CURRENT SCIENCE

Volume 90 Number 11 10 June 2006

GUEST EDITORIAL

Some Perspectives on Research in Mechanical Engineering

Mechanical engineering is a vast discipline with a rich variety of research areas. Some of these traditional areas include thermal science, design and manufacturing processes. Mechanical engineering is also the key for several multidisciplinary research initiatives encompassing Aerospace, Materials science and Chemical engineering. Indeed, in recent years, the gamut of such research opportunities for the mechanical engineer has widened with bridges being built with fundamental sciences such as Chemistry and Biology. The purpose of this editorial is to highlight some exciting research prospects in Mechanical Engineering, which will hopefully motivate young undergraduate students to pursue advanced research in this field. Attention is restricted here to only a few topics.

Micro-electro-mechanical systems (MEMS) typically involve a movable mechanical structure of micron dimension. A wide range of commercial MEMS products are currently available, such as accelerometers, pressure sensors, micro-grippers and surgical tools. MEMS design is generally concerned with the development of elastically deforming structures such as beams and diaphragms which may be subjected to thermal, magnetic or piezoelectric forces. A key advancement in this design is the genesis of assembly-free compliant mechanisms. In these mechanisms, the elastic deformation of flexible members is exploited for transferring energy, motion and force instead of relying on traditional joints. Thus, their use reduces some inherent limitations, such as friction and wear-related failures of MEMS devices and imprecise motion due to large clearances. However, the design of compliant mechanisms is challenging owing to their increased complexity as compared to traditional rigid-body mechanism synthesis. Although some tools are available to facilitate compliant mechanism synthesis, there are many opportunities for further research in this field.

Perhaps, the most exciting applications of MEMS technology are in biological and medical fields. Some examples are biosensors, diagnostic systems, actuators, etc. It is important to recognize that manipulation and mechanical characterization of single biological cells and their contents hold the key for advancements in cellular mechanics, cell-based therapies and genomics. Here, innovative solutions may be conceived with MEMS designs using micro- and nano-scale tools which could be based on micro-cantilevers, smart materials or pneumatically actuated membranes. Alternately, vision-based measurements of displacements can be used to directly compute the forces with elastic structures that also serve as mechanisms to grasp and manipulate cells. Micro-fabrication plays a key role in the development of microsystems. At present, silicon seems to be the choice material for microsystems but it needs expensive clean-room setup and equipment. Alternate materials such as polymers, metals and ceramics are indeed necessary for newer applications of microsystems such as lab-on-a-chip, power-MEMS, etc. Further, inexpensive manufacturing techniques which are likely to lead to more commercially viable products are needed.

Protein molecules may be considered as nano-machines due to their folded 3D shape with the amino-acid residues serving as hinge joints. Their functionality is governed by the manner in which they move and transfer forces. Thus, with sound background in theoretical and applied kinematics, mechanical engineers will be able to provide key insights to predict protein folding, understand their behaviour and design them. For example, one may apply topology optimization techniques which have been developed for structural optimization to formulate the combinatorial problem of the design of sequence of amino acids in a protein. However, such approaches are not without some difficult challenges which need to be overcome through sustained research efforts. First, the development of optimization methods for predicting the 3D structure of a protein is a complex computational problem. Secondly, quantitative models of forces that exist and the motions that they induce in polypeptide chains are needed. Finally, advanced kinematics analysis of peptides could be used to ascertain the mobility and dexterity of their chains.

Future research in strength, fracture and fatigue of materials will be directed towards rapidly growing fields such as MEMS, thin films, biomaterials, metallic glasses and geo-materials (such as in earthquake fault systems). New and innovative experimental procedures need to be developed to characterize the mechanical and fracture response of biomaterials like tissues, bones, cartilages, etc.

This is challenging because the volume of materials to be tested is small and also they exhibit time-dependent behaviour. Some specific issues that need to be addressed are toughening mechanisms, fatigue-induced microdamage in bones (for example, due to osteoporosis or age), mechanical properties of teeth, etc.

Novel computational techniques such as extended finite element method (or, X-FEM), cohesive finite elements and molecular dynamics (MD) are employed along with emerging experimental procedures such as nano-indentation and advanced microscopy methods to understand the mechanical behaviour of materials at different length scales. For example, considerable effort is being devoted to understand fracture phenomena on the nano- and micro-scales through atomistic simulations. On the other hand, the X-FEM method holds good promise for fracture modeling on the macroscopic scale because discontinuous interpolation and basis functions for near-tip fields can be easily introduced. An important challenge is to develop robust methods that seamlessly link modeling at multiple length scales ranging from nano-meters to 1 m. The simulation of formability and fracture response of engineering (especially aluminium) alloys, relevant to aerospace and automobile applications, using realistic microstructures is an important area of future research. However it is expected to be computationally intensive since large 3D models need to be analysed. Hence, it would require high-powered computer systems and finite element algorithms capable of performing effectively on parallel processing machines. The results obtained will enable in understanding the role of texture and microstructure on fracture and fatigue resistance of these alloys as well as their formability.

Micro-fluidics is another exciting development in Mechanical Engineering (see, for example, H. A. Stone *et al.*, *Annual Reviews in Fluid Mechanics*, 2004, **36**, 381–411). It is concerned with devices and methods for controlling and manipulating fluid flows with length scales less than a millimeter. These flows can be manipulated by imposing different kinds of external fields such as pressure, electric, magnetic, etc. For example, fluid motions on micro-scale can be generated by controlling the spatial variations of surface tension which can be created by applying thermal, chemical or electrical gradients. Potential applications of micro-fluidics include cooling methodologies for micro-electronic components and biological systems. There are broadly three research areas in micro-fluidics. The first pertains to development of functional elements such as valves, pumps, actuators, switches, etc. for controlling micro-fluid flows. The second area is concerned with development of methods for visualization of micro-flows. Most techniques which are currently used for this purpose are based on optical methods, like particle image velocimetry and fluorescence microscopy. Finally, significant fundamental research is needed to understand fluid motion and associated transport processes in micro-systems.

Increasing environmental concerns over vehicular pollution, a continuing quest for highly efficient engines with very low specific fuel consumption, and the prospect of new fuels, particularly renewable ones, are the current drivers in internal combustion (IC) engine research. For this purpose, new engine technologies are becoming more rapidly implemented such as gasoline direct injection, turbo-charging, exhaust gas re-circulation and after-treatment. These recent advances would have been impossible without the progress in Computational Fluid Dynamics (CFD) modeling. Indeed, the IC engine represents a challenging fluid mechanics problem to model for reasons such as large density variations, cyclic and highly unsteady processes, and the necessity to deal with physics of atomization and breakup of liquid fuel sprays. In addition, the geometry of the combustion chambers is complex and has moving walls (pistons and valves). The standard approach in CFD is to solve the two-phase flow in a Lagrangian–Eulerian framework, and use sub-models to account for the various phenomena such as turbulence, fuel spray, combustion chemistry, etc. Thus, the challenge is not only to produce a sufficiently accurate mathematical description of the physics, but also a modeling tool that meets the designer needs at an acceptable time frame and cost.

In the context of Indian institutes and universities, it is important that more undergraduate students in Mechanical Engineering pursue graduate degrees so that the vast and emerging research opportunities discussed above can be effectively addressed. Unfortunately, there has been a declining trend over the last decade or so, in highly qualified undergraduate students in engineering joining the research programs at our leading academic institutes like the IITs and IISc. Further, even the students who take up research degrees tend to strongly prefer modeling and simulations as opposed to experimental work. It must be emphasized that the latter is a key component of engineering research that will eventually lead to major technological advances. The declining trend in graduate research student enrolments in our academic institutes noted above will lead to a dearth of highly trained research manpower capable of guiding important engineering initiatives such as in the areas of space, atomic energy, defense and health-care technology. It is hoped that this trend will be reversed in the near future as more undergraduate students become aware of exciting new developments in Mechanical Engineering and opt for advanced research degrees.

ACKNOWLEDGEMENT: I gratefully acknowledge my colleagues at the Indian Institute of Science, Bangalore for many useful inputs.

R. Narasimhan
e-mail: narasi@mecheng.iisc.ernet.in