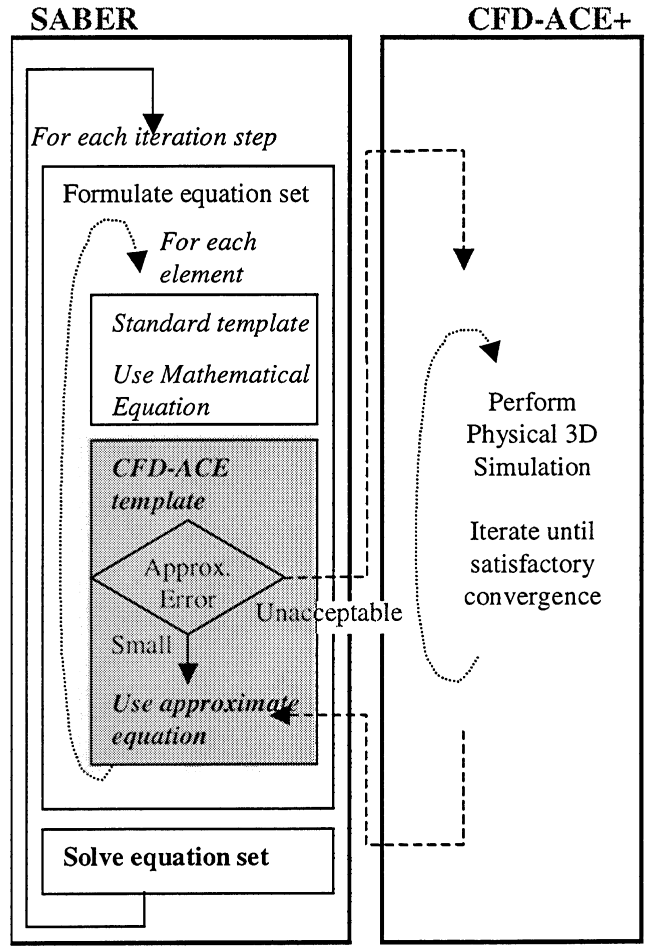

Figure 2: Operation flow during the coupled simulation.

4 APPLICATION EXAMPLES

4.1 Power Control Circuit with IGBT and 3D Package Cooling

The power-electronics example circuit was simulated using the presented approach. The problem consists of electro-mechanical system simulated at system level, and the full thermal environment simulated at physical level. A 3D model is used to simulate airflow in system case and its cooling effect on IGBT. The circuit schematic presented in Figure 3 contains mechanical load connected to a DC motor controlled by an IGBT.

The IGBT model available in SABER [3] contains additional thermal pin connected to physical simulation template. This pin allows a two-way coupling between the simulations. SABER sends to CFD-ACE+ information about the power dissipation in IGBT, and receives back the actual temperature, calculated from full 3D thermal environment of the electronic device and its package.

The circuit contains also a simple fan control module which uses the current temperature of IGBT as a feedback signal to control the airflow (pressure) generated by fan built into the system case. The airflow generated by the fan influences the device cooling and the temperature computed by 3D physical simulation.

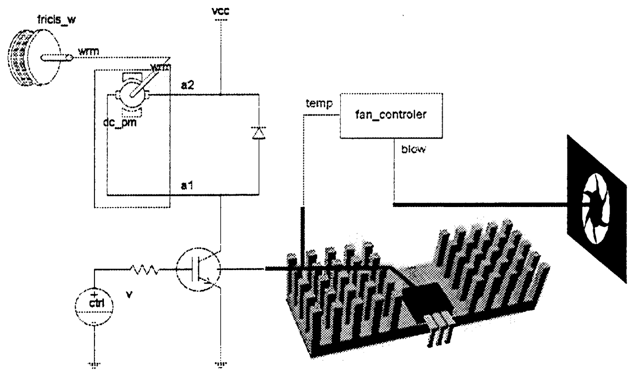

Figure 3: Power-electronics system modeled by circuit coupled with 3D models.

There are two coupling connections between SABER and CFD-ACE+ in this setup. First, there is a two-way thermal coupling between IGBT lumped model and 3D physical package model. The power dissipation computed by SABER is used in CFD-ACE+ to find temperature of the IGBT, and the temperature computed from 3D model is used in SABER as the IGBT working temperature. The second coupling allows the circuit to control the fan to change air pressure at the case inlet. The implementation of this controller makes air flow dependent on current temperature increase.

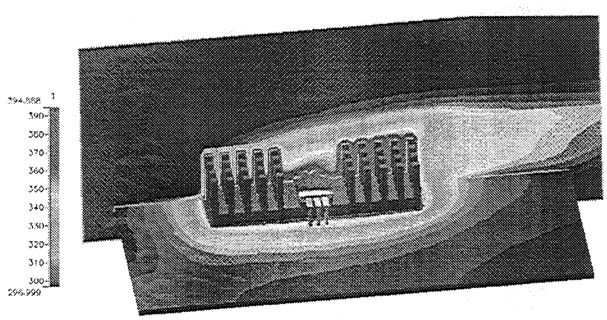

Figure 4: Temperature on surfaces of the radiator, IGBT package and of the flowing air.

Figure 4 shows chosen steady-state results obtained for this system. The power dissipated in IGBT was for this example 12.21W. The voltage applied to gate as well as power supply was 50V DC. The motor speed computed in the simulation for a given load was 47.7 rotations per second. The resulting average temperature of IGBT was computed as 394.4K (121.2°C).

The cooling effect depends on airflow speed forced by the fan controlled by the feedback circuit. Figure 5 presents the airflow obtained from CFD-ACE+ 3D simulations.

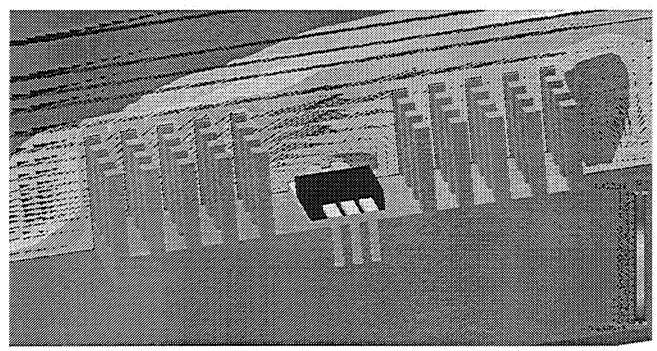

Figure 5: Airflow around IGBT package

4.2 Microfluidic Tesla Valve Circuit

A microfluidic circuit was also simulated using the coupled simulation. The system consists of two Tesla valves [4] simulated at physical level, and a fluid pressure source simulated at system level (Figure 6). The objective of those simulations was generation of data necessary to build reduced models of the valves, and later to be able to perform system-level simulation using only compact models. The coupling simulation was used to obtain valve characteristics for model reduction.

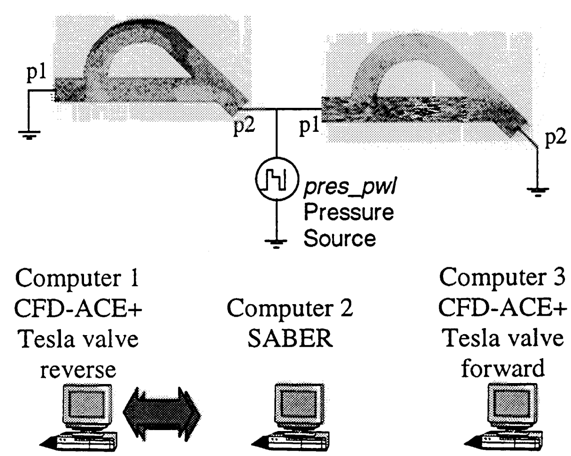

Figure 6: Mixed-levels Simulation of Microfluidic Circuit

The simulation used the fluidic pin type in SABER for connection to CFD-ACE+. The model contains two Tesla valves, each of them is simulated using 3D physical model on different computer. The circuit-level simulation sends to the physical 3D simulations information about the instantaneous pressure, and receives back the actual fluid flow value calculated through integration on the surface connected to the pin.

This example demonstrates the capability of the coupling where a circuit-level simulation can be performed on one computer, and each of physically modeled elements can be simulated separately on other computers.

4.3 Precise Thermal Control of Polymerize Chain Reaction

A Quadratic Controller with Kalman Filter feedback was used to control temperature inside Polymerize Chain Reactor (PCR). The system consists of a PCR simulated at physical level and a complex controller simulated at system level (Figure 7). The PCR device contains DNA sample, heater, and cooler. The objective of those simulations was to design a controller for precise tracking of required temperature values inside the reactor. The temperature of DNA samples should change in time, and required time delays are much smaller than thermal constant of PCR. Therefore, the controller should predict those effects and apply correct heating (or cooling) schemes with an appropriate timing.

The simulation used the thermal pin-type in SABER for connection to CFD-ACE+. The circuit-level simulation sends the information about power dissipation in the heater to the physical 3D simulator and receives back the actual temperature of the DNA sample.

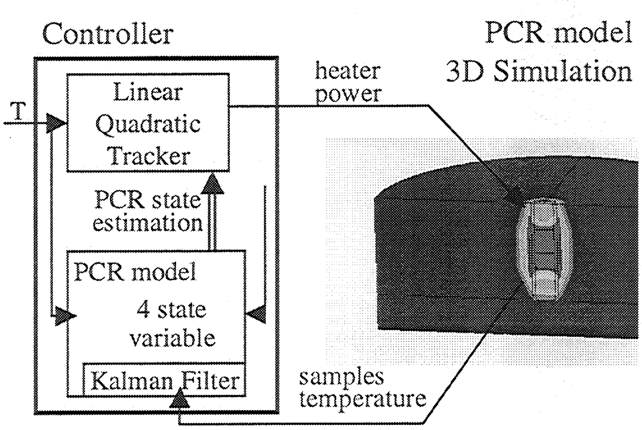

Figure 7: Thermal control of Polymerize Chain Reaction.

4.4 VCSEL Array

Another application of the presented simulation technique is an analysis of thermo-mechanical behavior of a Vertical-Cavity Surface-Emitting Lasers (VCSEL) array and its connectors/package together with the driving electronic circuits. The integration of the VCSEL compact models (implemented in SABER) into a 3D thermo-mechanical model in CFD-ACE+ is illustrated in Figure 8. This kind of simulation allows determining thermally induced displacement of a laser and its potential optical misalignment to optical fibers or waveguides.

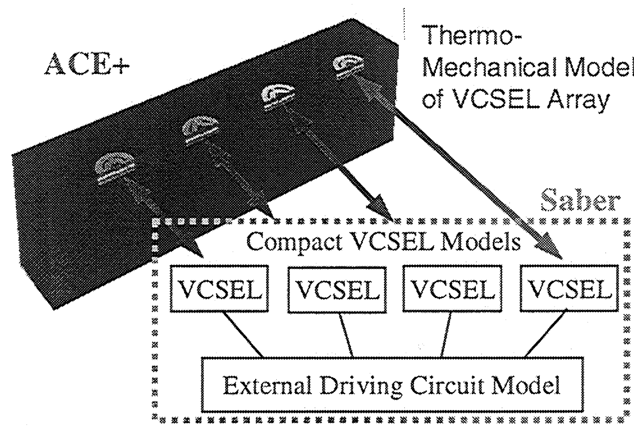

Figure 8: Mixed-levels Simulation of VCSEL Array

5 CONCLUSIONS

In this paper, software tools developed for Mixed-Level Coupled Simulation have been described. The presented approach links SABER as a system-level simulator with CFD-ACE+ multi-physics solver as a physical-level 3D simulator. The system-level simulation uses the circuit theory approach, where each element of the system is modeled either through mathematical equation, or through coupling with physical-level 3D simulation. The physical-level simulation solves numerically partial differential equations for the elements for which compact models are not available. The coupling communication has been realized using CORBA, therefore respective SABER and CFD-ACE+ modules can be run on the same or separate computers.

The presented technique is very general and can be used to solve any problem that cannot be directly simulated at system-level due to complexity of its elements or lack of compact models of some components. On the other hand, it can be useful for a physical 2D/3D simulation of complex devices (like e.g. MEMS structures) surrounded by external circuit for which the system level modeling is the most appropriate.

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