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Laboratory report:

Research laboratory on the mechanics of smart materials and structures, Zhejiang University

Jian LI[1,2], Chun-li ZHANG[1,2,3], Rong-hao BAO[1,2,3], Wei-qiu CHEN[†‡1,2,3]
[1]*Key Laboratory of Soft Machines and Smart Devices of Zhejiang Province, Hangzhou 310027, China*
[2]*Department of Engineering Mechanics, Zhejiang University, Hangzhou 310027, China*
[3]*Soft Matter Research Center, Zhejiang University, Hangzhou 310027, China*
[†]E-mail: chenwq@zju.edu.cn

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1 Overview

The Research Laboratory on the Mechanics of Smart Materials and Structures (MS^2 Laboratory) focuses on understanding the mechanisms underlying the experimentally or numerically observed phenomena of smart materials and intelligent structures, so as to enrich the knowledge for the development of advanced functional devices, machines, and robots. Particular attention is paid to the multi-field coupling behaviors of a variety of high-performance materials (e.g. piezoelectric materials, multiferroic composites, quasicrystals, piezoelectric semiconductors, and dielectric elastomers) and their effects on the structural responses. Free vibration, wave propagation, and instability of structures made of these smart materials are among the most important topics in the laboratory. Although analytical methods are concentrated upon, both experimental and numerical approaches are also widely explored for the research tasks that are carried out.

The ultimate aim of the laboratory is to develop new intelligent and multi-functional devices with exceptional performance to meet special or general requirements in various laboratory, industrial, and even societal applications. The emerging intelligent society needs materials and structures at a level higher than ever before to engineer more flexible, active, and automatic capabilities of machines and systems in reaction to more and more complex environments. There is thus a strong need for the mechanics of smartness.

2 Research staff

Professor Wei-qiu CHEN, is the leader of the MS^2 Laboratory. He is an expert in solid mechanics, and his current research interests include the mechanics of smart materials/structures, mechanics of soft materials and structures, vibration/waves in structures, and multi-scale control of structures. He has co-authored over 400 peer-reviewed journal articles and three English monographs (Ding and Chen, 2001; Ding et al., 2006; Pan and Chen, 2015).

Professor Rong-hao BAO, is a principal investigator in the laboratory. He specializes in the dynamics of advanced structures by means of numerical modelling and experimental study. He is collaborating with Professor Wei-qiu CHEN on tunable wave propagation in soft periodic structures. He is also interested in the design, analysis, and high-speed data acquisition of sensors and actuators in relation to automation.

Professor Chun-li ZHANG, a principal investigator in the laboratory, specializes in all aspects of multi-field coupling behavior in functional materials and structures. He is now particularly interested in the mechanics of piezoelectric semiconductors as well as the design of micro/nano energy harvesters and of self-power sensor systems.

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‡ Corresponding author
ORCID: Wei-qiu CHEN, https://orcid.org/0000-0003-0655-3303

There are about 15 PhD students and 5 MS students. Fig. 1 and Fig. 2 show a few members of the laboratory and a discussion between them, respectively. In addition to working with other research groups in Zhejiang University, we also collaborate with a number of outstanding scientists all over the world, including Professor Chuanzeng ZHANG (University of Siegen, Germany), Professor Jia-shi YANG (University of Nebraska–Lincoln, USA), Professor Ernian PAN (University of Akron, USA), Professor Jie YANG (RMIT, Australia), Professor Michel DESTRADE (National University of Ireland Galway, Ireland), Professor Erasmo CARRERA (Politecnico di Torino, Italy), Professor Yue-sheng WANG (Tianjin University, China), Professors Guo-zheng KANG, Xiang-yu LI, and Jiang-hong YUAN (Southwest Jiaotong University, China), to name only a few.

Fig.1 A few members of the laboratory

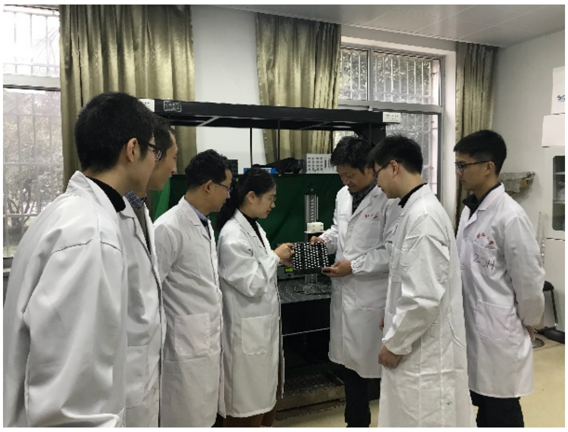

Fig. 2 A discussion

3 Research directions

3.1 Vibration and instability of intelligent structures

The laboratory conducts in-depth research on the vibration and instability of advanced structures made of functional materials, such as piezoelectric materials, multiferroic materials, and dielectric elastomers. A large number of analytical solutions have been found, and some have been documented in the three monographs (Ding and Chen, 2001; Ding et al., 2006; Pan and Chen, 2015). These solutions provide a solid basis for the better understanding of multi-field coupling behaviors in various types of smart structures and multi-functional devices (Zhu FB et al., 2016; Wang W et al., 2017; Li et al., 2018; Liu et al., 2018; Su et al., 2018a, 2018b; Wu B et al., 2018a, 2019; Wu F et al., 2018; Yuan et al., 2019). This study has been recently extended to take account of fluid-structure interactions, which have important implications in engineering as well as in biology.

Innovative computational and experimental studies have also been carried out. In particular, transducers of both the contacting and non-contacting types (including a wide range of accelerometers, a wide range of shaker systems, a scanning vibrometer, and multichannel analogue and digital instrumentation recorders for high definition) are available for the measurement of acceleration, velocity, displacement, and force.

3.2 Design and manufacture of soft metamaterials

Mechanical metamaterials have a number of novel properties. It is of great importance to design, manufacture, and test such materials. In recent years, the laboratory has been endowed with the capability to prepare various soft materials (e.g. elastomers and gels). Based on numerical simulation and theoretical analysis, the optimized structures of metamaterials with desired properties may be designed (Zhou et al., 2017, 2018; Wang J et al., 2018). Then, using 3D printing technology and other facilities, we are able to manufacture these delicate structures from soft materials. The manufactured metamaterials can exhibit remarkable changes in geometry and material properties due to their hyperelasticity, leading to tunable bandgaps which may be utilized to manipulate waves propagating in the structures. Other mechanical properties such as Poisson's ratio can be tuned as well (Gao et al., 2019a).

3.3 Tunable waves in phononic crystals and metamaterials

We are undertaking a key project supported by the National Natural Science Foundation of China (NSFC), which is led by Professor Yue-sheng WANG of Tianjin University. The project aims at understanding the behavior of wave propagation in soft periodic structures and exploring the tunability of waves in these structures for the innovative design of acoustic devices. A few particular periodic structures with interesting bandgap properties made of soft materials have been proposed (Gao et al., 2018; Huang et al., 2018, 2019). A particular focus of the research is the multi-field coupling effect, and phononic crystals made of dielectric elastomers, which exhibit electromechanical coupling, have been studied (Wu B et al., 2018b; Zhu J et al., 2018). Based on the relevant equipment, we have successfully performed frequency response measurement for phononic plates made of hard materials (Gao et al., 2019b). Currently, we are concentrating on the wave testing of soft phononic crystals, especially the frequency response of soft periodic structures undergoing large deformations (Gao et al., 2019a).

3.4 Multi-field coupling behaviors of smart materials and structures

Multi-field coupling phenomena in smart materials and structures (e.g. piezoelectric/piezomagnetic materials, multiferroic composites, piezoelectric semiconductors, and dielectric elastomers) offer significant novel engineering applications in many fields. We have been studying the mechanical behaviors of these smart materials and structures under external (e.g. mechanical, electrical, magnetic, and thermal) loadings with experimental and theoretical methods over decades, trying to reveal the underlying physical mechanisms. At the same time, the behaviors of smart materials and structures at nanoscale are also always a research concern and, in this area, surface and flexoelectric effects have been well investigated. One particular topic that is of current research interest is the interaction among deformation, polarization, and carriers (e.g. electrons, holes, and ions) in piezoelectric semiconductors and conducting polymers (Zhang CL et al., 2016; Luo et al., 2017, 2018a, 2018b; Cheng et al., 2018).

3.5 Development of piezoelectric, multiferroic, and piezotronic devices

The ultimate aim of the laboratory is to design new intelligent and multi-functional devices (e.g. sensors, actuators, transducers, and energy harvesters) which are significant building blocks for smart robots/equipment/systems. These devices play a key role in the era of artificial intelligence. In recent years, we have successfully proposed and demonstrated a series of prototypes of piezoelectric sensors/actuators/transducers, magnetic field harvesters, and piezotronic devices with unique structures (Zhang and Chen, 2010; Zhang S et al., 2018). A variety of tuning and controlling mechanisms of these intelligent and multi-functional devices through mechanical/electrical/magnetic/thermal loadings have been studied systematically. In addition to experimental validation, either theoretical modeling or numerical simulation with commercial finite element software is frequently adopted to analyze and design novel devices.

3.6 Design of smart multi-axis force/moment sensors

Multi-axis force/moment sensors are now widely applied in the fields of robots, automation, haptics, rehabilitation, and neurology to measure the interaction forces/moments between bodies. A platform is being developed, with computer aided engineering (CAE) and finite element method (FEM), which can be utilized to design and topologically optimize the structure of an elastic body, so that the coupling of forces/moments and mechanical nonlinearity of the sensor can be minimized. A testing and calibrating system is being planned to verify and calibrate the accuracy of the designed multi-axis force/moment sensors, and machine learning will be explored to improve its industrial application with smart sensors.

4 Facilities

The laboratory is equipped for:

1. Fabrication of soft materials. It possesses a 3D printer, a vacuum drying chamber, a draught drying cabinet, and some other relevant apparatus. With these, soft materials can be readily prepared, for the

purpose of manufacturing soft metamaterials for example.

2. Structural dynamics and wave tests. There are different types of accelerometers for different working conditions. Devices such as optical table, laser vibrometer, shaker, signal generator, power amplifier, data acquisition module, and computer are all available and are essential to the vibration/wave testing system.

3. Characterization of smart materials. The laboratory possesses a piezoresponse force microscope (PFM) which can be used to characterize the properties of materials with electromechanical coupling. It can also be used as an atomic force microscope (AFM) to obtain the surface pattern of a sample, and to test the elasticity, hardness, and fracture toughness of the material. The laser cutter can be used to prepare samples or to manufacture a structure with a particular topology.

The above-mentioned facilities and some other typical apparatus are exhibited in Fig. 3.

5 Perspectives

Although the study of smart materials and structures has already been carried out for nearly 40 years, and has led to many novel applications in modern technology and engineering, the demands for mechanics of smartness will be endless in the coming intelligent society. Sensors and actuators are the basic blocks of such a society, and smart materials and structures are always the core of these fundamental devices. Besides, the development of new-type multifunctional materials obviously brings new vigor and vitality into the mechanics of smart materials and structures. Furthermore, new concepts in science,

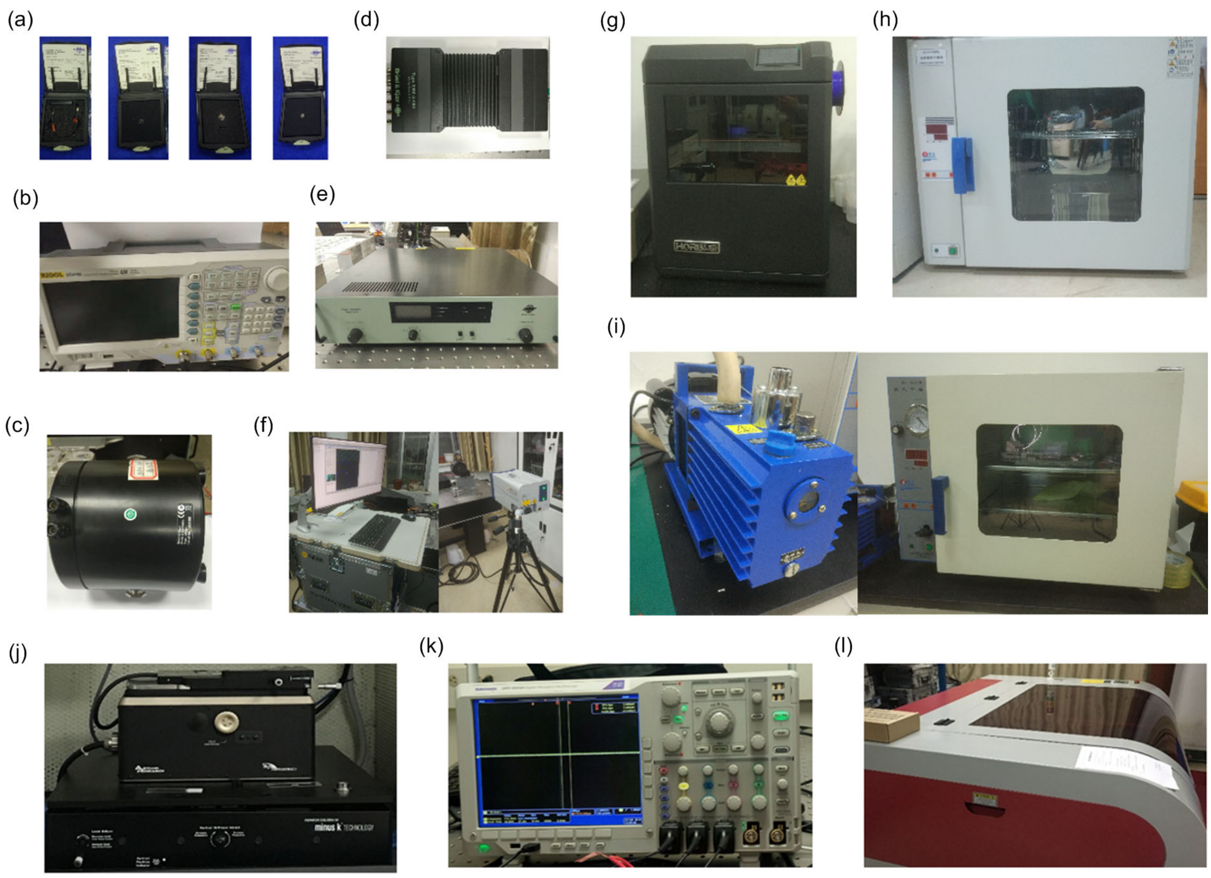

Fig. 3 Laboratory facilities and testing systems

(a) Accelerometers; (b) Signal generator; (c) Shaker; (d) Data acquisition module; (e) Power amplifier; (f) Laser vibrometer; (g) 3D printer; (h) Draught drying cabinet; (i) Vacuum drying chamber; (j) Piezoresponse force microscopy; (k) Oscilloscope; (l) Laser cutter such as topological physics, will also lead to new directions in the study of smart materials and structures. The laboratory will continue to contribute to the basic science, technological development, and practical applications of smart materials and structures.

6 Recent events

The laboratory is organizing the International Congress on Thermal Stresses (ITS2019, http://ts2019.zju.edu.cn) during June 1–5, 2019, and the Asian Workshop on Theoretical and Applied Mechanics (AWTAM2019) during August 25–27, 2019. Both events will be held in Hangzhou. ITS2019 will be chaired by Professor Wei-qiu CHEN and co-chaired by Professors Richard HETNARSKI (USA) and Naotake NODA (Japan). The secretary of ITS2019 is Professor Ji-zhou SONG of the Department of Engineering Mechanics, Zhejiang University, who can be reached via his email: jzsong@zju.edu.cn. AWTAM2019 will be co-chaired by Professor Xi-qiao FENG (Tsinghua University, China) and Professor Wei-qiu CHEN, and the secretary is Professor Chao-feng LÜ of the Department of Civil Engineering, Zhejiang University, who can be reached via his email: lucf@zju.edu.cn. We warmly welcome all of you to participate in these two wonderful events.

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中文概要

题　目： 浙江大学智能材料与结构力学研究实验室

目　的： 如今新兴的智能化时代比以往任何时候都更需要性能优越的材料和结构来设计更灵活、更主动、更自动化的机器和系统，以应对越来越复杂的环境。本实验室力图探求智能材料与结构在实验或计算中观测到的力学现象（如自由振动、波传播以及结构失稳等）或是多场耦合行为背后的机理，从而为先进功能设备、机械以及机器人的创新发展提供参考。最终，开发具有卓越性能的新型智能多功能器件，以满足各种实验室、工业甚至社会应用的特殊或一般要求。

研究点： 1. 智能结构的振动与失稳分析；2. 软材料的设计与制备；3. 声子晶体和超材料中弹性波的调控；4. 智能材料和结构中的多场耦合行为分析；5. 压电、多铁性以及压电电子学器件的研发；6. 多轴力/力矩智能传感器的设计。

展　望： 虽然对智能材料和结构的研究已有近 40 年的历史，且其在许多现代技术和工程领域中已有了成功的应用，但是即将到来的智能化时代对“智能力学”的需求将是无穷无尽的。如果说传感器和驱动器是智能化时代的基础，那么智能材料和结构就是这些基本设备的核心。新型多功能材料的开发显然为智能材料和结构力学带来了新的生机和活力。此外，拓扑物理学等新的科学概念也将为智能材料和结构的研究开辟新的方向。本实验室将继续为基础科学、技术发展以及智能材料和结构的实际应用做出贡献。

关键词： 智能材料和结构力学；多场耦合；智能器件；智能力学