On The Necessity of Multiphysics Simulation Experiments in MEMS Teaching

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Abstract—**Microelectromechanical system (MEMS) is an interdisciplinary research and education field. The multiphysics simulation can make the abstract theory on MEMS design concrete and improve the learning efficiency. A MEMS course design is presented in this paper. The content consists of fundamental theory on MEMS design and hands-on simulation experiments. The essence of multiphysics coupling is revealed. Simulation cases are displayed. Teaching approaches are applied in the course design including hands-on simulation experiments, from an easy task to the difficult one and integration of simulation cases and theory lectures. The course design has guiding significance for other science and engineering curriculum design.**

Keywords—multiphysics simulation, hands-on experiment, MEMS theory, visualization.

I. INTRODUCTION

The human brain has different mapping reception or reaction to different forms of information. The richness of information carried by texts, formulas, curves, images and videos is enhanced in succession, and the impact on the brain is also enhanced successively with the above presentations of information.

In the field of science and engineering, fundamental theories are usually difficult to learn and be understood because they are often abstract. From the perspective of methodology, if the theoretical concepts could be represented in the form of curves, images or videos with rich and detailed information, to interpret highly abstract texts or formulas, it will greatly reduce the difficulty of theoretical learning and stimulate students' interest in studying. Professional simulation tools are required to realize the visualization of information. Nowadays, the widely use of computers and networks provides support for the creation of visual simulation tools in science and engineering teaching, which makes this advanced and novel teaching mode possible.

With the rapid development of microelectromechanical system (MEMS) technology, the demand for talents in this field is increasing year by year, and many universities have offered MEMS courses for graduate students and undergraduates in mechatronics engineering. Generally, a MEMS course includes three parts: fundamental theory, fabrication process technology and its application progress. The fundamental theory on MEMS design is quite important and is the most difficult part in MEMS learning. A good approach to improve theoretical study is using teaching facilities such as simulation to make the abstract theory concrete and vivid [1-2].

At present, the MEMS courses offered by various colleges and universities mainly focus on MEMS fabrication technology and its application in multiple disciplines. Some of these courses have also introduced the fundamental theory on MEMS design, but there are few contents concerning its modeling and simulation. The teaching of fundamental theory is mainly based on texts and formulas, which results in unsatisfactory learning effects. In addition, the academic textbooks in MEMS field also focus on the design, fabrication and application [3-6], while the simulation is rarely involved.

MEMS is an interdisciplinary research field, as shown in Fig. 1, involving material, machinery, mechanics, electronics, thermotics, optics, magnetics *et al.* A MEMS device often works with multiple physical fields, so its design must be a complex multiphysics problem. We have to consider the subtle and close relationship between multiple disciplines in a MEMS device. The coupling of multiple physical fields has always been a profound and abstract theoretical problem. It is quite challenging for beginners. Some numerical simulation tools, such as COMSOL Multiphysics, ANSYS Multiphysics and so on, are very powerful in multiphysics coupling and have been widely used in MEMS design. It will be a good way to introduce such kind of modeling and simulation tools to design theories in MEMS teaching.

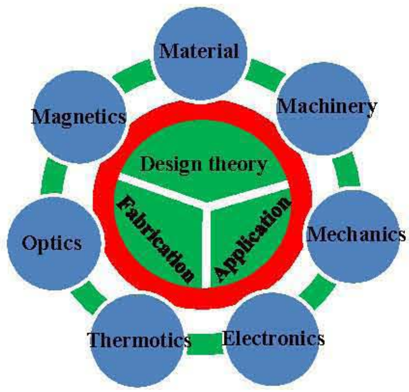


Fig. 1. MEMS as an interdisciplinary research field

Although there are few books on MEMS simulation that can be directly referenced, there are numerous literatures [7-

12] in this field for teachers to refer to when preparing lessons. A large number of relevant literatures provide abundant source for the course preparation of simulation cases, and are helpful for continuous improvement of the lessons.

From the literatures, purely theoretical lectures suffer from the disadvantage that students pay less attention to the contents, which results in poor learning effect [13]. The well-known solution to this problem is the use of a memory test in many forms from an easy task to the difficult one with deeply involved activities during the study [14-17]. Furthermore, in the experiments of individual participation, the attention concentration, brain thinking activity and understanding degree are much higher than those who only listen to others [18-19]. Therefore, the simulation class should be carried out in the form of hands-on experiments with students' deep participation rather than simple demonstration and operation by teachers.

Based on the above consideration, we offer a MEMS course entitled "Microsystem Design and Multiphysics Simulation" for the first-year graduate students. The hands-on simulation experiments accounts for more than 50% of the total class hours of the course.

II. Course Content

This course focuses on the fundamental theory on MEMS design. A simulation tool, COMSOL Multiphysics, is applied to make the abstract theory concrete in a visual way.

The course content consists of two parts: fundamental theory on MEMS design and hands-on simulation experiments. The two parts are not independent, but are integrated and closely linked.

It is a two credits course with an expected student workload of 32 class hours for the graduates in College of Optics and Photonics in M.S. (Master of Science) level. Among them, 14 class hours are allocated to fundamental theory lectures and the rest to hands-on simulation experiments. It is offered during the 5.5-week teaching period of every spring semester.

A. *Fundamental Theory on MEMS Design*

As illustrated in Table I, the fundamental theory on MEMS design includes eight sections: solid mechanics, fluid mechanics, heat transfer, thermal sensing and actuation, piezoelectric sensing and actuation, electrostatic sensing and actuation, piezoresistive sensing and magnetic actuation.

TABLE I. Content of Fundamental Theory on MEMS Design

No.	Fundamental Theory on MEMS Design	
	Content	***Discipline***
1	Solid mechanics	Mechanics
2	Fluid mechanics	
3	Heat transfer	Thermotics
4	Thermal sensing and actuation	
5	Piezoelectric sensing and actuation	Electronics
6	Electrostatic sensing and actuation	
7	Piezoresistive sensing	
8	Magnetic actuation	Magnetics

Beams and diaphragms are the most concerned structures in MEMS devices, so the mechanics of these microstructures are the core of the fundamental theory. These structures work in a fluid environment, including air and liquids, so the mechanics should contain solid mechanics and fluid mechanics. The coupling between solid and fluid is an important issue.

With the beam and diaphragm structures as the core, the sensing or actuation function can be obtained combining with thermotics, electronics, magnetics *et al.* The basic theory of heat transfer should be taught before studying thermal sensing and actuation. Considering that the graduate students in College of Optics and Photonics benefit a profound background on electronics and magnetics, the basic theory on the two parts is excluded from the scope of teaching in this MEMS course.

Table II summarizes the coupling of multiphysics in MEMS devices. Specific case studies concerning multiphysics coupling are designed in the part of hands-on simulation experiments. Therefore, the key points of the fundamental theory part lies in solid mechanics, fluid mechanics and heat transfer.

TABLE II. Coupling of Multiphysics

No.	Coupling of Multiphysics	
	Physical Field	***Coupling***
1	Solid mechanics	Solid-Fluid Coupling
	Fluid mechanics	
2	Solid mechanics	Solid-Heat Transfer Coupling
	Heat transfer	
3	Fluid mechanics	Fluid-Heat Transfer Coupling
	Heat transfer	
4	Electric current	Electric Current-Heat Transfer Coupling
	Thermal sensing and actuation	
5	Solid mechanics	Solid-Electrostatic Coupling
	Piezoelectric sensing and actuation	
6	Solid mechanics	Solid-Electrostatic Coupling
	Electrostatic sensing and actuation	
7	Solid mechanics	Solid-Electric Current Coupling
	Piezoresistive sensing	
8	Solid mechanics	Solid-Magnetic Coupling
	Magnetic actuation	

B. *Hands-on Simulation Experiments*

The cases of hands-on simulation experiments include two parts: single physical field simulation and multiple physical fields simulation. The simulation cases are interposed when reaching a certain knowledge point during the theory lectures. In this way, the simulation experiments and class lectures are well integrated. Table III displays the cases concerning single physical field simulation and multiple physical fields simulation.

TABLE III. SIMULATION CASES OF SINGLE PHYSICAL FIELD AND MULTIPLE PHYSICAL FIELDS

No.	Single Physical Field	
	Physical Field	***Simulation Case***
1	Solid mechanics	Bending cantilever
		Vibrating cantilever
		Bending membrane
		Vibrating membrane
2	Fluid mechanics	Gaussian pulse in air
		Vibrating partical in water
3	Heat transfer	Heat microexchanger in fluid
		Thermoelastic damping in solid
No.	**Multiple Physical Fields**	
	Physical Fields	***Simulation Case***
1	Coupling of Solid-Fluid	Ultrasound flow meter
2	Coupling of Solid-Acoustics	Vibrating micromirror
3	Coupling in Piezoelectric sensing and actuation	Composite piezoelectric transducer
4	Coupling in Electrostatic sensing and actuation	Capacitive pressure sensor
5	Coupling in Piezoresistive sensing	Piezoresistive pressure sensor
6	Coupling in Magnetic actuation	Nonlinear magnetostriction
7	Coupling in Thermal sensing and actuation	Ultrasound induced heating

III. TEACHING METHOD

Several methods are employed in MEMS teaching. On one hand, we make full use of the simulation tool, and the key points in fundamental theory are presented in visual simulation results. It inspires the learners' enthusiasm in theory study. On the other hand, MEMS research is characterized by coupling of multiple physical fields. The essence of multiphysics coupling is stressed and revealed in detail. Moreover, in the hands-on simulation experiments, the approach from an easy task to a difficult one is applied. Aimed at a specific knowledge point, a simple simulation subject and a more difficult simulation assignment are designed. Thus, the simulation experiments contains pre- and post- ones.

A. Essence of Multiphysics Coupling

In the field of science and engineering, finite element analysis (FEA) is more and more involved to solve real physical problems. Early FEA methods focused particularly on the field of mechanics, to simulate such as stress or fatigue problem. However, the coupled physical phenomena are quite complex rather than an isolated one. For example, the motion produces heat, which affects some material properties, such as electrical conductivity, elasticity of solid, viscosity of fluid, etc. The change in these physical quantities will react to the motion in turn. The coupling of such physical systems is the so-called multiple physical fields, which is much more complicated to analyze than to analyze a single one. In fact, these problems can be solved using FEA method by constructing a set of coupled equations of mathematical physics.

Equations of mathematical physics are usually in the form of some partial differential ones (also including integral equations and ordinary differential equations) , deduced from the combination of the constitutive equations relating two or more physical quantities and the governing equations describing the physical laws. To efficiently solve these equations, optimized mathematical algorithm and stronger computing ability are highly demanding. After decades of hard work, the development of computational science provides us with more concise and fast algorithms and stronger hardware configuration, which makes it possible to simulate multiple physical fields by FEA method.

For example, Eq. (1) represents the constitutive equation in solid mechanics.

$$\boldsymbol{T} = \boldsymbol{c}\,\boldsymbol{S} \tag{1}$$

where $\boldsymbol{T}$, $\boldsymbol{c}$ and $\boldsymbol{S}$ represent the mechanical stress, elasticity constant and strain tensors, respectively.

In piezoelectric solid, the constitutive equation should be replaced by Eqs. (2) - (3). For solid mechanics field, electric field contributes to stress together with train. For electrostatic field, strain contributes to electric displacement together with electric field. The coupling of solid mechanics field and electrostatic field is a prominent feature of piezoelectric problem.

$$\boldsymbol{T} = \boldsymbol{c}^{\boldsymbol{E}}\,\boldsymbol{S} - \boldsymbol{e}^{T}\,\boldsymbol{E} \tag{2}$$

$$\boldsymbol{D} = \boldsymbol{\varepsilon}^{\boldsymbol{S}}\,\boldsymbol{E} + \boldsymbol{e}\,\boldsymbol{S} \tag{3}$$

where $\boldsymbol{D}$, $\boldsymbol{E}$, $\boldsymbol{\varepsilon}^{\boldsymbol{S}}$ and $\boldsymbol{e}$ represent the electric displacement, electric field, dielectric permittivity and piezoelectric stress constants, respectively. $\boldsymbol{e}^{T}$ is piezoelectric stress transposed matrix. $\boldsymbol{c}^{\boldsymbol{E}}$ is mechanical stress constants under $\boldsymbol{E} = 0$.

Furthermore, electromagnetic equation or heat conduction equation can also be coupled when the piezoelectric solid works in high-frequency electric field or the thermal loss is considered.

B. Pre- and Post- Simulation Experiments

In the hands-on simulation experiments, a simple simulation subject and a more difficult simulation assignment are designed aimed at each specific knowledge point. These cases are executed in three procedures: (1) Before class, students simulate the simple subject. (2) In class, students demonstrate their simulation results. Then all students discuss about the simulation results. Finally, the teacher explain and conclude. (3) After class, students simulate the difficult subject.

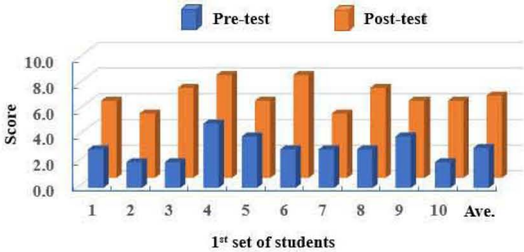
In this way, with preparation of the simple simulation subject before class, the students have been involved in thinking of the problem. They can easily concentrate on the demonstration of the simulation case in class and will have a better understanding beyond the simple case. In addition, the assignment of the difficult simulation case can inspire the students to challenge more complex design problems independently.

The main task left to the teacher is to design appropriate simulation cases for the key and difficult points of theoretical knowledge. For example, Table IV illustrates some cases with different degrees of difficulty for the same knowledge point in MEMS design.

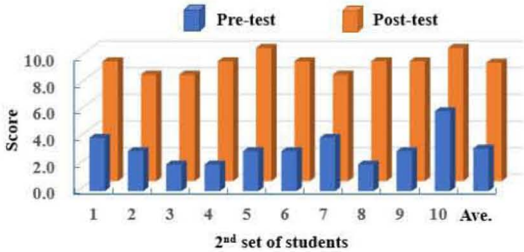
TABLE IV. CASES WITH DIFFERENT DEGREES OF DIFFICULTY

No.	Aimed at A Specific Knowledge Point	
	Simple One	***Difficult One***
1	Silicon bender with load	Piezoelectric Silicon bender; Electrostatic Silicon bender; Magnetic Silicon bender
2	Vibrating Silicon cantilever	Vibrating Si/SiO_2 cantilever
3	Prestressed resonator	Biased resonator
4	Fluid-structure interaction	Micropump mechanism
5	Piezo-acoustic transducer	Prestressed piezo-acoustic transducer
6	Thickness shear quartz oscillator	Surface acoustic wave (SAW) gas sensor
7	Thin film bulk acoustic wave (BAW) resonator	Thin film BAW sonsor
8	Ultrasound flow meter	Flow meter with piezoelelctric transducer
9	Controlled diffusion micromixer	Electroosmotic micromixer
10	Microresistor beam	Thermal actuator

To evaluate the effect of multi physical fields simulation on the fundamental theory learning, two sets of pre- and post-tests are carried out as a controlled experiment. Fig. 2 presents the results of the two sets of tests. In the first set, multi physical fields simulation are not applied in the fundamental theory learning. The average result shows that the pre-test score is 3.1 and the post-test score is 6.4 which just crosses the pass line (6.0). In the second set, multi physical fields simulation are applied. From the average result, the pre-test score is 3.2 and the post-test score is 8.9 which almost arrives at the excellent line (9.0). It demonstrates that the multi physical fields simulation plays an important role in the MEMS fundamental theory teaching.



(a)



(b)

Fig. 2 Results of two sets of pre- and post- tests: (a) multi physical fields simulation are not applied in the fundamental theory learning; (b) multi physical fields simulation are applied in the fundamental theory learning.

IV. CONCLUSION

A multiphysics simulation tool is applied in MEMS course to make the abstract theory concrete and vivid. To improve the participation of students, the simulation classes are carried out in the form of hands-on experiments. In the hands-on simulation experiments, a simple simulation subject and a more difficult simulation assignment are designed for each specific knowledge point. It is challenging for the teacher to design appropriate simulation cases for the key theoretical knowledge points. Fortunately, numerous relevant literatures can be referenced.

The course design can greatly improve the learning effect of MEMS design theory and has guiding significance for other science and engineering curriculum design. Colleagues are welcome to put forward more constructive suggestions on the content of this course, and welcome to contact us and give feedback.

For some profound theoretical knowledge, the dynamic animation display of solution is a much more desired way. With the rapid development of E-learning and E-books, more and more researchers will devote to make the abstract theory vivid using dynamic display. This means enormous work for the authors and teachers. Nevertheless, it’s worth the effort.

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