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Review:

The renaissance of continuum mechanics*

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Abstract: Continuum mechanics, just as the name implies, deals with the mechanics problems of all continua, whose physical (or mechanical) properties are assumed to vary continuously in the spaces they occupy. Continuum mechanics may be seen as the symbol of modern mechanics, which differs greatly from current physics, the two often being mixed up by people and even scientists. In this short paper, I will first try to give an illustration on the differences between (modern) mechanics and physics, in my personal view, and then focus on some important current research activities in continuum mechanics, attempting to identify its path to the near future. We can see that continuum mechanics, while having a dominating impact on engineering design in the 20th century, also plays a pivotal role in modern science, and is much closer to physics, chemistry, biology, etc. than ever before.

Key words: Continuum mechanics, Quantum mechanics, Engineering, Current research activities, Renaissance
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1 Introduction

When Isaac Newton (1642–1727), the greatest scientific genius of all times, put forward the three fundamental laws of motion in his *Principia* in 1687, a way was paved for people to understand the nature and change the world in a manner quite different than ever before. It is the scientific way, evolving gradually over time, equipped also with the findings of other great scientific minds (and many others) such as Robert Hooke (1635–1705), Daniel Bernoulli (1700–1782), Leonhard Euler (1707–1783), Joseph-Louis Lagrange (1736–1813), Claude-Louis Navier (1785–1836), Siméon Poisson (1781–1840), Augustin-Louis Cauchy (1789–1857), George Green (1793–1841), James Clerk Maxwell (1831–1879), Gustav Kirchhoff (1824–1887), Heinrich Hertz (1857–1894), Ludwig Boltzmann (1844–1906), William Thomson (1st Baron Kelvin, 1824–1907), John Strutt (3rd Baron Rayleigh, 1842–1919), etc. We also note that Galileo Galilei (1564–1642) has played a major role in the scientific revolution just prior to Newton.

In the earliest stages, mechanics is generally regarded as a central part of physics, while also falling underneath another umbrella—natural philosophy, as evidenced by the title of Newton's masterpiece (Newton, 1687). Other parts of physics deal with the nature of light, and electric and magnetic fields. However, the situation changed a bit since around 1900 when mechanics finds wide applications in engineering, while physics goes deeply into the tiny atomic world. Modern mechanics is then formed and departs from modern physics, both however sharing a common mechanical base in the regime of Newtonian mechanics or classical mechanics.

2 Modern mechanics and physics

In the early 20th century, efforts from a group of famous physicists such as Albert Einstein (1879–1955), Max Planck (1858–1947), Niels Bohr (1885–1962), Werner Heisenberg (1901–1976), Max

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Born (1882–1970), Louis de Broglie (1892–1987), Erwin Schrödinger (1887–1961), Wolfgang Pauli (1900–1958), Paul Dirac (1902–1984), etc. gave birth to two essential branches and aspects of modern physics, one being quantum mechanics and the other the relativity theory. While the relativity theory deals with motions of bodies at a speed comparable to the speed of light, quantum mechanics considers motions of small particles (e.g., protons, electrons) at atomic and subatomic length scales. Quantum mechanics can be seen as the symbol of modern physics since the (mechanical) determinism in classical mechanics is no longer valid, and the uncertainty principle becomes one of the rulers in the small world of atoms.

Modern mechanics, however, prefers to present itself in a very deterministic way, which accords with most daily-life experiences. This way or view is demonstrated very well through engineering activities which have been greatly expanded in the 20th century. One may try to imagine the following scenarios: One drives a car at 100 km/h, which switches suddenly to 10 km/h a second later, or one wants to produce a watch but obtains a hammer instead, which would cause great uncertainty in the roles that we play in life. No one would like such aftermaths if they occurred, and fortunately in the macroscopic world, mechanical determinism works quite well and modern mechanics survives the impact of quantum mechanics.

While modern mechanics still bases its principles on Newton's fundamental laws of motion, as well as other conservation principles which were developed before 1900, great achievements have been made in the 20th century. I will now give some examples.

Alan Griffith (1893–1963), an English aeronautical engineer, published a paper in 1921 on the rupture of solids using an energy argument by assuming that the work needed should be equal to the increase of surface energy during the formation of cracks. This work resolves the discrepancies between the existing theoretical calculations and the experimental observations in a study on the effect of surface scratches on the mechanical strength of solids, which was then carried out at the Royal Aircraft Establishment (Griffith, 1921). It was shown that the strength of solids, when having small defects, could be significantly lower than the theoretical strength necessary to break the bonds between atoms. Griffith's work, together with efforts from George Irwin (1907–1998), Egon Orowan (1902–1989), James Rice (1940–), etc. eventually led to a new branch of mechanics—fracture mechanics. The fracture mechanics criteria are completely different from the classical material failure criteria, and hence were an entirely new concept to engineering. Fracture mechanics analysis has already become a common practice in designs of important engineering structures (e.g., airplanes, warships, bridges, dams, high-rise buildings) and their components, in order to ensure their life-time safety.

Modern aerodynamics dates back to earlier times, but the greatest steps could only be made after the Wright brothers' first successful flight in a powered aircraft on December 17, 1903. In 1904, Ludwig Prandtl (1875–1953) presented a lecture on fluid flow and suggested a simple but innovative approach to dealing with drag and streamlining by making use of the concept of the boundary layer (Prandtl, 1904). This opened a new era in aerodynamics, to which contributions from Frederick Lanchester (1868–1946), Nikolay Zhukovsky (1847–1921), Martin Kutta (1867–1944), Theodore von Kármán (1881–1963), Hsue-shen Tsien (1911–2009), etc. should also be included. Modern aerodynamics (including aeroelasticity which deals with fluid-structure interaction) has been the main foundation which has allowed people to fly in the air, to stroll in outer space, to go to the moon, and to take an extrasolar trip. It also provides us with the basis for identifying what caused the collapse of the Tacoma Narrows Bridge on November 7, 1940, only four months after its opening to traffic. With the aid of modern aerodynamics, we are now able to construct a bridge much longer than the Tacoma Narrows Bridge, and also skyscrapers with heights of approximately 900 m.

The finite element method (FEM) is the last example I want to present here. Though there are certain beginnings for the idea of FEM before the 1950s, which are mainly immersed in mathematical literature (e.g., the studies by Richard Courant (1888–1972) in the USA and Kang Feng (1920–1993) in China), it gets its real impetus in the 1960s and 1970s through the works of Ray Clough (1920–), John Argyris (1913–2004), Olgierd Zienkiewicz (1921–2009), Richard Gallagher (1927–1997), and their coworkers. In particular, the paper of Clough

(Turner *et al.*, 1956), which aims at providing a general method for numerically solving plane problems based on a scheme of domain discretization, receives considerable attention within engineering. Their paper also addresses the displacement convergence characteristics of planar elements, which is followed by many talented researchers including Ivo Babuška (1926–), Theodore Pian (1919–2009), Ted Belytschko (1943–), Thomas Hughes (1944–), etc. It is noted that energy principles play a unique role in the finite element analysis, and with this in mind, I would like to mention the work of Hai-chang Hu (1928–2011), who suggested a three-field variational principle in 1954 (Hu, 1955), which is now widely known as the Hu-Washizu principle. FEM can deal with very complex problems while other methods cannot. More importantly, it is easily programmed and can be well integrated with the increasing number of computing facilities. Powerful commercial FEM software packages (e.g., ABAQUS, ADNIA, ANSYS, NASTRAN) have been developed and deeply embraced by multitudinous engineering applications.

Now, from the above three typical branches of modern mechanics, we can abstract the following main attribute. Modern mechanics strongly coheres with modern engineering—its growth is usually catalyzed by problems arising in engineering applications, and the achievements in modern mechanics in return are immediately used to guide engineering activities, which gave us the birth of modern engineering. This may be attributed to the huge demand from engineering spurred by the two world wars in the 20th century as well as to the spirit of applied mechanics formed at Götingen and which spreads throughout the world. In contrast, modern physics developed mostly along a somewhat more conventional track, which is full of interest in unsolved problems in nature (the physical world). The achievements in modern physics completely change the existing science landscape and the associated common concepts, leading to a new and exciting era in modern science.

Though modern mechanics and modern physics have their own prominent characteristics, it is not easy to identify a clear boundary between them. Nor is it necessary to do this. Actually, efforts have been consistently made to make use of the achievements from both sciences. An example of this is the relativistic elasticity concept first advocated by Herglotz (1911).

3 Present continuum mechanics

Continuum mechanics is a general subject, focusing on the general framework of mechanics of the continua, in which the details of atomic structure and the interatomic interaction, both central to modern physics, are not studied. As clarified above, modern mechanics has a legitimate engineering background, and as its symbol, continuum mechanics certainly bears the same characteristics, though it looks quite different at first glance.

The history of continuum mechanics can be traced back to the earlier studies on fluids and solids, but its formation does not really develop until the 1950s and 1960s (Maugin, 2013). While linear theories for elastic Hookean solids and Newtonian viscous fluids have been fully developed and widely applied in the 19th century, the phenomena (e.g., the Poynting effect, the rod-climbing effect, the shear thickening/thinning, the Mullins effect) observed within complex fluids (such as polymeric solution) and solid materials with large deformations (such as rubber) are still open to new theories and methods. It is well known that synthesized polymers and natural rubbers are both in very high demand from both industry and society, especially after World War II. Notable figures like Eugene Bingham (1878–1945), Markus Reiner (1886–1976), Paul Flory (1910–1985), Leslie Treolar (1906–1985), Ronald Rivlin (1915–2005), Albert Green (1912–1999), Clifford Truesdell (1919–2000), James Oldroyd (1921–1982), Anthony Spencer (1929–2008), Jerald Ericksen (1924–), Walter Noll (1925–), Richard Toupin (1926–), Bernard Coleman (1930–), and Morton Gurtin (1934–) are all involved in the development of shaping continuum mechanics into a general theoretical framework for the mechanics of continua. A significant contributor in this area is Ronald Rivlin, who spent nine years in the British Rubber Producers Research Association (BRPRA), which played an important and critical role in the theoretical and experimental developments of rubber elasticity. Nevertheless, the most influential works are the two volumes by Truesdell and Toupin (1960) and Truesdell and Noll (1965) respectively, both appearing in *Handbuch der Physik*, the latter volume being sometimes referred to as the Bible of continuum mechanics. In these two treatises, a Bourbaki's approach is pursued through starting with only a very few basic definitions and principles. Such a writing style has spread fast and influenced many subsequent books and research papers, thereby making continuum mechanics seem more mathematically abstract than practically useful.

One essential part of continuum mechanics is to develop proper and reasonable constitutive relations for practical materials, to which several axioms (or principles) should apply. These include the following various axioms: axiom of objectivity (or principle of frame-indifference), axiom of material invariance, axiom of determinism, axiom of equipresence, axiom of memory, axiom of neighborhood, axiom of causality, and axiom of admissibility (Eringen, 1980). The axiom of objectivity is the most important one, which states that the constitutive equation should be invariant under a change of frame or with respect to different observers. Though we have these axioms or principles for modeling material responses, great difficulties still exists since they are too general to deduce the concrete form of constitutive relations for a particular material. There are also some unsettled controversial issues, especially those concerning irreversible thermodynamic processes (Müller, 2007).

Nevertheless, continuum mechanics, as an established general theoretical framework, could and should play an important role in the study of novel complex continua that have not been fully explored or even previously addressed before. In fact, with the rapid development of modern science and technology, continuum mechanics has found great importance in almost all cutting-edge research activities. This fact is well demonstrated in Fig. 1, the data being acquired from the Web of Science$^{\mathrm{TM}}$. We can clearly see the formation of continuum mechanics in the 1950s and 1960s from Fig. 1a, and its steady development during the 1970s and 1980s from Fig. 1b. It is emphasized here that, the data in Fig. 1 does not represent the actual number of papers published on continuum mechanics all over the world, but rather that the trend should be representative in indicating the increased importance of the study of continuum mechanics. For example, as we get into the smaller world at nano-scale in the 1990s, it becomes necessary to discriminate continuum mechanics approaches from physics methods, hence giving rise to a rapid increase in the paper numbers shown in Fig. 1c.

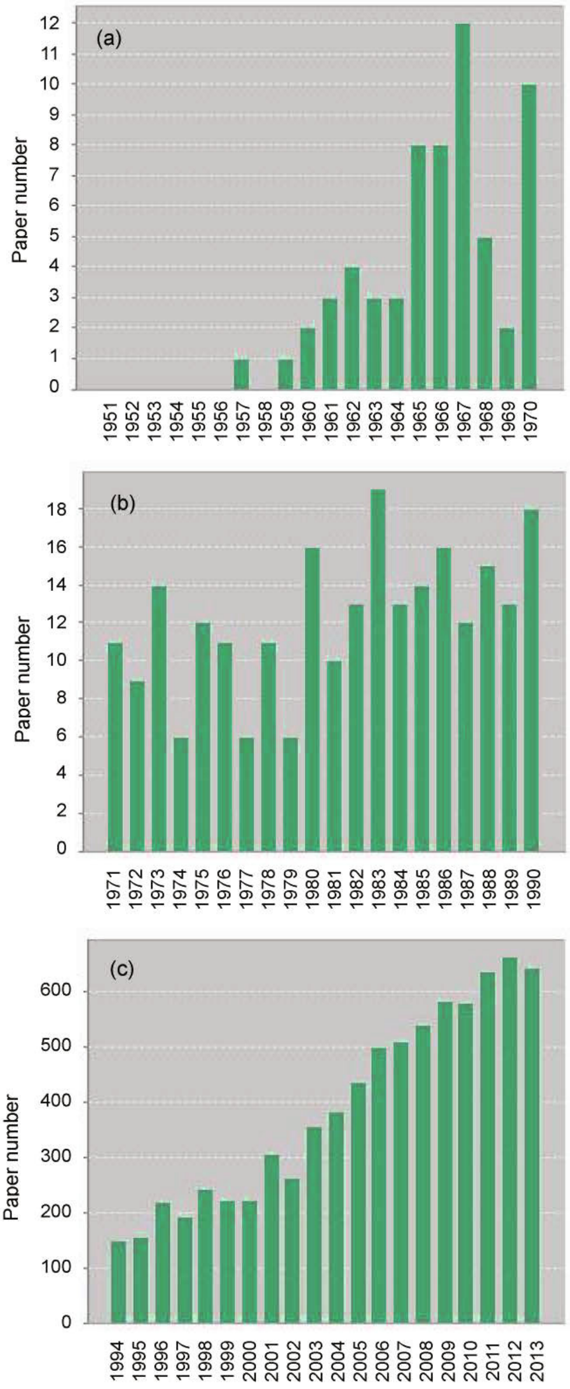

Fig. 1 Number of papers published in journals included in the database of SCI-Expanded, through searching the topic "continuum mechanics"

(a) Year 1951–1970; (b) Year 1971–1990; (c) Year 1994–2013

To illustrate such an explosive growth of research in continuum mechanics, I would like to go into a little further detail for three different key areas where continuum mechanics manifests its importance as well as its renaissance from various aspects of research and applications.

3.1 Mechanics gets closer to quantum mechanics

The first key area seems to be relatively bewildering since mechanics (either classical or modern) and quantum mechanics abide by quite different laws, which are the right cause of separation of modern mechanics from modern physics. But, with the development of micro- and nano-electromechanical systems (MEMS/NEMS) and their wide applications, mechanicians are led, either willingly or unwillingly, into a world that deals with studies in the scale of piconewtons (10^{-12} N) and nanometers (10^{-9} m), which is much smaller than before and is usually considered to be within the realm of physicists. Through the years, it has been shown that continuum mechanics can be used to characterize precisely the mechanical behavior of structures even at the nano-scale. A good example may be the mechanics study of nanotubes (Zhang *et al.*, 2002; Qian *et al.*, 2002), which was possibly initiated by Yakobson *et al.* (1996) who employed a continuum shell model and explained successfully the buckling behavior of nanotubes subjected to axial strain. Wong *et al.* (1997) proposed an experimental setup to examine the elastic properties of nanostructures, the principle of which is based on a continuum beam model. Continuum mechanics models have also been adopted in the study of nanoindentation (Saha and Nix, 2002) and the mechanics of graphene (Young *et al.*, 2012; Liu *et al.*, 2013). Note that the applicability of the conventional continuum beam models in the mechanics of nanotubes and nanorods has been previously discussed by Harik (2001). However, these models may not be able to capture the kaleidoscopic size-dependent phenomena that have been widely observed, either numerically or experimentally, in nanomaterials/nanostructures (Shenoy, 2005; Chen *et al.*, 2006). In such cases, generalized (or enriched) continuum mechanics models, such as nonlocal theory (Wang, 2005), gradient theory (Zhang *et al.*, 2006), surface theory (Duan *et al.*, 2008; Chen, 2011), and other high-order theories may need to be adopted.

The parameters in the conventional or generalized continuum mechanics models are usually identified from *ab initio* or semiempirical (such as molecular dynamics) results (Yakobson *et al.*, 1996). In this sense, mechanics has been strongly linked with quantum mechanics, and it is in agreement with the concept of *Physical Mechanics* advocated as early in 1953 by Tsien (1953). Such an approach of linking the continuum mechanics regime with the quantum mechanics regime belongs to concept of sequential multiscale modeling. Another approach is through concurrent multiscale modeling, in which most parts of the problem domain under consideration is treated macroscopically based on a continuum model, while the other very small part is solved using quantum mechanics (Tadmor *et al.*, 1996). In concurrent multiscale modeling, a difficulty is to establish the proper hand-shaking scheme between different scales (Fish, 2006).

Recent progress in MEMS/NEMS has indicated a bright future in the study of quantum phenomena through a mechanical device with the force and mass sensitivity reaching zeptonewtons (10^{-21} N) and zeptograms (10^{-21} g), respectively (Bordag *et al.*, 2001; Ekinci and Roukes, 2005). Some interesting and intriguing related stories also can be found in the introductory article by Schwab and Roukes (2005).

3.2 Mechanics meets chemistry here and there

Chemistry represents a totally different study area from mechanics, since the two are governed by quite different principles. However, it is not that simple actually. According to Beyer and Clausen-Schaumann (2005), the first report of a mechanochemical reaction was filed by Theophrastus of Ephesus (371–286 B.C.), a student of Aristotle. It is difficult, just like any other scientific branch, to fix exactly the time when mechanics met chemistry in their modern forms. We only have to know that mechanochemistry, defined by Wilhelm Ostwald (1853–1932) as “a branch of chemistry dealing with the chemical and physico-chemical changes of substances in all states of aggregation”, is already an established field in material science and solid-state chemistry (Gilman, 1996; Boldyrev and Tkáčová, 2000), in which mechanicians, however, do not play a significant role. This situation has seemed to change gradually in recent years.

A recent topic on IMechanica—the Web for Mechanics and Mechanicians (www.imechanica.org) is posted by Professor Zhi-gang Suo at Harvard University with the title "Lithium batteries—when mechanics meets chemistry". In the study of lithium batteries, concepts and models from continuum mechanics have been found very helpful in obtaining better performances such as in high capacity, fast charging, and long service time. For example, Xiao *et al.* (2011) suggested a simple patterning approach to improving the cycling stability of silicon electrodes (the next generation negative electrodes in lithium batteries) based on a fracture mechanics argument; Zhao *et al.* (2011) established a model by considering diffusion, elastic-plastic deformation, and fracture, which predicts that fracture may be averted for a small and soft host of lithium. More recently, Cui *et al.* (2012) developed a stress-dependent chemical potential for solid state diffusion under multiple driving forces including mechanical stresses, and showed that it may be used to explain some unusual observations from experiments that were conducted by other researchers.

We also note that the term mechanochemistry has an intimate accompanier, i.e., chemomechanics, which focuses more on reactive kinetics and molecular interaction. A recent excellent study was carried out by Freund (2009), who established a theoretical model to characterize the resisting force when a molecular bond is separated forcibly. Such a kinetic model at the molecular level is considered to be an important constituent in multiscale modeling which in addition includes continuum mechanics models both at the macromolecular level (where statistical mechanics is usually adopted to obtain the averaged properties) and the microscopic level (Huang and Boulatov, 2011). By chemomechanics, mechanics meets chemistry also in biology (Girard *et al.*, 2007; Wilson *et al.*, 2013) and in engineering (Hu and Hueckel, 2007).

3.3 Biomechanics evolves into mechanobiology

Living things or biological systems are more complex than natural materials and man-built structures. The mechanical behavior of biological materials and structures is the subject of biomechanics. Yuan-cheng Fung (1919–), an American citizen of Chinese origin, has made an incomparable contribution to biomechanics, and is regarded as the father of modern biomechanics. The three volumes on biomechanics published by Fung (1990; 1993; 1996) are considered to be milestones in biomechanics.

Traditionally, there involves two main activities in biomechanics. The first is to find accurate constitutive descriptions of biomaterials, such as soft tissues (e.g., tendons, ligaments, skin, fibrous tissues, fat, lymph, muscles, nerves, and blood vessels) and bones. The second is to study responses of biological structures and systems subjected to mechanical stimuli. We will not go further into biomechanics at this time, but the interested reader can be referred to Fung's books indicated above and a recent article by Volokh (2013). Here we will just note the following key hallmarks in the study of biomechanics:

1. Soft tissues generally exhibit inhomogeneous and anisotropic characteristics, and are usually subjected to large strains and stresses (Humphrey, 2003);
2. Growth and remodeling are two particular phenomena associated with biological materials, which require special treatments in constitutive modeling (Skalak *et al.*, 1982; Taber, 1995; Cowin, 2004);
3. Multiple fields (e.g., mechanical, chemical, thermal, electrical, and physiological) coexist and may couple together (Fukada, 1968; Liu *et al.*, 2012; Wilson *et al.*, 2013).

While biomechanics gets into the cell or molecular level (Janmey and McCulloch, 2007; Zhang *et al.*, 2013), ongoing research interest has gradually veered towards biological functions and physiopathological consequences resulting from mechanical properties or responses of biological systems. This leads to a new emerging field of science, i.e., mechanobiology, which is also at the interface of biology and mechanics (engineering) but with more emphasis being placed on the biological side (Stoltz and Wang, 2002). Tissue remodeling may also be categorized as being part of this new field. One of the central issues in mechanobiology is mechanotransduction—the mechanism by which biological systems sense and respond, mostly in a biochemical way, to mechanical signals (Ingber, 2006). Fig. 2a clearly shows the increasing research interest in mechanobiology in the most recent two decades. Interestingly, the number of papers on mechanotransduction seems much larger than that for mechanobiology, as shown in Fig. 2b. This is however not surprising since mechanotransduction has become a central issue in other disciplines (e.g., biology, biomedicine, biochemistry, biophysics, and bioengineering) as well.

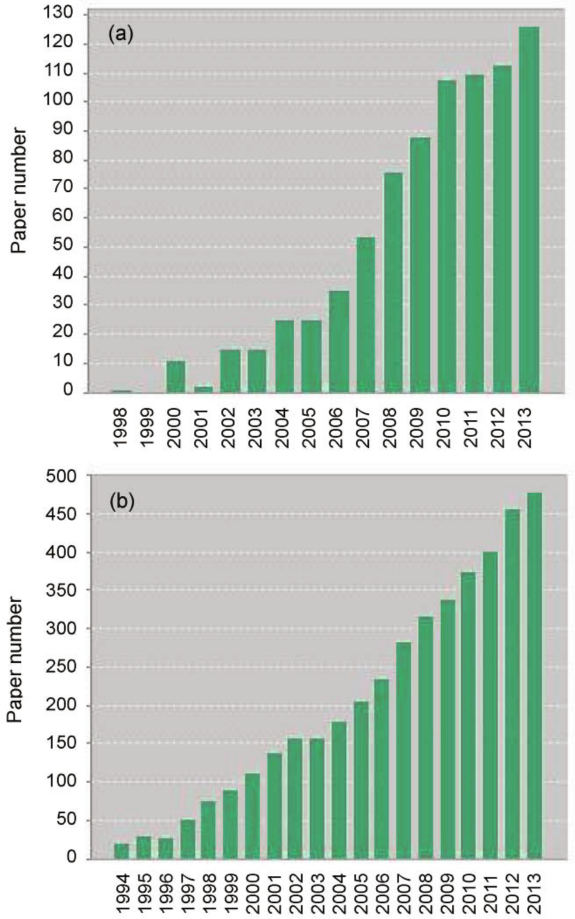

Fig. 2 Number of papers published during 1994–2013 in journals included in the database of SCI-Expanded
(a) Searching the topic "mechanobiology"; (b) Searching the topic "mechanotransduction"

4 Conclusions

To summarize the conclusions from this short paper, which is presented in an obvious personal and limited view, I will first highlight the following:

1. Hybrid vigor in nature has its counterpart in science. Continuum mechanics should and will get its momentum and energy from interdisciplinary research by coupling itself with physics, chemistry, biology, medicine, information science, and/or social science, as it has been doing with engineering. Multiscale modeling becomes a natural choice when different scales are involved (Fish, 2006).

2. Most living systems are very complex and soft, usually with multi-field coupling, and hence ongoing continuum mechanics approaches will manifest themselves in biology in terms of efficiency and accuracy. There are a lot of challenges (Volokh, 2013), which also indicate a great chance and brilliant future for mechanicians (Kim *et al.*, 2011; Shi *et al.*, 2011; Li *et al.*, 2012).

3. The current framework of continuum mechanics is far from complete (or perfect), especially for non-smooth, non-linear problems involving shocks, phase changes, irregular boundaries and contact. New directions such as peridynamics (Silling and Lehoucq, 2010) and geometric continuum mechanics (Epstein, 2010) deserve further exploration.

I have offered the course "Continuum Mechanics" for four years to graduate students majoring in mechanics at Zhejiang University. One frequent doubt expressed by a certain number of the students as to why they should learn this seemingly difficult subject can be summarized as "We have already powerful software like ANSYS and ABAQUS, therefore it may be no longer necessary to study these tangled concepts and complex formulae". While possibly I am not a good teacher, the students should know that man can do more than just use software. Without the understanding of the basic concepts, the software may not be used correctly. Moreover, FEM software cannot evolve in time by itself, at least currently, and its development solely depends on our understanding of the nature behind thus use of such software.

In summary, we have witnessed the renaissance of continuum mechanics in recent years, and we still have a huge amount of work to do in research as well as in education. Let me quote the following words from Newton to conclude this paper:

"I do not know what I may appear to the world, but to myself I seem to have been only like a boy playing on the seashore, and diverting myself in now and then finding a smoother pebble or a prettier shell than ordinary, while the great ocean of truth lay all undiscovered before me."

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Dr. Wei-qiu CHEN

Introducing Associate Editor-in-Chief:

Dr. Wei-qiu CHEN is a new Associate Editor-in-Chief of *Zhejiang University-SCIENCE A (Applied Physics & Engineering)* in 2014. He received his BS degree in engineering mechanics and his PhD degree in solid mechanics from Zhejiang University, Hangzhou, China, in 1990 and 1996, respectively. From 1997 to 1999, he was a Postdoctoral Fellow at the University of Tokyo, Tokyo, Japan. From 1996 to 2008, he was with the Department of Civil Engineering, Zhejiang University, where he became an Associate Professor in 1999, and a Full Professor in 2000. He moved to Department of Engineering Mechanics of the same university in 2009, and had been the Deputy Director of the Institute of Applied Mechanics from 2009 to 2013. He is now the Dean of Department of Engineering Mechanics.

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中文概要：

本文题目：连续介质力学的复兴

The renaissance of continuum mechanics

本文概要：连续介质力学，正如其名称所喻示的，研究的是所有连续介质的力学问题。所谓连续介质，就是其宏观的物理或力学性质沿空间连续变化，而不必考虑各组成原子或分子的结构及其相互作用。连续介质力学可以看作是现代力学的标志，后者与现代物理学区别明显，但经常被大众甚至科学家所混淆。在此，首先从个人理解的角度阐述了现代力学与现代物理学的区别，特别指出现代力学与重大工程应用紧密相关，这从其新兴于二十世纪的三个分支学科—断裂力学、空气动力学和有限元的发展历史即可看出。然后，基于 Web of Science 的检索数据（图 1），清楚揭示了二十世纪五、六十年代是连续介质力学的形成期，七、八十年代是其平稳发展期，而从九十年代起至今就是其复兴期。最后，着重从三个方面展示了连续介质力学的复兴和新发展：在纳机电领域与量子力学的衔接，在能源等领域与化学的耦合，在生物学领域由生物力学向力生物学的转变。可以看到，正如其在二十世纪的工程设计中扮演了轴心角色一样，连续介质力学将通过学科交叉（与物理、化学、生物学、医学、信息科学、社会科学等）而在现代科学的版图中持续发挥重要作用。

关键词组：连续介质力学；量子力学；工程；研究现状；复兴