Laboratory for Mechanics and Experimental Dynamics

Our research focuses on analytical and numerical modeling of mechanical systems and corresponding experiments. We determine the properties (density, viscosity, viscoelasticity) of a fluid by quantifying its interaction with a vibrating system. We also study the vibrational characteristics of water turbines and, at smaller scales and higher frequencies (MHz), we work on modeling and design of devices for ultrasonic particle manipulation. Further areas of research include the study of wave propagation in structures and thin films (nanosonics), as well as time dependent phenomena in snow mechanics.

Figure 1: Large and small viscosity sensors: the vibrational characteristics are changed by a fluid interacting with the vibrating structure

Dynamic viscosity and density sensing

When a vibrating system, such as a tube or rod, is brought in contact with a fluid, the vibrational characteristics of the fluid (resonance frequencies and damping) undergo changes. These changes can be related to the density and viscosity or even viscoelasticity of the fluid by calibration or by modeling. We use resonators that are rod- or tube-shaped (Fig. 1), or, in cases where small quantities of fluid are being investigated, U-shaped (Fig. 2,[1]*). These are excited to a near-resonance state using electromagnetic forces, for example; and are then made part of a gated phase locked loop, such that the vibration is stabilized near the resonance frequency with a resolution of up to 1 in 10'000'000. We then determine damping with a digital measurement, where the resonator is driven at two phase values close to the resonance frequency. Our research can be applied to the measurement of fluid properties in the oil-and-gas and food industries, and also has applications within DNA research.

Ultrasonic particle manipulation

When a high power ultrasound field is generated in a fluid containing particles (bacteria, functionalized beads etc.), these particles experience a force field that is approximately derived from Gorkov's potential. Such fields can be generated in microfluidic systems (Fig. 3, 4, [2]*, [3]*, [5]*, [7]*), which are excited harmonically by piezoelectric transducers at frequencies in the MHz regime. The frequencies are tuned to one of the resonance frequencies of the system, such that a strong standing wave field is obtained. Our research focuses on the modeling of such systems at all scales. The assembly consisting of transducer, fluid cavity etched into a silicon chip, fluid and particles is modeled using COMSOL

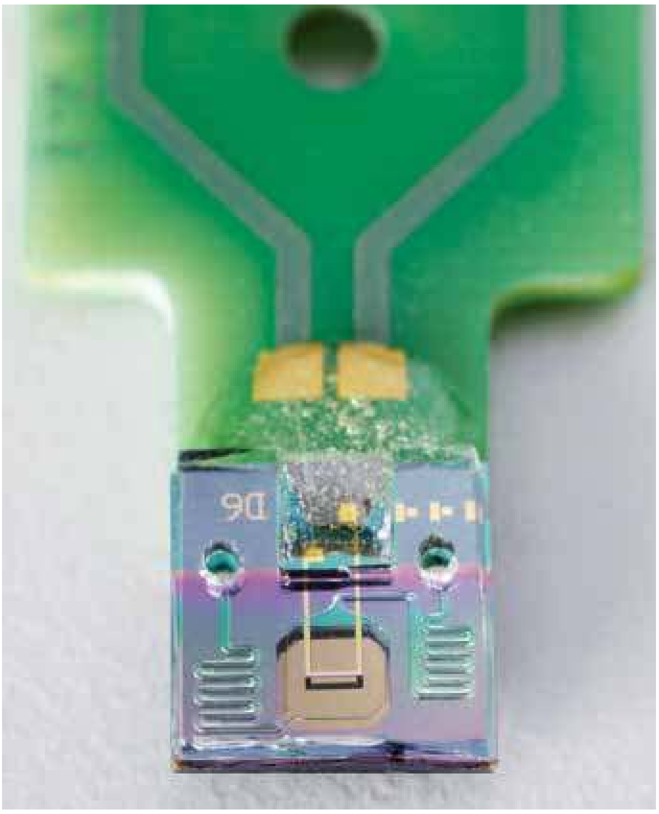

Figure 2: A vibrating U structure is interacting with a fluid in a microcavity for very high sensitivity viscosity measurements with small sample volumes

* reference to Key publications

multiphysics to obtain the acoustic field. The system's potential landscape can then be computed from the field using Gorkov's potential. Varying frequencies produce time-varying potentials so that patterns of particles in the cavity, such as lines or dots, can be observed. Particles can also be rotated by manipulating the fluid's acoustic radiation torque or viscous torque (Fig. 3). Modeling efforts are underway to determine forces in nonstandard conditions, including systems that involve viscous effects or the effects of nearby boundaries.

Further topics
We investigate time reversal in structural wave propagation to find multiple cracks in structures. Further topics include the experiments and modeling of vibrations in water turbines (Fig. 5) and ultrasonics in the GHz regime using an optical pump probe setup for probing nanostructures and thin films. In collaboration with the Swiss Avalanche Institute, modeling of avalanche release systems is also under way.

Highlights and achievements

- In the area of fluid resonating sensors, we founded a spin-off to develop a sensor for downhole applications for the oil and gas industry. Industry was very enthusiastic of our work and fully supported the project financially.
- Our research contributed to the development of a microscopic viscosity sensor capable of detecting changes in water viscosity of better than 1 %. This research has applications in the area of biomedical analysis.
- In the area of ultrasonic particle manipulation, and in collaboration with our colleagues from USWNet, we contributed to the publication of a series of 23 papers [2]* in the highly-selective Lab on a Chip Journal. We also developed software that allows the computation of acoustic radiation forces and torques for arbitrarily shaped particles. We recently received funding for latest-generation PLD and DRIE systems that will further improve our capabilities in designing ultrasonic particle manipulation systems.
- Using a combination of time reversal and suitable pulse shapes, we were able to detect multiple cracks with high precision in beams by using the dispersive nature of bending waves.
- We are proud that, in teaching basic mechanics, we have kept a high level of teaching quality despite a small number of contributing faculty.

* reference to Key publications

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Jürg Dual (1957) studied mechanical engineering first at ETH Zurich, then with a Fulbright grant at the University of California in Berkeley under Prof. W. Goldsmith. He received his Dr.sc.techn. degree at ETH Zurich with Prof. M. Sayir in Mechanics. In 1989, he was awarded the Latsis Prize at ETH Zurich for his dissertation. After one year as Visiting Assistant Professor at Cornell University in Ithaca, NY, he returned to ETH Zurich as Assistant Professor. Since 1998 he serves as Full Professor of Mechanics and Experimental Dynamics in the Center of Mechanics at ETH. He is a Fellow of the ASME, a member of the Swiss Academy of Technical Sciences, Honorary Member of the German Association for Materials Research and Testing, and a Swiss delegate within International Union of Theoretical and Applied Mechanics. In 2012–2013 he was CEO of the startup Viscoteers GmbH.
He was President of the Planning Commission (2000–2004) and of the University Assembly (2008–2012) at ETH and is President of the Swiss-American Society of Zurich.

Goals and future priorities

Going forward, we will remain focused on resonating sensors and ultrasonic particle manipulation. These topics both have a strong component of fluid structure interaction, thereby fostering each other.

Most of the fluids that need to be characterized are Nonnewtonian. Therefore viscoelastic properties will be determined using multifrequency control of resonating sensors. We will also investigate the behavior of non-homogeneous fluids (suspensions).

We will continue our modeling efforts in the area of particle manipulation. Gorkov's potential is only valid for ideal compressible fluids, spherical particles and infinite space. We are currently using a newly-acquired high-speed camera and optical trap to investigate methods for calibrating force fields, and are comparing our findings with available theories. We will also pursue quantitative predictions of acoustic streaming. As we take further steps towards applications for our research in the biomedical field, we will expand collaboration with industry and within academia.

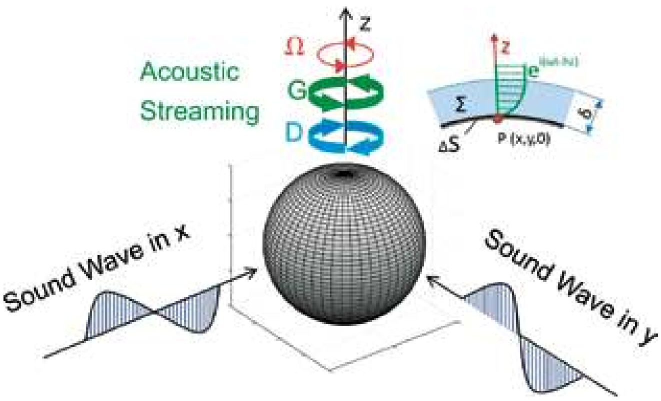

Figure 3: Viscous torque for the rotation of spherical particles

With respect to my teaching responsibilities, I am planning a new course in acoustofluidics, which will be comparable to the summer school course offered on this topic by the International Center for Mechanical Sciences (CISM).

Organization of the professorship

Our group forms part of the Institute of Mechanical Systems. It consists of eleven doctoral students and two postdocs. Experimental work is conducted in dedicated labs, where doctoral students with similar topics work together with common equipment. There are currently six laboratories dedicated to wave propagation, micromanipulation, fluid characterization, nanosonics, biochemistry and water turbines. To facilitate communication and discussion within the major groups, monthly meetings are held with all group members. Wherever possible, infrastructure is also shared with neighboring institutes. Dr. Stefan Blunier runs the CLA part of the Frontiers in Research: Space & Time (FIRST) clean room facility, a shared facility for fabricating microstructures like acoustic manipulation devices. I am also part of the FIRST management team. Within the Institute we share minimal infrastructure consisting of one secretary, one technician and one electronics engineer. Computers are coordinated and administered by Dr. S. Kaufmann, together with a part-time external member of staff. Dr. Kaufmann also helps us to carry the very large load of teaching, along with a group of over 40 student assistants.

Figure 4: A microcavity etched into a silicon wafer is used as a precise chamber for ultrasonic manipulation of particles.

Teaching activity

Over the last eight years, Profs. Glocker, Mazza, and Dual have had a very high teaching load as a result of there being two open positions in mechanics at ETH. My group contributed to the lectures on statics and strength of materials for mechanical and civil engineering, as well as mechanics for electrical engineering and environmental engineering. In these basic lectures, students learn for the first time how to apply mathematical analysis to real physical systems. As there are no entry examinations for new students, their capabilities must first be brought to the high academic standards of ETH. We accomplish this by offering classical lectures and small recitation sections, which are given by excellent senior students.

At the 6th semester Bachelor level, Prof. Dual regularly teaches a class on experimental mechanics for approximately 50 students. Knowledge of basic physics and electrical engineering is applied to the modeling of experiments in mechanics. The students conduct three experiments: phase-locked loop stabilization of resonating structures, nondestructive testing (NDT) using resonant ultrasound transducers, and vibrational analysis using a scanning laser interferometer. At the Master level, Prof. Dual regularly teaches a course on wave propagation in solids, primarily geared toward mechanical and civil engineering students, which covers many aspects of structural and 3D waves.

As an institute, we also offer a tools course in Mathematica, as well as didactic courses for students who are interested in pursuing teaching.

Additionally, together with colleagues at USWNet, we have organized an international summer school at CISM in Udine on the topic of ultrasonic particle manipulation.

Fostering young academics

32 doctoral students and many Bachelor and Master students have graduated from our group.
We have received many prizes, including several R.W.B Stephens Prizes, IUTAM Prizes for Solid Mechanics, Silver Metals at ETH, Georg A. Fischer Prizes, several prizes for Best Paper, as well as the Goldene Schiene. See our website for more detail.
Academic positions for former postdocs and doctoral students include:

> Prof. O. O`Reilly, UC Berkeley; Prof. E. Mazza, ETH; Assoc. Prof. A. Neild, Monash University; Senior Lect. N. Szita, University College of London; Assistant Prof. P. Federolf, University of Calgary.