Sustainability in Environment
ISSN 2470-637X (Print) ISSN 2470-6388 (Online)
Vol. 4, No. 4, 2019
www.scholink.org/ojs/index.php/se

Original Paper

Piezoelectric Devices in the Sustainable Society

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Received: August 18, 2019 Accepted: September 8, 2019 Online Published: September 11, 2019
doi:10.22158/se.v4n4p181 URL: http://dx.doi.org/10.22158/se.v4n4p181

Abstract

Our 21st century faces to a "sustainable society", which enhances (a) usage of non-toxic materials, (b) disposal technology for existing hazardous materials, (c) reduction of contamination gas, (d) environmental monitoring system, (e) new energy source creation, and (f) energy-efficient device development in the piezoelectric area. With reducing their size, the electromagnetic components reduce their efficiency drastically. Thus, piezoelectric transducers with much less losses are highly sought recently. Piezoelectric devices seem to be all-around contributors and a key component to the above mentioned five R&D areas. Some of the efforts include: (a) Since the most popular piezoelectric lead zirconate titante ceramics will be regulated in European and Asian societies due to their toxicity (Pb^{2+} ion), lead-free piezoelectrics have been developed. (b) Since hazardous organic substances can easily be dissolved by the ultrasonic irradiation in water, a new safe disposal technology using piezoelectric transducers has been developed. (c) We demonstrated an energy recovery system on a hybrid car from its engine's mechanical vibration to the rechargeable battery. (d) Micro ultrasonic motors based on piezoelectrics demonstrated 1/20 reduction in the volume and a 20-time increase in efficiency of the conventional electromagnetic motors. This paper introduces leading piezoelectric materials, devices, and drive/control methods, relating with the above "sustainability" technologies, aiming at further research expansion in this area.

Keywords

piezoelectric actuators, sustainable society, Pb-free piezoelectric, ultrasonic cavitation, piezoelectric energy harvesting, efficiency

1. Introduction-Change in Product Planning Strategy

After the wars, mass production technologies were sought for the reconstruction and recovery of the country, and a sort of "Econo-Engineering" revived under the direction of the political leaders until 1990s in Japan. **Figure 1** shows the country power (GDP) change with year for the top three countries, Japan, USA (20 years ahead), and China (30 years behind) visualized by using typical growth curves. We will discuss the change in product planning strategy below taken historically by the Japanese industries, as an example (Uchino, 2017).

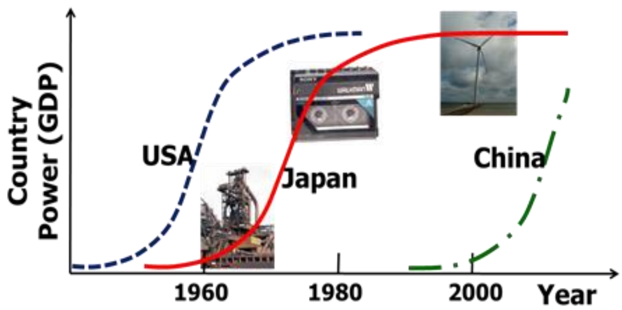


Figure 1. Country Power (GDP) Change with Year for Japan, USA (20 Years Ahead), and China (30 Years Behind) Visualized by Typical Growth Curves

In 1960s, the slogan was "*heavier, thicker, longer, and larger* (重，厚，長，大)"; that is, manufacturing heavier ships, thicker steel plates, constructing longer buildings, and larger power plants (dams) were the key strategies for recovering from the ruins of World War II. This societal mood made me choose Electrical Engineering in the university to become a water-dam engineer. Though Japanese people became wealthy, subsidiary effects started to surface: i.e., "*industrial pollution*". The southern part of the sea in Japan was contaminated by the heavy metal (mercury) disposal by Nippon Chisso Company (chemical fertilizer manufacturer), which created thousands of "neurological syndromes (insanity, paralysis, coma, and death follow within weeks of the onset of symptoms)" in that wide area. Steel industries produced air pollution (yellow sky!) and "asthma" even for small kids. Traffic congestion generated severe acoustic noise even in suburban areas. One of the most technological industries, nuclear power plants, leaked hazardous radio-active wastes multiple times.

A completely opposite slogan started in the 1980s; that is, "*lighter, thinner, shorter, and smaller* (軽，薄，短，小)". Printers and cameras became lighter in weight, thinner computers and TV's (flat panel) gained popularity, printing time and information transfer period became shorter, and air-conditioners and tape recorders ("Walk-man" by SONY) were smaller. Because of this societal mood, I, as a young university professor then, started working on compact "piezoelectric actuators & motors". Refer to **Table 1**. Though the serious industrial pollution diminished gradually during this period in proportion to the country power (high GDP per person), different subsidiary effects started: (1) "greenhouse effect" and "global warming" due to CO_2 gas generated by over-produced automobiles, (2) energy crisis due to over-consumption of energy and lack of fossil energy sources (oil), in addition to the political mismanagement, and (3) population growth due to advanced medical technologies. Longer life time is welcomed by individuals (now the average life time for Japanese is 87 for female, and is approaching to 82 for male; the world-eldest). However, over-population of humans will create an imbalance against other animals/natures, and senior population, in particular, causes societal and economic problems (pension, health insurance, work force, etc.).

Now, what, where, or how will be our 21st century? We will inevitably face the concept of a "*sustainable society*", including the population density. The author discusses this issue from an engineering viewpoint (in particular, in the piezoelectric device area) in this paper. When the 21st century began, environmental degradation, resource depletion, and food famine have become major problems. Global regulations are strongly called, and the government-initiated technology, that is, "*politico-engineering*" has become important in order to overcome the regulations. The author would like to propose in this paper a new four-Chinese-character keyword for the era of "politico-engineering", "協, 守, 減, 維 (*cooperation*, *protection*, *reduction*, and *continuation*: *Four -tions*)". Global coordination and international cooperation in standardization of internet systems and computer cables became essential to accelerate the mutual communication. The Kyoto Protocol in December 1997 is an international agreement linked to the United Nations Framework Convention on Climate Change (unfccc.int/kyoto_protocol/items/2830.php). Its major feature is to set binding targets for 37 industrialized countries and the European community for reducing greenhouse gas emission. Protection of the territory and environment from the enemy or natural disaster, and of infectious disease spread is mandatory. Reduction of toxic materials such as lead, heavy metals, dioxin, and of the use of resources and energy consumption is also the key, and the society continuation, i.e., *status quo* or *Sustainable Society*, is important to promote.

1960s	Heavier	--	Ship manufacturing
	Thicker	--	Steel industry
	Longer	--	Building construction
	Larger	--	Power plant (dam)
1980s	Lighter	--	Printer, Camera
	Thinner	--	TV, Computer
	Shorter	--	Printing time
			Communication period
	Smaller	--	"Walkman"
			Air conditioner
2000s	Cooperation	--	Global standard - internet
	Protection	--	Defense technologies
	Reduction	--	Pb, Dioxin, CO_2
			Energy consumption
	Continuation	--	Food supply
			Population–Med technology

Figure 1. Technology Development Paradigm in Japan after World War II

Figure 1 summarizes the technology development paradigm in Japan after World War II so far discussed. Considering situation in the world such as terrorist attacks, territorial aggression, major disasters (natural and human), we need "crisis technologies" as "politically-initiated engineering" (Refer to Uchino, 2017); Uchino (2018) for the details). While, the sustainable society requires the following technologies:

- Power and energy (lack of oil, nuclear power plant, new energy harvesting);
- Rare material (rare-earth metal, Lithium);
- Food (rice, corn-bio-fuel);
- Toxic material;
  – Restriction (heavy metal, Pb, Dioxin);
  – Elimination/neutralization (Mercury, Asbestos);
  – Replacement material;
- Environmental pollution;
- Energy efficiency.

Electric components such as motors and transformers are mostly based on electromagnetic transduction at present. With reducing their size (power level less than 30W), the efficiency of these electromagnetic components reduces drastically due to the Joule heat in their thin coil wire (i.e., the resistivity in the coil becomes significant). Thus, piezoelectric actuators and transducers with much less losses are highly sought after in the 21st century. Refer to **Figure 2** (Uchino, 2018; Uchino, 2020). In the past 30 years (i.e., after the 1980s), most researchers put efforts on improving the piezoelectric performance from the "real-part" property's viewpoint: that is, improved displacement, force, responsivity, etc. An example from this approach created single crystals based on $Pb(Zn_{1/3}Nb_{2/3})O_3$-$PbTiO_3$, which were discovered by our group (Kuwata et al., 1982), and now have become widely researched for medical and underwater applications. However, from the viewpoint of efficiency and reliability such as heat generation or performance degradation under high voltage/power drive, the key is the "*imaginary-part*"; that is, "*loss and hysteresis mechanisms*". Thus, in the 2000s, the author, as a senior professor, has been studying loss mechanisms in piezoelectrics, including high-power characterization system (HiPoCS) (Uchino et al., 2011), and practical high-power piezo-ceramics, in addition to highly energy efficient compact piezoelectric actuators and transducers.

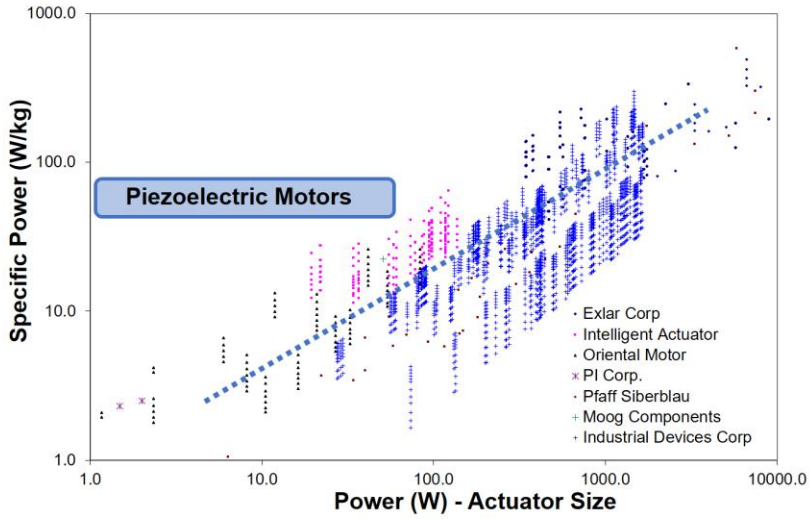


Figure 2. Specific Power (∝ efficiency) vs. Power (∝ Actuator Size) for Various Electromagnetic Motors. Piezoelectric Motor Performance Is also Inserted (Uchino, 2020)

The author discusses the following sustainability technologies in the piezoelectric device area: (a) usage of non-toxic materials, (b) disposal technology for existing hazardous materials, (c) reduction of contamination gas, (d) environmental *monitoring system*, (e) new energy source creation, and (f) energy-efficient device development. The descriptions in this article are widely indebted to two conference ("Actuator Bremen") proceedings titled "Piezoelectric Actuators—Piezoelectric Devices in the Sustainable Society—" (Uchino, 2010) and "Politico-Engineering in Piezoelectic Devices" (Uchino, 2012).

2. Usage of Non-Toxic Materials

2.1 Pb-Free Piezoelectric Materials

21^{st} Century is called "The Century of Environmental Management". In 2006, European Community started RoHS (Restrictions on the use of certain Hazardous Substances), which explicitly limits the usage of lead (Pb) in electronic equipments. Basically, we may need to regulate the usage of lead zirconate titanate (PZT), most famous piezoelectric ceramics, in the future. The Japanese and European communities may experience governmental regulation on the PZT usage in these 10 years. Pb (lead)-free piezoceramics have started to be developed after 1999. **Figure 3** shows preliminary patent statistics of various lead-free piezoelectric ceramics. The share of the patents for bismuth compounds (bismuth layered type and (Bi, Na)TiO_3 (*BNT*) type) exceeds 61%. This is because bismuth compounds are easily fabricated in comparison with other compounds. Note that the toxicity of Bi^{3+} is not very low compared with Pb^{2+}, but that a regulation may not be proposed because this atomic element is not familiar to politicians fortunately. (Na, K) NbO_3 (*NKN*) systems exhibit the highest performance because of the morph tropic phase boundary usage.

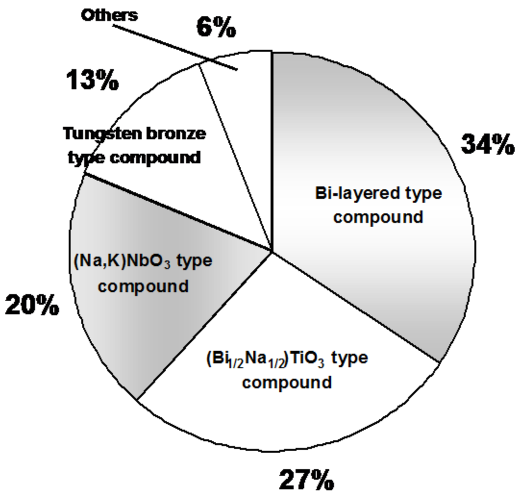


Figure 3. Patent Disclosure Statistics for Lead-Free Piezoelectric Ceramics (Total Number of Patents and Papers is 102)

Figure 4 shows the current best data reported by Toyota Central Research Lab, where strain curves for oriented and unoriented $(K,Na,Li)(Nb,Ta,Sb)O_3$ceramics are shown (Saito, 1996). Note that the maximum strain reaches up to 1500×10^{-6}, which is equivalent to the PZT strain. Drawbacks include their sintering difficulty and the necessity of the sophisticated preparation technique (topochemical method for preparing flaky raw powder). Tungsten-Bronze (*TB*) types are another alternative choice for resonance applications, because of high Curie temperature and low loss. Refer to a review paper on Pb-free piezoelectrics by T. Tsurumi (Tsurumi, 2005). Though their piezoelectric performance is not superior to the PZTs, commercialization efforts have been already made by two companies, which are introduced in the following sections.

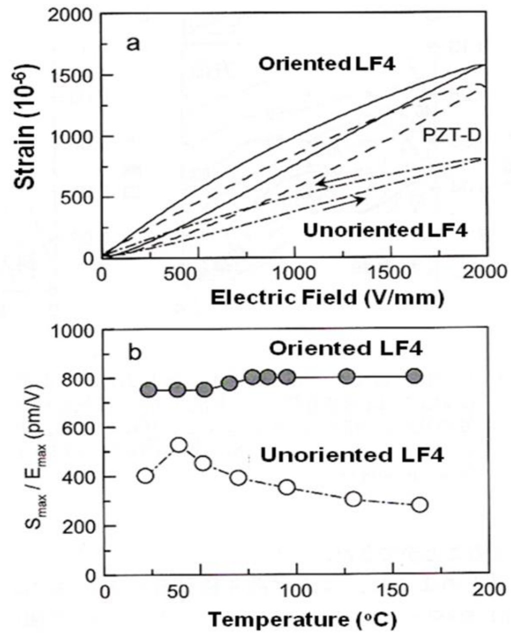
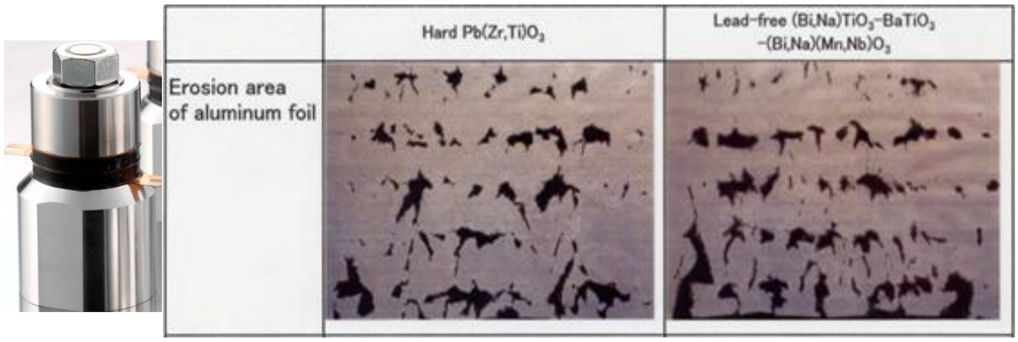


Figure 4. Strain Curves for Oriented and Unoriented (K, Na, Li) (Nb, Ta, Sb) O_3 Ceramics. (Saito, 1996)

2.2 Langevin Transducers with BNT

Langevin transducers used popularly for underwater fish finders and hydrophones are also utilized for ultrasonic cleaning and hazardous material dissolving systems. For these ecological applications, it is reasonable to make the systems also environment-friendly. Honda Electronics, Japan developed Langevin transducers with using the BNT based ceramics for ultrasonic cleaner applications (Tou et al., 2009). The composition0.82 $(Bi_{1/2}Na_{1/2})$ TiO_3 -0.15$BaTiO_3$ -0.03$(Bi_{1/2}Na_{1/2})$-$(Mn_{1/3}Nb_{2/3})O_3$ exhibits d_{33} = 110×10^{-12} C/N, which is only 1/3 of that of a hard PZT, but the electromechanical coupling factor k_t = 0.41 is larger because of much smaller permittivity (ε = 500) than that of the PZT. Furthermore, the maximum vibration velocity of a rectangular plate (k_{31} mode) is close to 1 m/s (rms value), which is higher than that of typical hard PZTs.

The Langevin transducer shown in Figure 5(a) (28 kHz) was tested in an erosion chamber. The ultrasonic power of lead-free piezoelectric transducer was equivalent to that of a hard PZT type, and the cleansing effect of both types was verified to be practically the same by comparing the erosion areas on aluminum foils (see Figure. 5(b)).



(a) (b)

Figure 5. (a) Langevin Transducer (28 kHz) for Cleaner Applications, and (b) Cleansing Effect Comparison among Pb-Free and PZT Types on Aluminum Foils (Tou et al., 2009). (Courtesy by Honda Electronics)

2.3 Ultrasonic Motors with TB

Taking into account general consumer attitude on disposability of portable equipment (printers, cellular phones), Taiyo Yuden, Japan developed micro ultrasonic motors using non-Pb multilayer piezo-actuators (Doshida, 2009). Their composition is based on Tungsten Bronze (TB) ($(Sr,Ca)_2NaNb_5O_{15}$) without heavy metal or even K (potassium seems to be a little toxic in comparison with Na). The basic piezoelectric parameters in TB (d_{33} = 55~80 pC/N, T_C = 300ºC) are not very attractive. However, once the c-axis oriented ceramics are prepared, the d_{33} is dramatically enhanced up to 240 pC/N. Further since the Young's modulus Y_{33}^E = 140 GPa is more than twice of that of PZT, the higher generative stress is expected, which is suitable to ultrasonic motor applications.

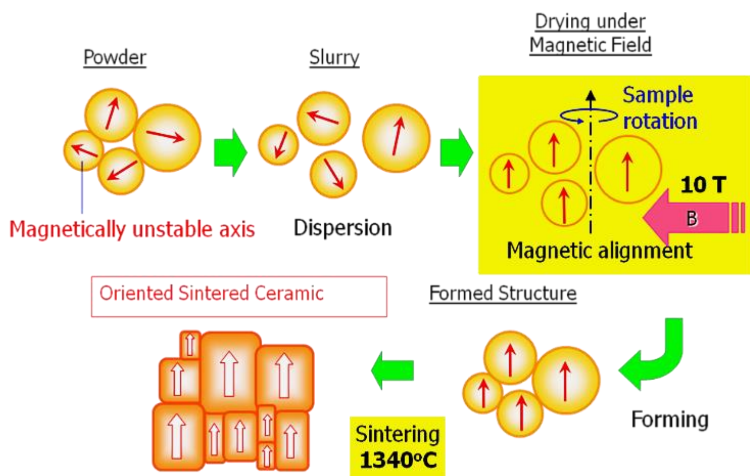
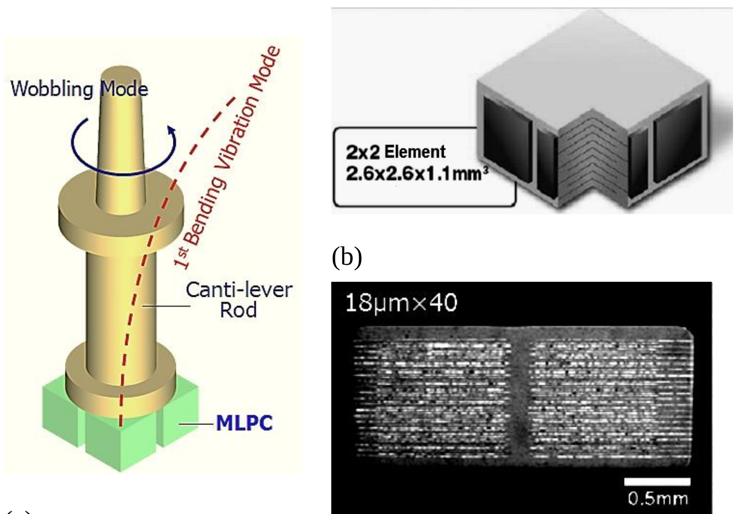


Figure 6. Principle of Ceramic Powder Orientation under Magnetic Field (Doshida, 2009)

Taiyo Yuden developed a sophisticated preparation technology for fabricating oriented ceramics with a multilayer configuration: that is, preparation under strong magnetic field, much simpler than the flaky powder preparation. **Figure 6** illustrates the principle of ceramic powder orientation under magnetic field. Since most of piezo-ceramics are diamagnetic, the ceramic powder suspended in slurry will be aligned along its magnetically-stable axis under a strong magnetic field (such as 10 T). Because the polariza-tion axis in their particular TB composition corresponds to the mag-netically-unstable axis, they used the magnetic field parallel to the green sheet. A cut-green-sheet was rotated practically under steady magnetic field during drying period. These oriented green sheets were electroded, laminated, and sintered. They reported beautiful crystal orientation degree of the sintered product with Lotgering factor 0.9 (Doshida, 2009).

Figure 7(a) shows their compact rotary ultrasonic motor with a piezoelectric multilayer actuator (MLA) (Doshida, 2009). A canti-lever rod is wobbled by a 2×2 arrayed MLA element, driven by a 4-phase voltage (sine, cosine, –sine and –cosine). They fabricated monolithic 2×2 arrayed elements with the size 2.6×2.6×1.1 mm^3 including buffers with layer thickness as thin as 18 μm [Refer to **Figures 7(b)** and **(c)**]. Because of this layer thinness and dramatic enhancement in the piezoelectric performance owing to the magnetic field alignment, the ultrasonic motor was successfully driven under only 3 $V_{p\text{-}p}$ which is low enough to be adopted in mobile phones without coupling a step-up drive circuit.



(a) (b) (c)

Figure 7(a). Compact rotary Ultrasonic Motor with a Piezoelectric Multilayer Actuator, (b) 2×2 Arrayed Element, and (c) Cross-Section View of the 18 μm-Layer ML Element (Doshida, 2009)

2.4 Biodegradable Polymers

The above Pb-free described materials are non-toxic and disposable. Murata Manufacturing Co., Japan is further seeking bio-degradable devices with using L-type poly-lactic acid (PLLA). PLLA is made of vegetable corn based composition. Because it exhibits pure piezoelectric without pyroelectric effect, the stress sensitivity is sufficient for leaf-grip remote controllers (with Nintendo Game Boy), which do not need a very long life time (www.murata.co.jp/corporate/ad/article/metamorphosis16/Application_note/).

3. Disposal Technology of Hazardous Materials

3.1 Ultrasonic Cavitation Effect

Ultrasonic lens cleaner is commonly used in home. Industrial ultrasonic cleaners are widely utilized in the manufacturing lines of silicon wafers and liquid crystal display glass substrates. With increasing the ultrasonic power level in water, *cavitation* (vacuum particle) is generated in water. Because the cavitation (cyclic adiabatic compression at around 28 kHz) generates more than 3,000°C micro-locally for a short period, we can make hazardous waste innocuous. Various hazardous wastes can be found underground or in sewer water, including dioxin, trichloroethylene, PCB, environmental hormone etc., which have been produced in the late 20th century. It is well known that dioxin becomes another toxic material when it is burned at a low temperature in typical garbage disposal furnaces, while it becomes innocuous only when burned at a high enough temperature. Ultrasonic irradiation is highly prospected for this application. Since the chemical reaction is induced in water (i.e., so-called sono-chemistry), dioxin can be dissolved into innocuous materials without apparently increasing temperature (average water temperature around 40°C, though micro-locally 3,000°C).

Honda Electronics added an ultrasonic stain remover on a washing machine produced by Sharp, Japan. **Figure 8** shows their L-L coupler horn to generate water cavitation for removing oily dirt from a shirt collar. It is noteworthy that we can reduce the amount of detergent (which is one of the major causes of the river contamination) significantly by this washing technique.

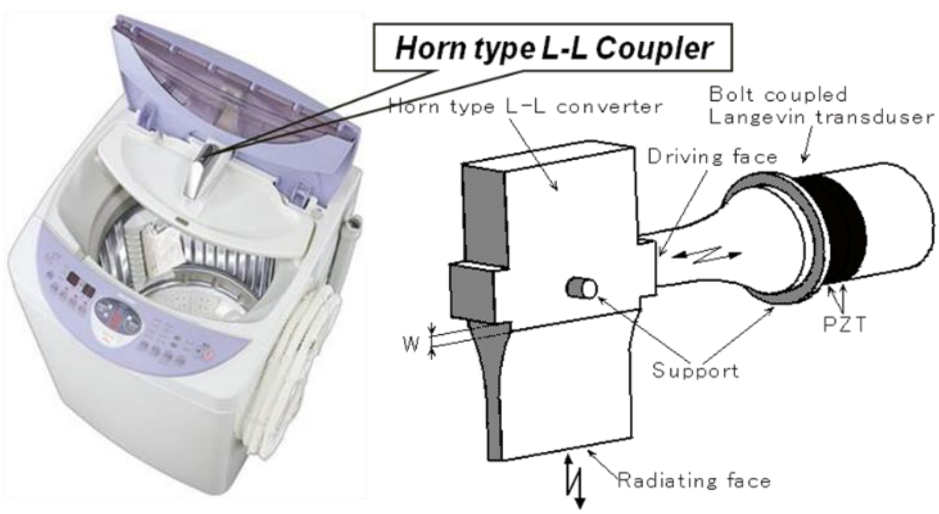


Figure 8. L-L Coupler Horn for a Washing Machine Application. (Courtesy by Honda Electronics)

3.2 Piezoelectric Diesel Injection Valve

Diesel engines are recommended rather than regular gasoline cars from the energy conservation and global warming viewpoint. Why? We need to consider the total energy of gasoline production; "well-to-tank" and "tank-to-wheel". The energy efficiency, measured by the total energy required to realize unit drive distance for a vehicle (MJ/km), is of course better for high octane gasoline than diesel fuel. However, since the electric energy required for purification is significant, the gasoline is inferior to diesel. As well known, the conventional diesel engine, however, generates toxic exhaust gases such as SO_x and NO_x. In order to solve this problem, new diesel injection valves were developed by Siemens, Bosch and Toyota with piezoelectric multilayer (ML) actuators. **Figure 9** shows a common rail type diesel injection valve (Fujii, 2005).

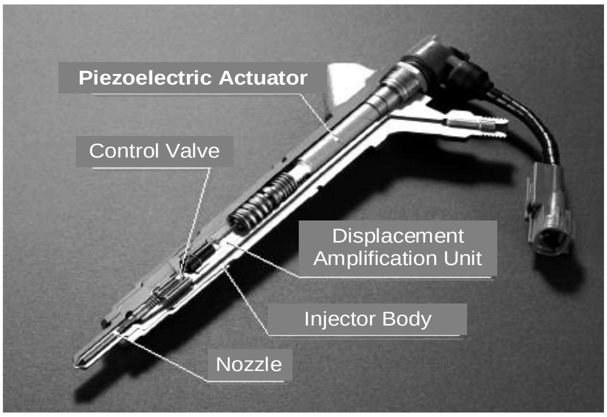


Figure 9. Common Rail Type Diesel Injection Valve with a Piezoelectric Multilayer Actuator. [Courtesy by Denso Corporation]

In order to eliminate toxic SO_x and NO_x and increase the diesel engine efficiency, high pressure fuel and quick injection control are required. **Figure 10** shows an example of diesel fuel injection timing chart. In this one cycle (typically 60 Hz), the multiple injections should be realized in a very sharp shape. For this purpose, piezoelectric actuators, specifically ML types, were adopted. The highest reliability of these devices at an elevated temperature (150°C) for a long period (10 years) has been achieved (Fujii, 2005). Note that the piezoelectric actuator is a key component to increase the burning efficiency and minimize the toxic exhaust gas elements.

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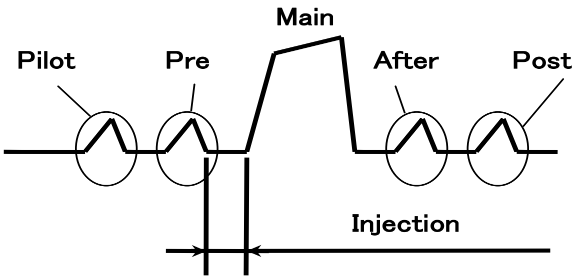


Figure 10. Diesel Fuel Injection Timing Chart in One Cycle (about 60 Hz Cycle)

4. Environmental Monitoring Devices

4.1 Bio Sensors

Quartz is used for various micro-mass sensors. Because the mechanical quality factor Q_m is very large ($\sim 10^6$), the monitoring resolution of the resonance frequency reaches $\Delta f_R/f_R \sim 10^{-6}$. Thus, even small mass change on the quartz surface can be finely detected through the resonance frequency shift. This micro mass sensor can be utilized as a bio-sensor for detecting bacteria, such as E. Coli and Salmonella. $10^4 \sim 10^7$ cells per *ml* is already critical to humans for Salmonella's case. A specific antibody/phage is coated on a single crystal quartz oscillator. Once particular bacteria are captured selectively by the *antibodies*, the surface mass of the oscillator is increased. A sensitivity of 10^4 cells per *ml* has been reported [Cheng (2003)].

4.2 Mechanical Noise Cancellation

Mechanical noise (vibration and sound noise) is a hazardous environmental problem, nowadays. Automobile sounds should be banned in residential areas. Ishii and Uchino reported the first passive damping concept with PZT ceramics in early 1980s (Uchino & Ishii, 1988). When a piezoelectric is adopted in a noise vibration system, cyclic electric field is excited. If this electric energy is consumed via a suitable resistor as Joule heat, mechanical noise vibration is significantly suppressed (Uchino & Ishii, 1988). Kobayashi Institute of Physical Research, Japan developed curved PVDF large panels for the highway noise active cancellation application (so-called *Noise Barrier*). 30~40 dB reduction of sound noise was achieved around a low frequency range (100-300 Hz) by combining a *Negative Capacitance Circuit*. Figure 11 shows transmission loss of these PVDF barriers (with and without a negative capacitance circuit), compared with the regular concrete, glass, iron walls (Fukada et al., 2004).

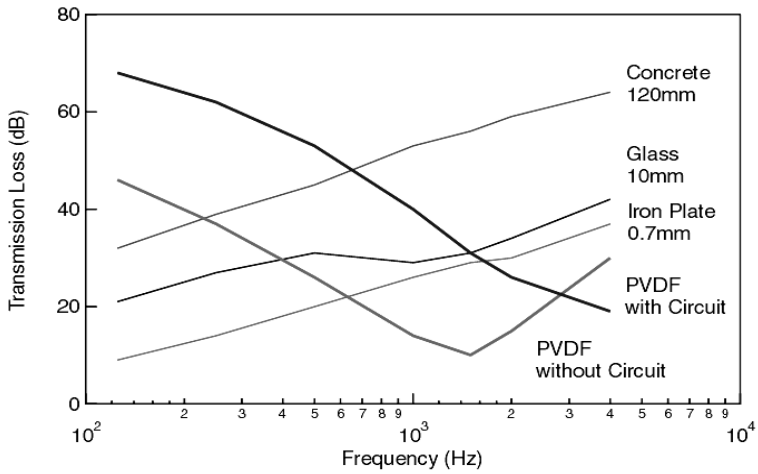


Figure 11. Transmission Loss of PVDF Barriers (with and without a Negative Capacitance Circuit), Compared with the Regular Concrete, Glass, Iron Walls (Fukada et al., 2004).

4.3 Magnetic Noise Monitoring

The sustainable society requires also sensors for monitoring hazardous environmental magnetic fields, which humans cannot sense biologically. Similar to nuclear radiation, magnetic irradiation cannot be easily felt by human, but it may increase the brain cancer probability. We cannot even purchase a magnetic field detector for a low frequency (50 or 60 Hz). The Penn State, in collaboration with Seoul National University, Korea, developed a simple and handy magnetic noise sensor. **Figure 12** shows a schematic structure of the device, in which a PZT disk is sandwiched by two Terfenol-D (magnetostrictor) disks. When a magnetic field is applied on this composite, Terfenol-D expands, which is mechanically transferred to PZT, leading to an electric charge generation via "*direct piezoelectric effect*" from the PZT. By monitoring the voltage generated in the PZT, we can detect the magnetic field. The key of this device is high effectiveness for a low frequency (Ryu et al., 2001).

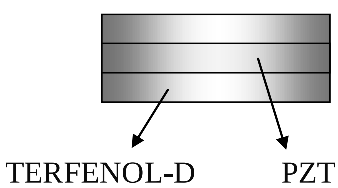
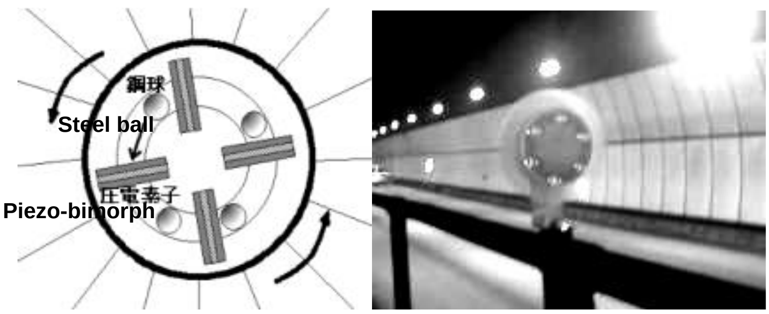


Figure 12. Magnetic Noise Sensor Consisting of a Laminated Composite of a PZT and Two Terfenol-D Disks (Ryu et al., 2001)

5. New Energy Source Creation

One of the most recent research interests is piezoelectric energy harvesting. Cyclic electric field excited in the piezoelectric plate by the environmental noise vibration is now accumulated into a rechargeable battery without consuming it as Joule heat. **Figure 13** shows an LED traffic light array system driven by a piezoelectric windmill developed by NEC-Tokin, Japan. Wind generated by passing automobiles is effectively utilized. Successful products (i.e., “million selling” devices) in the commercial market include “Lightning Switch” (remote switch for room lights, with using a unimorph piezoelectric component) by Pulse Switch Systems, VA [www.lightningswitch.com/], and the 25 mm caliber “Programmable Ammunition” (electricity generation with a multilayer piezo-actuator under shot impact) by ATK Integrated Weapon Systems, AZ [www.atk.com/MediaCenter/mediacenter_ video gallery.asp]. In addition to the living convenience, *Lightning Switch* (**Figure 14**) can reduce the housing construction cost drastically, due to a significant reduction of the copper electric wire and the aligning labor.

The Penn State group developed energy harvesting piezoelectric devices based on a “Cymbal” structure (29 mm, 1 - 2 mm thick), which can generate electric energy up to 100 mW under an automobile engine vibration (Kim, Priya, Uchino, & Newnham, 2005); Kim, Uchino, and Daue (2005); Kim, Priya, and Uchino (2006). By combining 3 cymbals in a rubber composite, a washer-like energy harvesting sheet was developed for a hybrid car application, aiming at 1 W constant accumulation to a rechargeable battery. **Figure 15** demonstrates soft-energy harvesting concept (Intelligent Clothing) by using a piezoelectric Macro Fiber Composite, in collaboration with Smart Materials, USA.



(a) (b)

Figure 13. Piezoelectric Windmill (a) for Driving an LEC Traffic Light Array System (b). [Courtesy by NEC-Tokin]

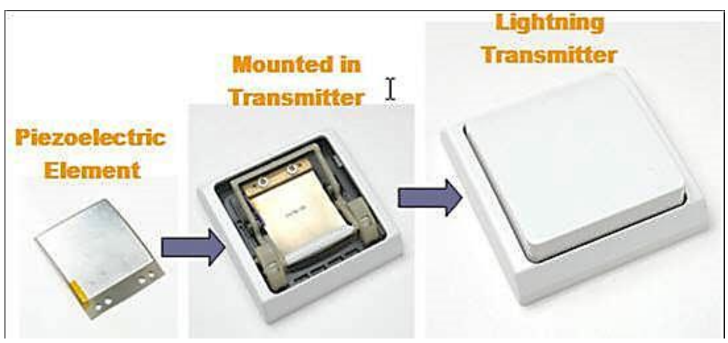


Figure 14. Lightning Switch with Piezoelectric Thunder Actuator. [Courtesy by Face Electronics]

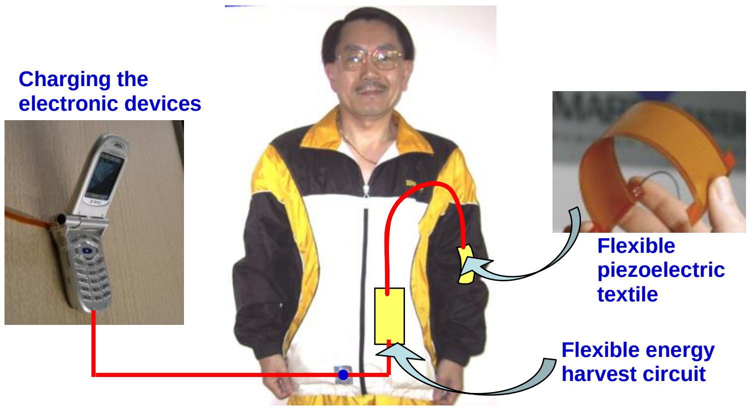


Figure 15. Concept of Soft Energy Harvesting; Intelligent Clothing with a Flexible Piezo-Fiber Composite

6. Energy-Efficient Devices/Control Methods

Figure 2 shows efficiency versus power relation for electromagnetic (EM) and piezoelectric devices (We collected 3000 data-points from the commercial EM motor catalogs, 2000). The significant decrease in the efficiency of the EM motor is mainly due to the Joule heat increase in reducing the coil wire thickness. More than 90% of the input electrical energy in a wrist watch motor is spent to generate heat! Since the efficiency of the piezo-device is insensitive to the size, it is effective in the power range lower than 30 W; that is, for portable devices. We have been developing in these 20 years various compact ultrasonic motors and smooth impact drive mechanisms with much higher efficiency and energy density than the EM motors. Refer to the author's previous proceedings articles of Actuator 2004, 2006 for the details (Uchino, 2004; Uchino, 2006). The author would like to point out here new development trends from the energy efficiency point of view: electrode material, antiresonance drive, and negative capacitance usage.

6.1 Electrode Materials

Because of the improved high-power piezoelectric ceramics development and multilayer (ML) design usage in recent devices, the impedance of the resonating ML piezo-device is rather low (~10Ω). Thus, the internal and external lead conductance influences the performance seriously. Ural et al. verified in ring-dot type piezoelectric transformers that pure Cu or Ag electrode material dramatically improves the power density of the transformers by 30% in comparison with the conventional Ag/Pd electrode usage, because of the poor electrical conductivity of Pd (Ural et al., 2008).

6.2 Antiresonance Drive Scheme

Many piezoelectric devices, such as ultrasonic motors, transformers, and sound projectors, are driven at the "*resonance*" frequency. Under the resonance the piezoelectric sample has the resistive characteristics, and for a given input voltage it exhibits the maximum vibration amplitude, maximum current and minimum electrical impedance. On the other hand, the piezoelectric material also has the resistor behavior under the "*antiresonance*", with the maximum electrical impedance. This indicates that a piezoelectric device can be driven at the anti-resonance as well by a high voltage but low current supply. What is the benefit of this antiresonance drive? Efficiency! The mechanical quality factors (inverse value of loss factor) for resonance Q_A and antiresonance Q_B for a rectangular plate specimen (k_{31} mode) are provided respectively by

$$Q_{A,31} = \frac{1}{\tan\phi_{11}'}, \quad \frac{1}{Q_{B,31}} = \frac{1}{Q_{A,31}} + \frac{2}{1+(\frac{1}{k_{31}} - k_{31})^2 \Omega_{B,31}{}^2} (\tan\delta_{33}' + \tan\phi_{11}' - 2\tan\theta_{31}')$$

Here, tan δ’, tan ϕ’, tan θ’ are dielectric, elastic and piezoelectric intensive losses (Zhuang et al., 2009). Since the piezoelectric loss is significantly large in PZT ceramics, the term (tanδ’+tanϕ’−2tanθ’) is negative, leading to the higher quality factor Q_B, compared to Q_A. Since the higher Q_B is also observed in the experiments, the antiresonance drive may be an effective alternative for the traditional resonance drive to reduce the loss and heat generation, which is essential for high power application and device miniaturization. In addition, using the high-voltage low-current supply can reduce the cost of the whole system, as compared to the high-current low-voltage power source for the resonance drive (Uchino, 2006).

Most recently, the ICAT discovered much higher mechanical quality factor between the resonance and antiresonance frequencies. Because the conventional admittance spectrum method can provide the Q_m only at two frequency points (i.e., resonance and antiresonance), a unique methodology for characterizing the *quality factor* in piezoelectric materials has been developed by utilizing real electrical power measurements (including the phase lag) (Shekhani & Uchino, 2014). The relation between mechanical quality factor and real electrical power and mechanical vibration is based on two concepts: (1) at equilibrium the power input is the power lost and (2) the stored mechanical energy can be predicted using the known vibration mode shape. The vibration mode is a similar sinusoidal shape in the frequency range between the resonance and antiresonance points under a reasonably small k_{31} condition (k_{31}< 0.80). We can derive the following equation from these concepts, which allows the calculation of the mechanical quality factor Q_m at any frequency from the real electrical power (P_d) and tip RMS vibration velocity (V_{RMS}) measurements for a longitudinally vibrating piezoelectric resonator (k_t, k_{33}, k_{31}):

$$Q_{m,l} = 2\pi f \frac{\frac{1}{2}\rho V_{RMS}^2}{P_d/(Lwt)}$$

The change in mechanical quality factor was calculated for a PZT (APC 841) ceramic plate (k_{31}) under vibration conditions of 100 mm/s RMS tip vibration velocity. The quality factor calculated at resonance was within 2% agreement with results from the impedance spectrum 3 dB method. The technique revealed the behavior of the mechanical quality factor at any frequency between the resonance and the antiresonance frequencies (**Figure 16)** and very interestingly, the mechanical quality factor reached a maximum value in-between the resonance and the antiresonance frequency, the point of which may suggest the optimum condition for the transducer operation and also for understanding of the behavior of piezoelectric material properties under high power excitation (Shekhani & Uchino, 2014).

A new Equivalent Circuit (EC) was proposed for the k_{31} mode, as shown in **Figure 17(a)**, in order to explain the maximum Q_m point between the resonance and antiresonance frequencies by obtaining all three losses as a function of frequency separately, deduced from the Revised Hamiltonian Principle (Shi et al., 2014). We derived equations below to correlate the physical losses based on the parameters of EC, which can be solved based on material properties and measurements of real part G and imaginary part B of admittance. That is, the experimental data of admittance provide the real parameters (C_m, L_m, C_d) first, then, leading to the imaginary parameters (R_m, G_d, G_m') or three losses as material properties.

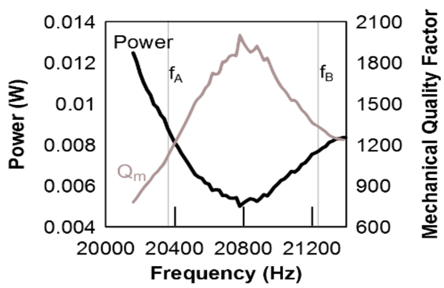


Figure 16. Mechanical Quality Factor Measured Using Real Electrical Power (Including the Phase Lag) for a k_{31} Plate

$$\tan\phi' = \frac{\mathrm{Im}[K^*]}{\mathrm{Re}[K^*]} = \omega C_m R_m$$

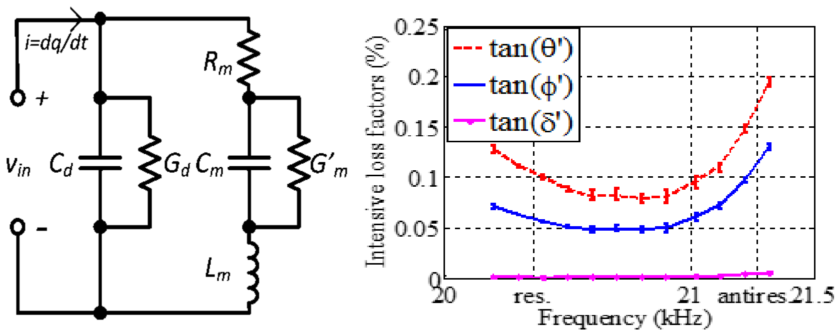
$$\tan\theta' = \frac{\mathrm{Im}[K^*/e^*]}{\mathrm{Re}[K^*/e^*]} = \tan(\phi' - \beta')$$

$$\tan\delta' = -\frac{\pi^2}{8}\mathrm{Im}\left[\frac{(e^*)^2}{K^*}\right] - \frac{\mathrm{Im}[c_p^*]}{C_0} = k_{31}^2 \tan(2\theta' - \phi') + \frac{G_d}{\omega C_d}$$

where the phase delay β':

$$\tan\beta' = \frac{\mathrm{Im}[e^*]}{\mathrm{Re}[e^*]} = \omega C_m / G'_m - \sqrt{(\omega C_m / G'_m)^2 + 1}$$

The frequency spectra of the losses for the k_{31} mode are shown in **Figure 17(b)**, indicating that the piezoelectric loss is not only non-negligible, but is also larger than other two components for a hard PZT material. Moreover, it is notable that the minimum total loss can be obtained around the geometrical average frequency of the resonance and antiresonance frequencies (Shi et al., 2014).



(a) (b)

Figure 17. (a) New Equivalent Circuit with Including Three Losses (Dielectric, Elastic and Piezoelectric); (b) Frequency Dependence of Intensive Three Loss Factors Obtained from Figure 16. Data for a Hard PZT k_{31} Plate

6.3 Negative Capacitance Usage

Piezoelectric actuators are a capacitive component under off-resonance operation. Many mechanical engineers have misconception on the drive/control scheme of these components. What does a good controller need to look like, different from usual linear power amplifiers, which exhibit 98% energy *inefficiency* for piezo-devices? Murray-Knowles piezoelectric theorem provides a suggestion: The admittance of any practical controller improving open loop performance consists of *–Cp//T* where *Cp* is the blocked capacitance of the piezoelectric device and *T* is a series R-C circuit. As schematically shown in **Figure 18** for a 200W level actuator, a generative power system of only 4~10 W can realize 98% energy *efficiency* with a negative capacitance (Knowles, 2007).

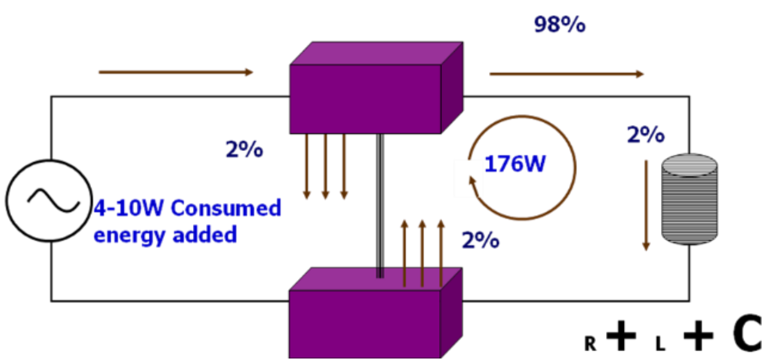


Figure 18. Generative Power System with a Negative Capacitance to Realize 98% Efficiency

7. Future Perspectives

The first quarter of 21st century seems to be the age of “Politico-Engineering”; that is, strong political initiative is required for promoting the engineering development. The paradigm shift from econo-engineering to politico-engineering is mandatory in Science & Technology development. In 1980s, i.e., “Bubble Economy” period, cost/performance technologies were sought, while in these 20 years, *sustainability and crisis technologies* should be the mainstream. The crisis includes (1) natural disaster (earthquake, tsunami, tornado, typhoon, thunder), (2) infectious/contagious disease (smallpox, polio-myelitis, measles, HIV), (3) enormous accident (Three-mile-island nuclear power plant melt-down, BP deep-water oil flow), (4) intentional (terrorist/criminal) incident, and (5) external & civil war/territorial invasion.

This article introduced the sustainability technologies in the piezoelectric device area, which include (a) development of *non-toxic piezo-materials*, (b) *disposal technology* for existing hazardous materials with using ultrasonic cavitation, (c) *reduction of contamination gas* with piezo-devices, (d) *environment monitoring*, (e) new *energy source* creation (i.e., piezoelectric energy harvesting), and (f) *energy-efficient piezoelectric device* development.

This paper, in particular, proposed a new four-Chinese-character keyword as the product planning strategy for the era of “politico-engineering” in these 10 years, “協, 守, 減, 維 (*cooperation*, *protection*, *reduction*, and *continuation*, *the “Four -tions”*)”. Global coordination and international *cooperation* in standardization of internet systems and computer cables became essential to accelerate the mutual communication. The “Kyoto Protocol” in is an international agreement linked to the United Nations Framework Convention on Climate Change. *Protection* of the territory and environment from the enemy or natural disaster, and of infectious disease spread is mandatory. *Reduction* of toxic materials such as lead, heavy metals, dioxin, and of the use of resources and energy consumption is also the key, and the society *continuation*, i.e., *status quo* or *Sustainable Society*, is important to promote.

Finally, we compare the difference among the product planning strategies for techno-, econo-, and politico-engineering. As illustrated in **Figure 19**, in the techno-engineering (exemplified by single crystal relaxor piezoelectrics), the fundamental Science and Technology (S&T) or the discovery comes first as the key, then followed by the development, and finally application products are created. In the econo-engineering (exemplified by piezo-multilayer components in the 1980s), the final product specs, in particular, in mass-production capability and manufacturing cost, come first. Based on these desired specs, manufacturing processes are developed as the key. To the contrary, in the politico-engineering (exemplified by Pb-free piezoelectrics in the 2000s), the legal regulation for the final products comes first with strict constraints in terms of law-issuing date, performance regulation (e.g., Pb fraction in the final product, CO_2, NO_x, or SO_x emission amount, specifications for rescue robots, new weapons). In the case of the automobile diesel injection valve, the multilayer actuator development was the key for providing the solution; while in the RoHS regulation on the PZT, we need to develop or even discover new Pb-free piezoelectric materials.

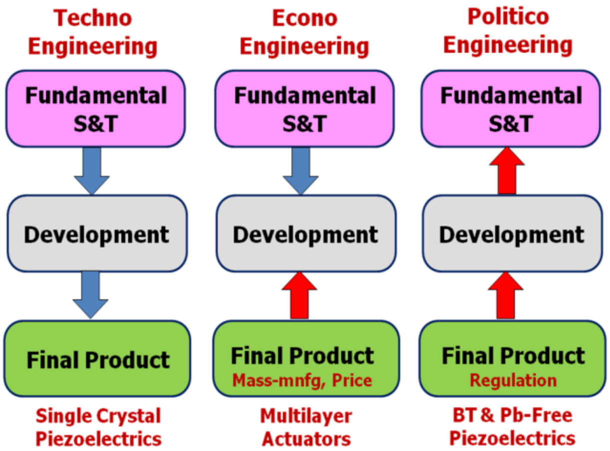


Figure 19. Difference among the Product Planning Strategies for Techno-, Econo-, and Politico-Engineering

The most important issue in the "politico-engineering" age is the leading politicians' action/motion on how to protect the domestic industries against the foreign pressure. Taking into account the current domestic S&T capabilities, with intimate collaboration with the leading domestic politicians, the global regulation needs to be accepted. In other words, the engineers need to instruct the leading politicians on the correct up-to-date technologies. Otherwise, the domestic industrial crush may happen. One of the typical items can be found in the power generation with nuclear power. Depending on the country's alternative energy generation capability, the electric blackout and industrial bankruptcy will happen, if the nuclear power plant would be shut down so soon just by considering general fear against the nuclear power. The key is to develop the safety/security systems for the nuclear power plants even under a crisis situation before deciding to remove them without alternative energy source (Uchino, 2017).

Acknowledgement

Most of our researches have been supported continuously by the US Office of Naval Research to ICAT/Penn State University in these 30 years.

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