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Published online: 13 Sep 2017.

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Innovative technologies in manufacturing, mechanics and smart civil infrastructure

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ABSTRACT

An overview on converging technologies that are the primary drivers of the 4th Industrial Revolution is presented, followed by new developments in advanced manufacturing, nano-,information-technologies and smart civil infrastructure technologies. Convergence of these transformative technologies is discussed. Emphases are on advanced manufacturing, nano mechanics/materials, sensors, structural control, smart structures/materials, energy harvesting, multi-scale problems and simulation methods.

1. Introduction

Nanotechnology is a very efficient way in the creation of new materials, sensors, devices and systems starting at the molecular level [1–5]. Smart materials on the other hand have seen new advances in terms of sensing, robustness, miniaturization, actuating, control, disaster mitigation, structural health monitoring, energy harvesting, advanced manufacturing, and other areas [6–14]. Mechanics is the common thread among these interdisciplinary areas [15,16].

The first 3 industrial revolutions occurred about 100 years apart and they changed the world. The 4th industrial revolution happened only a couple of decades from the 3rd one and it has already made profound impacts on the quality of life in terms of productivity, connectivity, education, and all aspects of life. Some of the examples of the latest progress are cloud computing, big data, Internet of Things (IoT), etc. According to ECN magazine 17 January 2017 issue, IoT enabled sensors will generate USD 10 B revenue globally in 2020. The following lists the attributes of the different industrial revolutions [5,17,18]:

- 1st 1784: mobilized the mechanization of production using steam power.
- 2nd 1870: mass production with the help of electric power.
- 3rd 1969: Arpanet, internet, digital revolution and the use of electronics and IT to further automate production.
- 4th present: a convergence of new technologies: AI, nanotechnology, cloud computing, robotics, 3-D/4-D printing, biotechnology, big data...

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According to the National Science Foundation (NSF; www.nsf.gov), some of the recent initiatives on smart systems involved:

- Robotics: Electronic, mechanical, computing, sensing devices and systems, controls, and intelligent systems that enable ubiquitous, advanced robotics
- Cyber-Physical Systems: Integration of intelligent decision-making algorithms and hardware into physical systems

2. Simulation

The widespread use of digital computers and simulation have had a profound effect in engineering and science [19–29]. A realistic and successful solution of an engineering problem usually begins with an accurate physical model of the problem and a proper understanding of the assumptions employed. With advances in big data, cloud computing, simulation-based engineering and sciences, computer hardware and appropriate software, we can model and analyze complex physical systems and problems. However, efficient and accurate use of numerical results obtained from computer programs requires considerable background and advanced working knowledge to avoid blunders and the blind acceptance of computer results.

With the senior author Chong's assistance, the National Science Foundation Blue Ribbon Panel on Simulation-based Engineering Science (chaired by Prof. J. Tinsley Oden) was formed in 2005 and came up with bold recommendations in computational mechanics, simulation and other related areas. This effort is continuing among Federal agencies with huge investment in R&D and great impact on engineering and sciences. Simulation-based Engineering Science [25] plays a key role in the current 4th Industrial Revolution. An example is the Material Genome Initiative (MGI) the US President announced in 2011 using vast databases and advanced computer modeling/simulation to design new material systems in half the time required (see: https://www.whitehouse.gov/mgi). MGI made reference to the NSF Blue Ribbon Panel report. Since the launch of MGI in 2011, the Federal government has invested over USD 250 million in new R&D in just 2 years. Industry investment is much more. The core issues of Simulation-based Engineering Science [25] are:

- Tyranny of Scales
- Verification, Validation, and Uncertainty Quantification
- Dynamic Data Driven Simulation Systems
- Sensors, Measurements, and Heterogeneous Systems
- New Vistas in Simulation Software
- Big Data and Visualization
- Next Generation Algorithms

According to the Moore's Law, the computer speed double every 18 months over the last 30 plus years. However the software usually lags behind the hardware. The following figure (Figure 1) is a rare example where the software is leading [26].
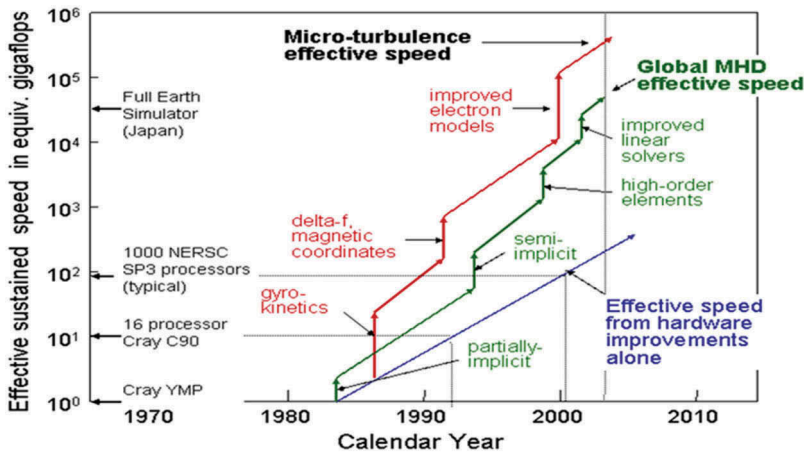
Fig: Moore's Law for MHD [magneto hydrodynamics] simulations. "Effective speed" increases from faster hardware and improved algorithms. [Keyes, et al ,2004]

Figure 1. Software speed leading hardware.

3. Multi-scale problems

Nanotechnology is a very efficient way in the creation of new materials, devices and systems at the molecular level – phenomena associated with atomic and molecular interactions strongly influence macroscopic material properties with significantly improved mechanical, optical, chemical, electrical and other properties [1,3,25,27]. NSF former Director Rita Colwell in 2002 declared, 'nanoscale technology will have an impact equal to the Industrial Revolution'. However, nanotechnology has to scale up to make useful systems and devices, hence we need to study the multi-scale problems [20,28–32]. In 2000 Boresi and Chong in an earlier edition of an Elasticity text [15] listed the following Table 1, detailing the different scales and their related topics.

Basically, there are two major methods of multi-scale modeling: sequential and concurrent. The following are the pros and cons of both methods [33],

- Sequential Multiscale Modelling

(pro) the idea is straightforward; the theories/principles at each level are mature (e.g. continuum mechanics, molecular dynamics, quantum mechanics, etc.), and therefore we just adopt different theories/principles at different scales and passed information in a bottom-up way or top-down way.

Table 1. Scales in materials/structures.

Materials		Structures		Infrastructures
Nanolevel~ *Molecular Scale*	microlevel~	mesolevel~ *Microns*	macro-level~ *Meters*	systems integration *Up to km Scale*
nanomechanics self-assembly nanofabrication	micromechanics microstructures smart materials	mesomechanics interfacial structures composites	beams columns plates	bridge systems lifelines airplanes

(con) the connection between different length scales is weak, since not all information at one scale can be totally passed to its higher or lower scale.

- Concurrent Multiscale Modeling

(pro) can solve the problem efficiently while still maintain high resolution at critical region
(con) some problems cannot be solved well. The typical un-solved challenge is how crack/dislocation/heat can propagate from the critical area to non-critical area.

4. Advanced manufacturing

According to the National Science Foundation, advanced manufacturing enables innovation capacity for manufacturing by emphasizing research on:

- cyber-enabled, adaptive, agile, and distributed manufacturing for the 'Factory of the Future'. Cyber manufacturing uses advances in sensors, networks, software, modeling, simulation, and computation transforming the 'Factory of the Future' and create new manufacturing eco-systems, which are distributed, flexible, adaptable, accessible, efficient, economic, personalized.
- nanosystems design and scalable nanomanufacturing
- advanced biomanufacturing

Advanced manufacturing is a family of activities that

(1) depend on the use and coordination of information, automation, computation, software, sensing, and networking, and/or
(2) make use of cutting-edge materials and emerging capabilities enabled by the physical and biological sciences, for example nanotechnology, chemistry, and biology.

It involves both new ways to manufacture existing products, and the manufacture of new products emerging from new advanced technologies [34,35]. Cloud manufacturing is also an enabling tool [36].

According to Jay Lee [18], future factories involve attributes based on 'self' sensing, controlling, networking – see Table 2.

Scalable nano-manufacturing (NSF 15–107; www.nsf.gov) is a NSF research initiative to *overcome the key scientific and technological barriers* that prevent the production of useful nanomaterials, nanostructures, devices and systems at an *industrially relevant scale*, reliably, and at low cost and within *environmental, health and safety guidelines.*

One of the shortcomings of 3-D printing [37] is the weak interfacial strength between layers of materials printed. The properties along the layers are different than those across the layers, behaving like a transversely isotropic material [15]. To overcome this weakness, vertical reinforcements can be pre-positioned like reinforcement in a concrete column shown below (Figure 2).

Table 2. Comparison of manufacturing technologies.

Comparison of Industry 4.0 Factory vs. Today's Factory

|	Data Source	Today Factory		Industry 4.0 Factory	
		Attributes	Key Technologies	Attributes	Key Technologies
Component	Sensor	Precision	Sensing	Self-Aware	Degradation Measurement
Machine	Controller	Quality & Performance	Monitoring & Diagnostics	Self-Predict Self-Compare	Health Prognostics
Production Systems	Networked Systems	Efficiency & Productivity	Lean & Green Manufacturing	Self-Reconfigure Self-Optimize	Worry-Free Production

Jay Lee, Germany Harting Tech New 26 ,2013
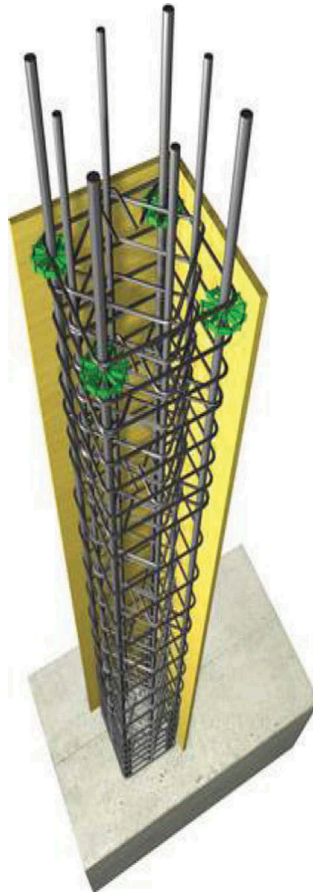
Figure 2. Vertical reinforcement in a column.

As for the 4-D printing [38], instead of building static 3-D items from layers of plastics, metals or other materials, 4-D printing employs dynamic materials, such as piezoelectric materials, that continue to evolve in response to their environment after fabrication.

5. Smart infrastructure

Smart structures refer to next-generation structures with self-diagnosis and prognosis, self-healing and repair, self-powered, and self-adaption abilities by integrating the technological advances in smart materials, smart sensors, structural health monitoring, structural control, and artificial intelligence. Smart structure technology may considerably enhance the functionality, reliability, safety and longevity of civil and mechanical structures. This section reviews the recent advances in the fields of structural health monitoring, structural control and energy harvesting.

5.1. Structural health monitoring

A sensory system is an important factor in structural health monitoring (SHM). For example, the Tsing Ma Bridge monitoring system established in Hong Kong in 1997 has around 280 sensors, including anemometers, temperature sensors, strain gauges, accelerometers, global positioning systems (GPS), displacement transducers, and level sensors [39]. An improved SHM system installed in the Stonecutters Bridge monitoring system (Hong Kong) later contains a total of over 1500 sensors [40], as shown in Figure 3. Various types of sensors produce a wide range of information for the implementation of an effective SHM and facilitate bridge safety/reliability assessment.
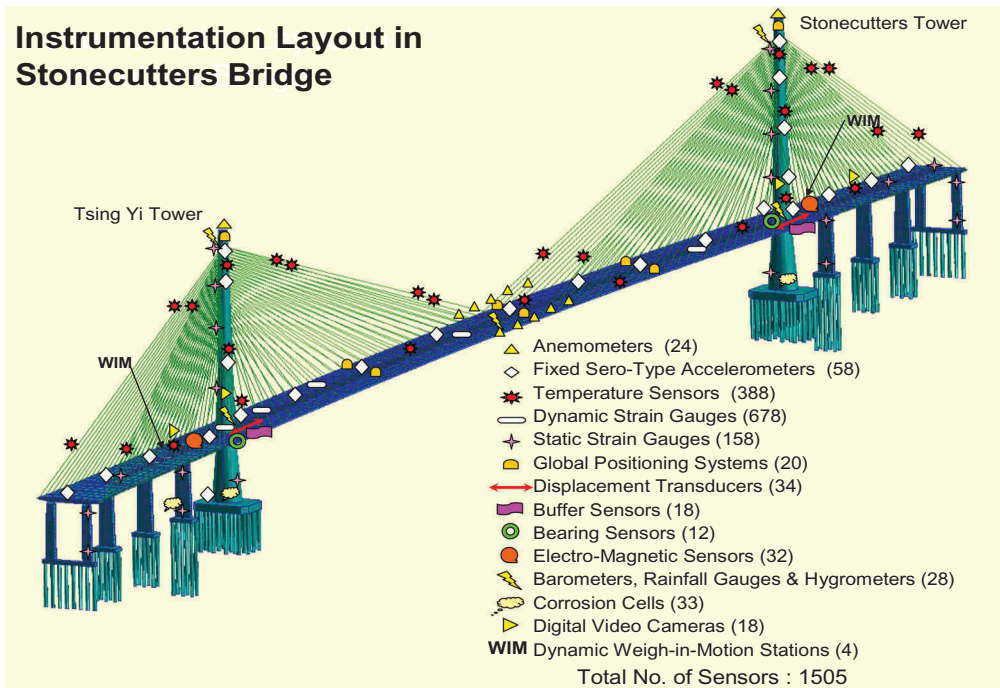

Figure 3. Layout of the sensory systems in Stonecutters Bridge [40].

With the rapid development of sensing technology, the possibilities for the application of improved SHM techniques are becoming increasingly feasible [41,42]. In a monitoring system for civil structures, sensors are primarily used to monitor three types of parameters: loading sources such as wind, seismic, and traffic loading; environmental effects including temperature, humidity, rain, and corrosion; and structural responses such as strain, displacement, inclination, and acceleration.

Since the pioneer work done by [43], fiber Bragg grating (FBG) sensors have been gain popularity in structural health monitoring because of the small size, light weight, non-conductivity, fast response, resistance to corrosion, higher temperature capability, immunity to electromagnetic noise and radio frequency interference, multiplexing and wavelength-encoded measure and information. An interrogation unit is required to address the large array of FBG sensors by using a single source. Various interrogation techniques for FBG sensors were reviewed in [44,45] and introduced four standard interrogation techniques: time-division multiplexing (TDM), spatial-division multiplexing (SDM), frequency-division multiplexing (FDM), and wavelength-division multiplexing (WDM). These interrogation techniques can be used alone or in combination with the other techniques. Given that FBG sensors are very fragile in nature, sustainable encapsulation is required before such sensors are placed into a regular monitoring service. Another attractive feature of FBG sensors is that they can serve as both the sensing element and the signal transmission medium. A great number of successful application examples in civil structures have been conducted (e.g. [44,46],).

Traditional displacement transducers include linear variable differential transformer, laser transducers, and level sensing stations, which can only be used for relative displacement measurement. Total stations provide absolute displacement measurement but are unsuitable for long-term monitoring. An emerging solution is global positioning systems (GPS). Although GPS was originally designed for navigation, the global coverage and the continuous operation in all metrological conditions make it an efficient tool for measuring both the static and dynamic displacement responses of structures. GPS is currently able to record the displacements at rates of up to 20 Hz with an accuracy of 1 cm horizontally and 2 cm vertically. Its measurement accuracy will be improved in the future with the further advancement. However, it also possesses disadvantages such as partial limitation by multipath, cycle slips, high cost, and the requirement for good satellite coverage [47].

5.2. Structural control

Structural control refers to the technology that protect structures against excessive vibrations induced by dynamic loads (e.g., construction, traffic, wind, and earthquakes) and thus prevent the damage to structural and non-structural components. In the last several decades, considerable attention has been given to a variety of structural control techniques operating in passive, active, semi-active or hybrid modes [48,49].

Passive structural control commonly adopts energy dissipation strategy through various damping devices, such as friction dampers, metallic-yield dampers, buckling-restrained braces, viscous fluid dampers, visco-elastic dampers, tuned-mass dampers, shape memory alloy dampers, eddy-current dampers, and so on. Another strategy is to reduce the seismic input energy using base isolation systems. Base isolation or seismic

isolation works by shifting a short fundamental period that is located in the dynamic excitation frequency range to a long fundamental period. Base isolation is usually used in low- to medium-rise buildings and nuclear power plants for seismic resistant design. However, base isolation systems are ineffective for wind-induced vibration mitigation [50]. The passive structural control systems do not require any external energy supply.

Active control shows an excellent control performance in comparison with relatively simple passive systems [48]. An active control system consists of a sensing system, control actuators, and a centralized controller/computer. Feed-forward or/and feedback control can be utilized in active structural control; however, feedback control is often preferable considering the difficulty in excitation measurement. Active control is often implemented by external-powered hydraulic or electromechanical actuators that apply control forces to host structures in a prescribed manner. A large power source is thus required for ensuring the active control system for large-scale structures. The practically available power source and limited peak control force required by active control systems may constrain its control performance. The first application of active control to a full-scale building was conducted in the Kyobashi Center, Tokyo, Japan, which was designed by Kajima Corporation in 1989 [51]. Two hydraulic active mass drivers (4.2 and 1.2 tons; approximately 1% of the structural mass; one for lateral motion suppression; the other for torsional motion suppression) were installed on the top floor of the 11-story structure. Although some other application cases of active control systems have been implemented(mainly in Japan), the cost effectiveness and reliability of the systems limit its wide spread acceptance in civil structures [52].

Semi-active control systems (Figure 4), which require relatively little external power and provide high reliability, are proposed to address some limitations of the active control systems. The semi-active control systems can be categorized into variable damping and variable stiffness devices. The nature of a semi-active device is adaptively adjusted to be optimal in real time based on the responses of structures or/and excitation. Variable damping systems, including variable-orifice fluid dampers, controllable friction devices, controllable fluid dampers, smart TMDs, and semi-active magneto-rheological (MR) fluid or elastomer dampers, are popular in recent years for structural vibration mitigation.
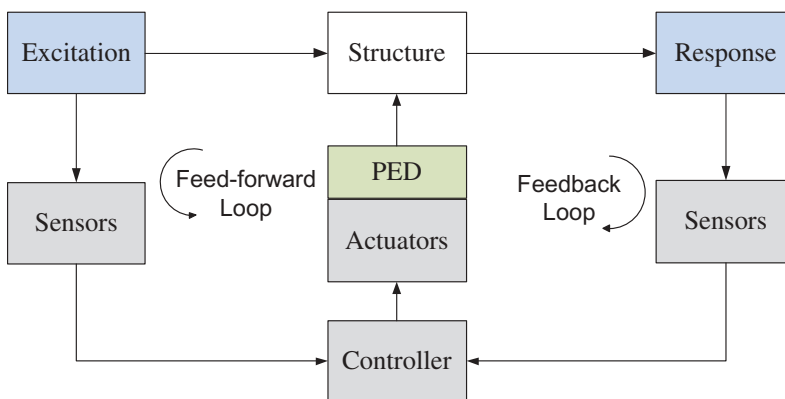

Figure 4. Schematic of the operation of a semi-active control system [49].

Variable stiffness devices or semi-active stiffness control devices work by tuning the stiffness of structural elements, thereby avoiding the resonant-type motion under dynamic excitations and reducing the input energy. Semi-active control systems do not add any mechanical energy to the structure, and the bounded-input and bounded-output stability of the system can be guaranteed [48]. Thus, they have received increasing interest because of their potential for a robust, reliable, and low-power structural control.

The comparison among the three categories of vibration control technologies reveals that a better control performance is often associated with higher complexity and low reliability. It will be appealing in practical applications if the reliability of passive control and the performance of active control can be achieved simultaneously. In the past studies on active control, it has been noted that the linear quadratic regulator (LQR) algorithm, which is a commonly adopted optimal control theory for active dampers, may produce a damper force-deformation relationship with an apparent negative stiffness feature that benefits control performance [53]. Thus, passive negative stiffness damper (NSDs), whose force-deformation relationship is shown in Figure 5(a), may be able to achieve control performance comparable to those of active dampers. Very recently, a family of NSDs have been developed, including passive negative stiffness springs based on the snap-through behavior of a pre-buckled beam, a passive negative stiffness mechanism composed of pre-compressed springs, a friction pendulum sliding isolator with a convex friction interface, and a magnetic NSD (MNSD) with several coaxially arranged magnets [54], as shown in Figure 6. In addition to NSD, inerter dampers are also recognized as another efficient vibration isolation technology. The force produced by inerter is proportional to the relative acceleration between the device terminals [55]. Figure 5(b) shows the typical force-deformation relationship of an inerter damper, which is similar to negative stiffness characteristics but is frequency-dependent. The inerter can be made mechanically through rack-and-pinion [55] or ball-screw, as shown by Figure 7 Some researchers also developed some tuned inerter dampers by emulating the principle of TMD, including tuned viscous mass dampers [57,58], tuned mass-damper-inerter systems (TMDI) [59] and tuned inerter dampers (TID) [60]. The main advantage of inerter is that the inerter can be designed to have an apparent mass significantly larger than its
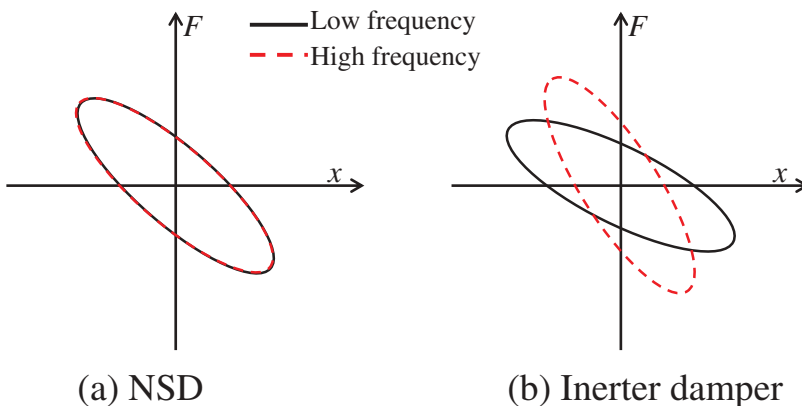

(a) NSD   (b) Inerter damper

Figure 5. Force-displacement of NSD and inerter damper. (a) NSD, (b) Inerter damper.

(a) a pre-buckled beam
with snap-through behavior

(b) a pre-compressed spring

(c) a friction pendulum isolator sliding
on a convex friction interface
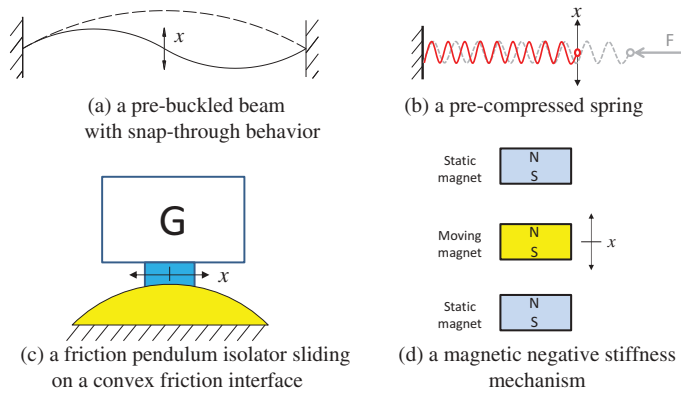
(d) a magnetic negative stiffness
mechanism

Figure 6. Representative negative stiffness mechanisms. (a) a pre-buckled beam. (b) a pre-compressed spring with snap-through behavior. (c) a friction pendulum isolator sliding. (d) a magnetic negative stiffness on a convex friction interface mechanism.

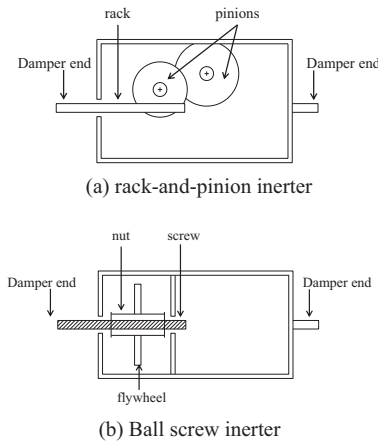(a) rack-and-pinion inerter

(b) Ball screw inerter

Figure 7. Representative inerter mechanisms [56]. (a) rack-and-pinion inerter. (b) Ball screw inerter.

actual mass. This advantage of inerter offers the potential for much higher mass ratios than those feasible for TMDs [60].

5.3. *Energy harvesting*

Energy harvesting is recognized as an emerging and promising technology in the next few decades [61]. Solar, wind, radio-frequency(RF) waves, and structural vibrations can provide green, sustainable, reliable and localized energy sources to low-power devices or systems, such as wireless sensors networks, semi-active controllers, alarm systems, etc. For example, Spencer et al. [62] proposed solar and wind energy harvesting as the power supplies for 113 wireless sensors in the smart monitoring system for Jindo Bridge in South Korea. The energy-harvesting performance is monitored by the wireless sensors themselves, which enables sensing nodes to manage the sensing scheme automatically

with respect to battery voltage status. Hassan et al. [63] proposed an energy-harvesting wireless crack monitoring sensor powered by a solar energy harvester. A comprehensive taxonomy of different energy harvesting sources for wireless sensor power supply has been presented in [64].

Meanwhile, vibration-based energy harvesting is one of the most rapidly growing research area [65–67].A typical configuration is a standard linear or nonlinear oscillator, in which part of the damping energy is converted into electrical energy by appropriate transduction mechanisms, including, but not limited to, piezoelectric, electromagnetic and electrostatic transductions [68], as shown in Figure 8. Piezoelectric transducers transform mechanical strain into electrical charge, known as direct piezoelectric effect [69]. Electromagnetic transducers generate voltage due to a relative motion between magnets and coils[70]. Electrostatic transducers are to utilize the variation in capacitance that can cause voltage increment in a constrained charge system or charge increment in a constrained voltage system [71]. The corresponding damping characteristics of these three transducers are different as well. More detail information about conversion mechanism are given in [72], and related derivation for output powers and efficiencies are given by [73].

Ambient vibrations, such as vibrations of mechanical and civil structures induced by various dynamic loads, provide energy sources for vibration-based energy harvesting. A special assessment of energy harvesting potential from a variety of vibration sources has been presented in [74]. Among them, civil structural vibration shows a relatively high feasibility because dynamic loadings, such as wind, earthquake, waves, and traffics, always result in relatively high structural vibration, especially for large-scale flexible structures. For example, a case study [75] shows that a power of more than 85kW could be harvested in buildings using an appropriate method. Recently, Tang and Zuo [76] utilized a regenerative TMD to harvest vibration energy from a three-storey building prototype, about 60mW energy was harvested when a proper harmonic force was applied to the prototype building. Zhu et al. [77] developed a dual-function EM device for simultaneous vibration control and energy harvesting. Later on, a self-powered vibration control and monitoring system (Figure 9) was developed based on energy-harvesting dampers and wireless sensors [78]. The effectiveness of energy-harvesting dampers was further illustrated in high-rise buildings during earthquake and stay cable vibration mitigation under wind loads [79,80]. In addition, Peigney and Siegert [81] employed a cantilever piezoelectric harvester to harvest traffic-induced vibration energy in a bridge. A relatively low mean power of around 0.03mW could be harvested and a controlled voltage ranging from 1.8V-3.6V was observed. Garuso et al. [82] successfully harvested as high as about 600W power from wind-induced bridge vibration through an adaptive tuned-mass energy harvester under a relatively high wind speed.

5.4. National science foundation (NSF) programs and projects

The NSF [www.nsf.gov] sensors program funds fundamental research on sensors and sensing systems. Such fundamental research includes the discovery and characterization of new sensing modalities, fundamental theories for aggregation and analysis of sensed data, new approaches for data transmission, and for addressing uncertain and/or partial sensor data. Other related programs are: Biosensing, Biophotonics or Biomedical
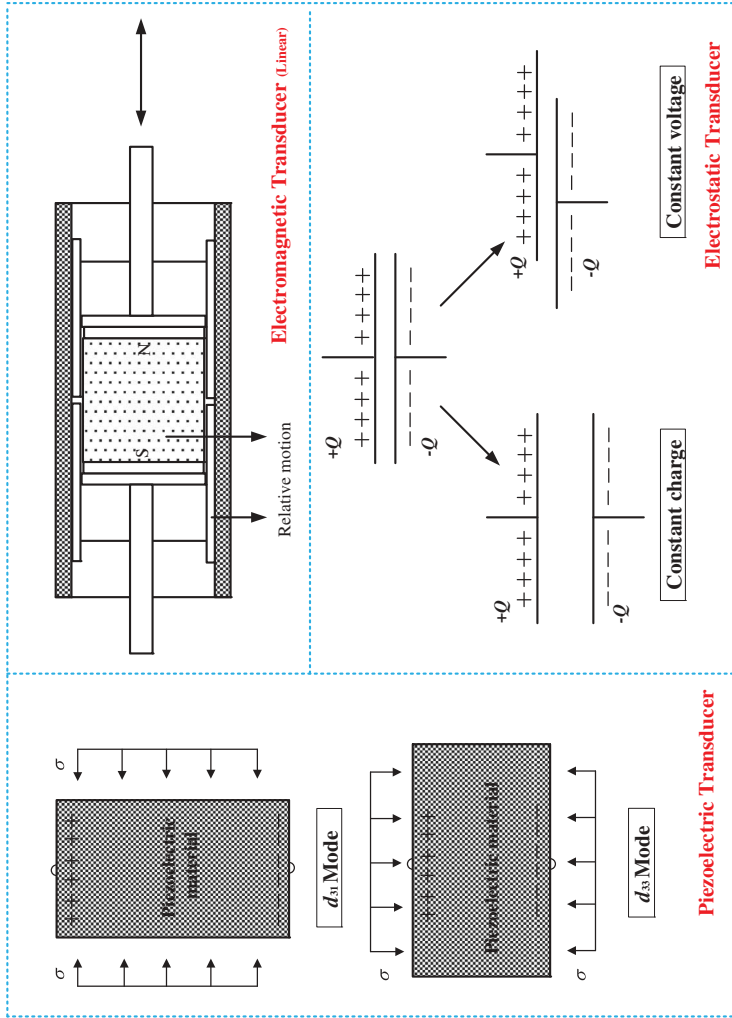
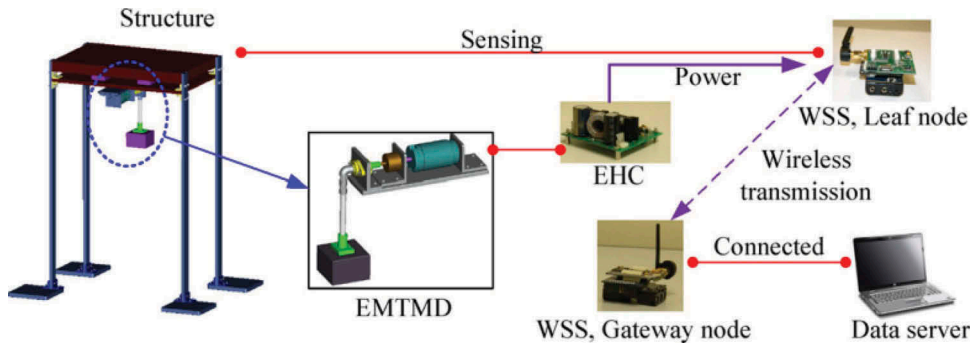**Figure 8.** The Sketch of three main transduction mechanisms.

Figure 9. Configuration of self-powered vibration control and monitoring system [78].

Engineering program, and also for areas of biosensing, sensors and actuators in the Electronics, Photonics, and Magnetic Devices program or the Communications, Circuits, and Sensing-systems program.

Examples of NSF active projects on sensors and smart materials:

(1) 4D Printing with Photoactive Shape-Changing Polymer; Award Number: 1,538,318; Principal Investigator: Jack Zhou; Co-Principal Investigator: Haifeng Ji; Drexel University.

(2) Development of Low-Cost and Portable Semiconductor Laser Based Evanescent-Wave THz Sensors; Award Number:1,437,168; Principal Investigator: Sushil Kumar; Lehigh University.

(3) Optical Carrier Based Microwave Interferometry for Spatially Continuous Distributed Monitoring of Structural Health; Award Number:1,359,716; PI: Hai Xiao; Clemson University.

(4) CAREER: Collaborative Modeling for Distributed Sensing and Real-time Intelligent Control to Improve Battery Manufacturing Productivity and Efficiency; Award Number:1,351,160; Principal Investigator: Qing Chang; SUNY at Stony Brook.

(5) GOALI/Collaborative Research: Self-powered Dual-mode Piezoelectric Resonant Pressure/Temperature Sensors for Oil and Gas Field Explorations; Award Number:1,529,842; Principal Investigator: Lei Zuo; Virginia Polytechnic Institute and State University.

(6) Optimal Control of a Swarm of Unmanned Aerial Vehicles for Traffic Flow Monitoring in Post-disaster Conditions; Award Number:1,636,154; Principal Investigator: Christian Claudel; Co-Principal Investigator: Stephen Boyles; University of Texas at Austin.

(7) CPS/Synergy/Collaborative Research: Cybernizing Mechanical Structures through Integrated Sensor-Structure Fabrication, Award Number:1,545,038; Principal Investigator: Yu Ding; Texas A&M Engineering Experiment Station.

(8) CAREER: Decentralized Monitoring and Control for Large-Scale Smart Structures with Wireless and Mobile Sensor Networks; Award Number:1,150,700; Principal Investigator: Yang Wang; Georgia Tech Research Corporation.

(9) Printing Embedded Sensors for Turbine Blades by Electro-spraying Polymer Derived Ceramics; Award Number:1,301,099; Principal Investigator: Linan An; University of Central Florida.

(10) Spectral Multiplexing of Fiber Bragg Grating Sensors for Low-Power Optical Sensor Networks; Award Number:1,536,936; Principal Investigator: Mark Pankow; North Carolina State University.

(11) EAGER: Interaction of Smart Materials for Transparent, Self-regulating Building Skins Award Number:1,548,243; Principal Investigator: Zofia Rybkowski; Co-Principal Investigator: Negar Kalantar, Tahir Cagin, Ergun Akleman, Terry Creasy;Texas A&M U.

6. Conclusions

An overview on converging technologies that are the primary drivers of the 4th Industrial Revolution is presented, followed by new developments and state of the art in advanced manufacturing, smart structures, nano-, information-technologies and sciences. Convergence of these transformative technologies is discussed, including advanced manufacturing, nano mechanics/materials, sensors, smart structures/materials, energy harvesting, multi-scale problems and simulation methods. The authors would like to thank the research communities for their input and feedback.

Disclosure statement

No potential conflict of interest was reported by the authors.

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