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Simulation and model analysis of MEMS

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Abstract: The modelling method, computer-aided modelling tools, multi-domain model libraries, and coupling different simulators are discussed from methodologic point of view. The electrical network concept is introduced in the simulation of different domain systems, in which equivalent circuits are applied to physical quantities between different domain systems. The building of component model libraries is considered because it is very important for the system modelling and simulation. The multi-terminal port elements can be introduced and described by linear and nonlinear differential equations. In addition, the order reduction problem, model optimization methods, related simulation tools and the coupling between simulators are analyzed.

Key words: multi-domain system simulation; generalized networks; optimization; model library

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1 Introduction

In terms of current state-of-the-art, VLSI design environments have reached a significant level of refinement, corresponding design environments for microelectromechanical systems (MEMS) are still in their infancy, with much work remaining to be done. Simulation approaches of MEMS mostly include the finite element method (FEM) and boundary element method (BEM) and so forth. In addition, other essential components in the MEMS design flow still require additional research. The system level simulation of MEMS may be benefited from the co-integration of the VLSI and MEMS design environments. MEMS are characterized by the interaction of components operation on different physical domains. The analysis of such complex systems requires the modelling and simulation of single components as well as the overall system simulation. Two general methods exist for system simulation at present:

® Coupling of special simulators for different physical domains or different abstraction levels.

® Modelling of the different components with a common modelling approach suitable for a powerful system simulator.

In this paper, we consider the connection of two methods. MEMS and other microsystems may be considered as multi-domain system which contains mechanical, electronic, thermal, optical and

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fluidic problems. The component level simulation must be considered very scrutinizingly and coupled together from the systems point of view. In this way, a very complicate design flow is needed for MEMS. Furthermore, because of the heterogeneity and complexity of diferent cmponent, simulation of MEMS can't be made by a single simulator. The diagrammatic drawing of modelling and simulation for MEMS is shown in Fig. 1[1].

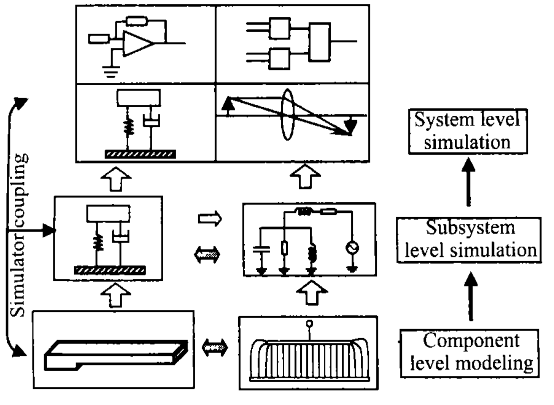


Fig. 1 Diagrammatic drawing of modeling and simulation for MEMS.

In practice, it is very difficult for us to build a MEMS simulator in which different physical domain problems could be modeled. The basic approach to simulating complex MEMS[2-5] is:

® partitioning the system into subsystems or components,

® modelling the behavior of components,

® simulation of the entire system by the coupling between simulators.

The practicability of this approach depends on the selection of the most appropriate modelling method and choice of the simulator for each level of abstraction or each physical domain. In this paper, the modelling method, computer-aided modelling tools, multi-domain model libraries, and coupling different simulators are developed from methodology point . The electrical network concept (for example, Kirchhoff's network model) is introduced in the simulation of different domain system in which equivalent circuits are applied to physical quantities between different domain system, for example, electromechanical and thermo-electrical conversion. Some examples such as micropump, micromachining resonator/filters, micromachining accelerometer, micromachining gyro etc. are given. The building of component model libraries is considered because it is very important for the modelling and simulation of system. The multi-terminal port elements can be introduced and described by the linear and nonlinear differential equations. In addition, the order reduction problem, model optimization methods, related simulation tools and the coupling between simulators are analyzed.

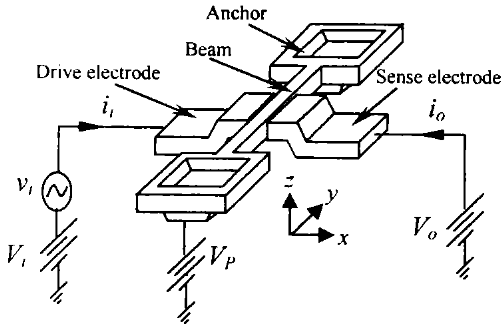
2 Electromechanical conversion and general Kirchhoff's network theory

Many systems which have different physical contents may be described by the same formal differential equation, they are referred to as "similar system". Using the similarity, we may apply equivalent circuit to solve the behavior of micromechanical system. Table 1 shows the mechanical-to-electrical correspondence in the current analogy.

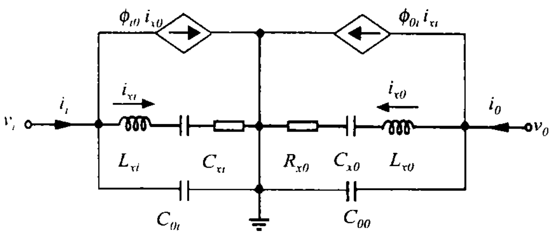
Table 1 Mechanical-to-electrical correspondence in the current analogy

Mechanical variable	Electrical variable
Damping, c	Resistance, R
Stiffness^{-1}, k^{-1}	Capacitance, C
Mass, m	Inductance, L
Force, f	Voltage, V
Velocity, v	Current, I

The micromechanical resonator and its equivalent circuit[6] are shown in Fig. 2.



(a) Schematic of the champed-champed beam micromechanical resonator



(b) Equivalent circuit for the micromechaical resonator

Fig. 2 Schematic of the champed-champed beam micromechanical resonator and its equivalent circuit

A two-resonator micromechanical filter and its equivalent circuit[6-7] are shown in Fig. 3.

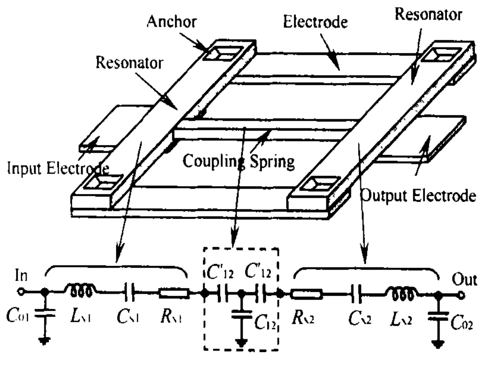


Fig. 3 Perspective view schematic of the two-resonator micromechaical filter and its equivalent circuit

Electrical circuits are often modeled as networks. The network concept is not restricted to the electrical domain. This concept may be generalized to other physical domains like mechanics or fluidics. There are some basic requirements which have to be fulfilled by the systems to be modeled as networks:

a) Networks consist of elements (components) and links between them.

b) Two kinds of quantities (variables) in various physical domains: flow quantities (electrical currents or mechanical forces), difference quantities (electrical voltages or fluidic pressures).

c) A link is an ideal element: the same difference quantity at each point, no loss of a flow quantity through it. The mathematical model of the network structure is a directed graph: the branches are related to the elements, the nodes are related to the links.

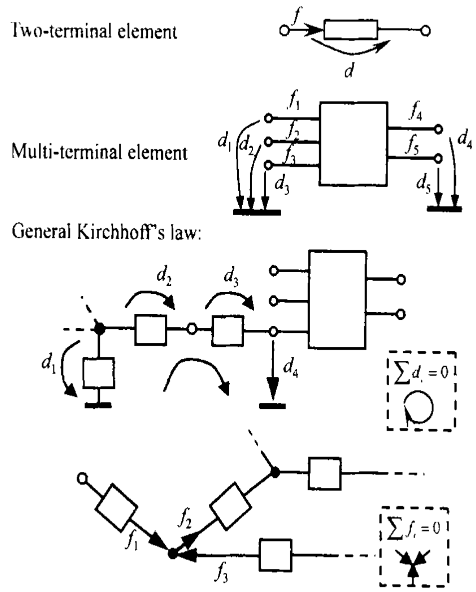
d) The elements are usually described as two-poles or multi-terminal elements.

e) The relation between flow and difference quantities is mostly given as implicit equations or differential equations, depending only on the terminal quantities and, possibly, internal states.

f) Two conservation laws:

- the sum of all difference quantities between nodes along each mesh in the network graph is zero,

- the sum of all flow quantities into each node is zero.



f :flow quantity; d :difference quantity

Fig. 4 Concept of general Kirchhoff's network

This network is referred to as general Kirchhoff 's network and its concept is described in Fig. 4. The network model of micropump based general Kirchhoff 's Network concept is shown in Fig. 5.

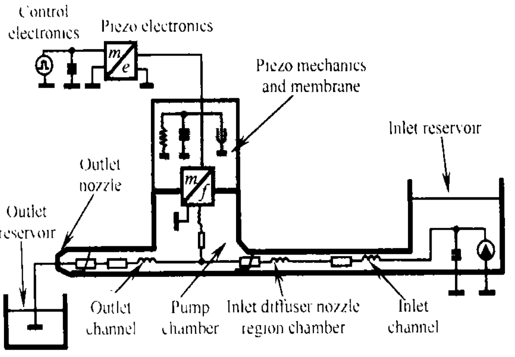


Fig. 5　Network model of micropump

Starting with the geometrical structure of the microsystem , a manual decomposition into subsystems or components is carried out. By further refinement of the partitioning in each physical domain - often in a hierarchical manner - the entire system may be decomposed into a lot of relatively simple basic elements. Mostly , it is possible to describe these elements mathematically in an analytical form and with explicit geometrical dimensions and material parameters. For example , the multi-terminal behavioral model[1] of a beam segment is shown in Fig. 6. The beam is used in many micromechanical devices such as micro-sensor , micro accelerometer , MEMS switch , and micromechanical gyro , etc. When the beam is analyzed by means of multi-terminal approach , it may be discomposed into many segments with smaller length L. and if the length of beam is small enough , it may be described by the following equation ,

$$Mr'' + Dr' + Sr = E , \qquad (1)$$

where vector r contains displacement w and rotational angle φ in all three spatial directions x , y and z. Vector E comprises external translational force F and torque T. M , D , and S are the mass , damping , and stiffness matrices of the beam segment , respectively. Force and torque are flow quantities , displacement and rotation angle are difference quantities affecting both ends ①, ②of the element.

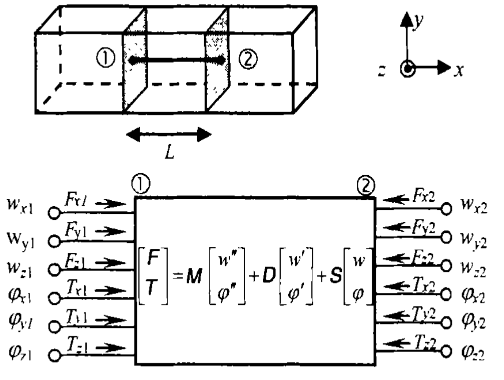


Fig. 6　Multi-terminal behavioral model of a beam segment

This decomposition approach seems to be supported in a very natural way by the general Kirchhoff 's network concept. The original system must possess the basic properties of the network modelling approach , especially the distinction between flow and difference quantities and the existence of conservation laws. This approach also has some limitations related to the partitioning procedure and the applicability of general Kirchhoff 's network in general , for example , the inhomogeneity for geometry of device , field and coupled field problem and so on.

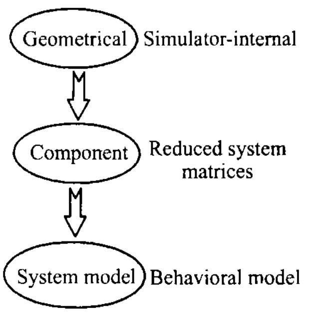


Fig. 7　Steps in reduced-order moel generation

In general , the microsystem may be decomposed into the basic elements with known analytical model. But some times , this approach can 't be used. The discretization of the partial differential equations may be applied so that in ordinary differential equations or differential-algebraic equations the number of equation are very large. In this situation, order reduction approach should be applied in order to obtain an element model with order reducing equations. The number of equation is decreased in this simplified model on condition that the error resulting in order reduction may be acceptable. In practical approach, some simulators (such as ANSYS) have special algorithms for order reduction and export the reduced model equations. In this way, a postprocessor is necessary to generate a system-level model in one of the well established model description languages or as a pure C language code. Steps in reduced-order model generation are shown in Fig. 7.

3 Element model libraries

Element model libraries are an essential part of the MEMS design flow. These libraries comprise basic element models and more complicated component models. All the models were derived either analytically, *i. e.* using equations from textbooks, or numerically, *i. e.* using measured data or FEM results and approximation algorithms to formulate the model equations. Partial library elements in the MEMS design include:

* Mechanical components: elastic beam, gear, rigid plates, flexible plate and shell etc.
* Electro-mechanical components: longitudinal comb structures, curved comb structures, lateral comb structures, electrodes and beam with electrode etc.
* Fluidic components: diffuser, nozzle, channels, reservoir, transducer, membrane and piezo element etc.
* Magnetic components: ferromagnetic section (nonlinear), ferromagnetic section (linear), air gap with force effect and variable width, air gap with constant width and sources of magnetomotive force etc.
* Optical components: lasers, detectors, thin lenses, mirrors, polarizer, beam splitters, optical waveguide and fiber emitters and receivers etc.

In the library, all components are described by multi-terminal modular or sign icon which contains basic physical effect and terminal signal type (for example, flow and difference quantities).

4 Optimization and simulator coupling

The optimization is necessary to determine model parameters and to improve the performance of the simulation system. A framework of modular optimization program is shown in Fig. 8.

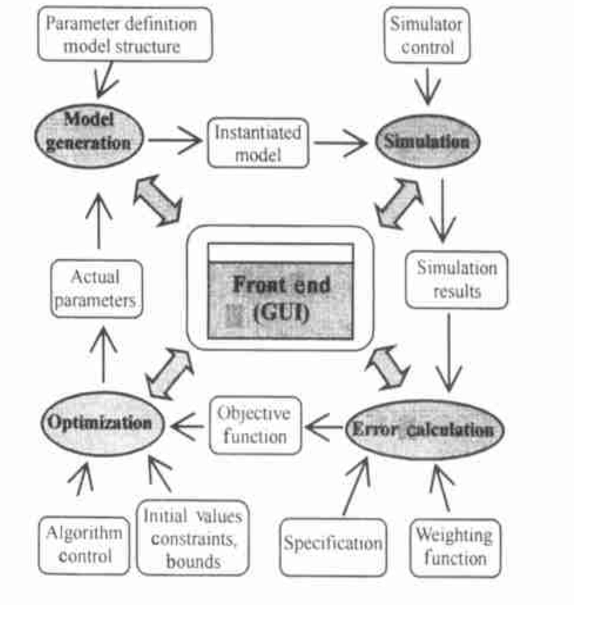


Fig. 8 Program frame of modular optimization

The following optimization algorithms are available at present: quasi Newton method, conjugate gradient algorithm, Powell algorithm, Nelder Mead simplex algorithm and simulated annealing algorithm.

The simulation of MEMS should be based on design of modularized programs which include many modules such as model generation, simulation, error calculation and optimization. These modules comprise many functions implemented by simulators such as ANAYS, ELDO, Saber and

MATLAB/ Simulink. C language interface is used to couple different simulator which models the MEMS device in the different physical domain. The information exchange between two software processes is supported by different mechanisms: coupling via files , pipes , sockets , or shared memory. There are some protocol layers to realize physically and logically the data transfer between software programs. The direct handling of protocol software is cumbersome and is supported by powerful software packages such as CORBA[8] (Common Object Request Broker Architecture) , PVM (Parallel Virtual Machine) , MPI (Message Passing Interface) , Java RMI (Remote Method Invocation) , COM/ DCOM (Distributed Common Object Model) .

5 Conclusion

MEMS and other microsystems can be referred to as a multi-domain system. In this paper , the modelling method , computer-aided modelling tools , multi-domain model libraries , and coupling between different simulators are discussed from methodology point. The general Kirchhoff 's networks concept is introduced in the simulation of different domain system in which equivalent circuits are applied to physical quantities between different physical domain systems. The order reduction problem of differential equations , model optimization methods , related simulation tools and the coupling between simulators are analyzed. The simulation and modelling of MEMS has been discussed in a few words. In the future , many works such as model libraries (linear , nonlinear) , order reduction of dynamic systems , coupled field problem should be done. Furthermore , the simulated optimization systems based LAN or Internet may be developed , so that an available simulation platform could be provided.

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微机电系统(MEMS)的仿真和模型分析

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摘要 :微机电系统(MEMS) 器件及系统仿真正日益受到 MEMS 研究者的重视。其仿真内容涉及力学、电子学、热学、光学、流体学等许多学科。MEMS 和其他微系统可看作为一个多域物理系统。本文从方法学观点讨论了建模方法、计算机辅助模拟工具、多域模型库以及不同仿真器的耦合问题。将电网络概念引入到不同域系统仿真中以及等效电路被应用到不同的物理域系统。对于系统模拟和仿真来说 ,元件模型库的建立非常重要 ,引入多端口元件 ,并用线性和非线性微分方程加以描述。另外 ,本文也简单分析了系统仿真中涉及的降阶问题、模型优化方法以及相关的仿真工具和仿真器间的耦合问题。

关　键　词 :多域系统仿真 ;广义网络 ;优化 ;模型库

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