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# A SURVEY OF APPLICABILITY OF ELECTRICALLY/MECHANICALLY STIMULATED MATERIALS TO SENSORS AND ACTUATORS IN SMART STRUCTURES

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An attempt is made to define the smart structure concept. The requirements imposed on properties of prospective materials for intelligent systems are presented and sensor/actuator functions are analysed. The properties of piezoelectrics and electrorheological fluids are considered as representatives of two types of materials coupling mechanical/electrical effects.

*Key words:* mechanics, elasticity, smart structures

## 1. Idea of smart structures

The idea of "smart" or "intelligent" structures springs up from an attempt to design and manufacture a system which would recognise the changes in the environment, analyse the situation, make the decision and react in a reasonable way (Fig.1). This idea corresponds to observation of living creatures which, to survive, must adapt to variation of environment. The latest achievements in material science, electronics, micromechanics and computer sciences made a smart structure concept feasible. A number of prospective applications are expected and investigated (cf Gandhi and Thompson (1992)). The great activity is pursued in aerospace and aeronautics, both in fixed and rotary wing fields (cf Agnes and Sendeckyj (1993); Narkiewicz and Done (1994)).

Different ways of putting the idea of smart structures into practice, can be classified in three groups (cf Narkiewicz (1993)): intelligent passive systems, intelligent materials and intelligent active systems. In illustrating these classification the analogies to living creatures are illustrative.

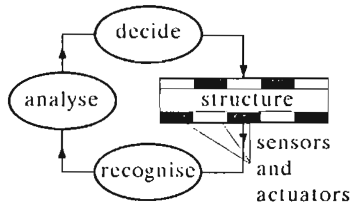


Fig. 1.

The intelligent passive system is designed in such a way that the acting stimulus causes the counteraction without any external control or energy supply. Animal or human bones which increase their stiffness under pressure, or "aeroelastic tailoring" in aeronautics, are good examples here.

Intelligent materials would monitor, make decision and respond to external stimulus on the molecular or "cell" level. For instance, some plants, such as sunflowers exhibit phototrophy, mechanism of which can be treated as an example of the "distributed intelligence". In intelligent materials, sensing, control and actuating functions cannot be separated. Artificial intelligent materials are under development and the most promising concepts seem to be "perceptive composites".

Intelligent active systems are considered the most often in engineering. They can be regarded as generalisation of controlled structures, which contain sensors and actuators linked in a closed loop way to the processor. Typical components of an intelligent active system are: host structure, network of sensors, network of actuators and real-time control computation capabilities based on microprocessor. In these systems, the network of actuators provides the muscles to make things happen; the network of sensors is an analogy to the nervous system to monitor and report the external stimuli; the structural material forms the skeleton. The computational capabilities provide the brains which process the data transmitted by the nervous system prior to ensuring the optimal performance of the overall system.

An intelligent active system, which reacts by changing its mechanical properties, is named the adaptive structure.

In intelligent systems actuators, sensors and processors are integrated with the structure and have structural functionality. For instance, in a mechanical device these elements are carrying the loading. Despite the processors, to perform the control task and process the vast amount of information, highly integrated electronics is needed for signal conditioning and power amplification. Control algorithms should be capable of adaptive learning. To make the intelligent systems more reliable their elements should have self-inspection and self-maintenance capabilities.

In smart structures, the reaction on the variation of the environment is realised by modifying/changing the structure states, geometrical characteristics and/or physical properties (electrical, magnetic mechanical, optical, thermal, etc.).

Up till now, sensing, actuating and controlling functions are usually provided by separate devices. A research attempt is undertaken to combine them into a multitask system. This would lead to qualitative changes in design philosophy and manufacture technology.

The fields of technology needed for smart structures development are:

- Sensing mechanism; for identification of environment state
- Data acquisition, transmission and processing to recognise and understand the problem
- Performing of control algorithm
- Reacting by actuators.

Each element of the system should fulfil general technical requirements concerning operational aspects like: low power consumption, efficiency in power utilisation, long life, compactness (i.e. low weight/volume ratio), maintainability, reliability and possibility to operate under extreme conditions. Specific features can be required for each design concept and each part of a smart structure.

In this paper a review of prospects of materials for smart structure application is presented. The generic approach is assumed, and no specific design or application is considered. Adaptive structures give the background for analysis of materials for sensors and actuators. The review is restricted to materials coupling electric/mechanical effects directly, i.e. piezoelectrics (electrostrictives) and electrorheological fluids.

## 2. Smart materials

In adaptive structure technology materials are investigated having in mind prospective applications to sensors or/and actuators These materials should be able to respond almost instantaneously to external stimuli and have an capability of cooperate or to be integrated with modern microprocessors and solid-state electronics. The materials which have not been applied widely yet are investigated to obtain multifunctional sensing/actuating capability.

Prospect of combining sensing/actuating within one element generates the interest to investigate materials with the ability of coupling different physical effects. Usually such materials, which couple various physical interactions (for instance, mechanical stress and electrical field) are considered as "smart materials". Full constitutive equations of these materials include description of mechanical, optical, electromagnetic, chemical and thermal properties, respectively. Cross coupling effects manifest themselves as off-diagonal terms in such constitutive equations.

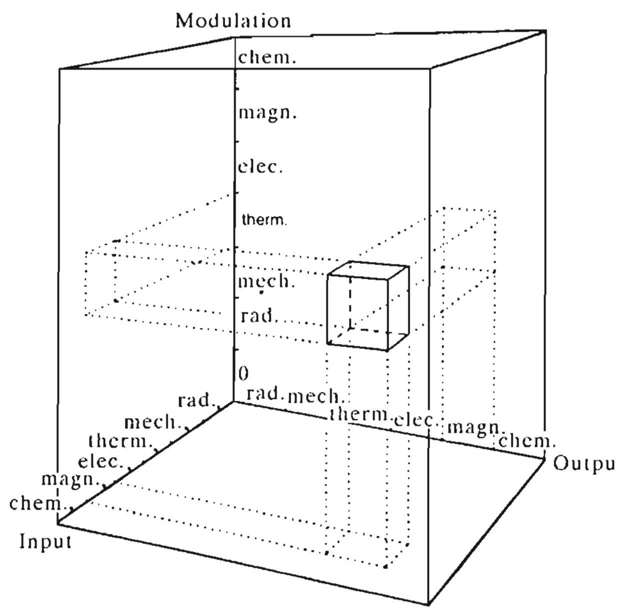


Fig. 2.

The possibility of cross coupling effect in material can be illustrated as sensing/interaction cube Fig.2 (cf Middelhoek and Hoogerwerf (1987)). The signals in Fig.2 concern various forms of energy:

- The radiant signal; it covers electromagnetic waves of all frequencies, ranging from the radio waves to gamma rays; the main parameters which can be measured are intensity, frequency (colour), polarisation and phase
- The mechanical signal; it deals with all kind of external parameters of the matter such as shape (size), place, velocity and acceleration

- The thermal signal; it has one parameter only, temperature
- The electrical signal; its parameters are: voltage and current
- The magnetic signal; it has one major parameter; field intensity
- The chemical signal; it depends on internal structure of the matter; the main parameters are concentration, crystal structure and aggregation state.

In Fig.2 the input signal is the quantity to be measured, while the output signal is the signal to be processed.

The physical phenomena can be regarded as selfgenerating or modulated effects. In selfgenerating effects, the energy of output signal is directly converted from the energy of input signal. In modulated effects, the main contribution of energy of output signal comes from an auxiliary source of energy. In Fig.2, the coordinate along the vertical axis indicates the type of the modulating energy. Selfgenerating effects lay in the input/output plane for no modulation.

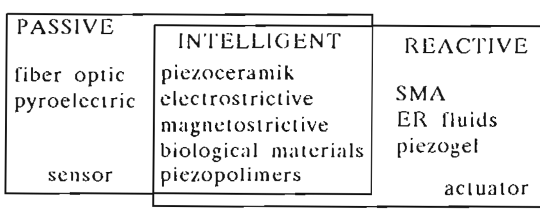


Fig. 3.

Prospective "smart materials" can be: passive, reactive or intelligent (Fig.3). Passive materials change their properties under external stimuli, but cannot transfer energy to the host structure. They can be used for sensing purposes only. Glass fibres used in fibre optics are an example. Reactive materials change their properties in such a way that the energy can be supplied to the structure. They are used for actuating purposes. Intelligent (smart) materials can act as both the sensing and actuating devices.

The most promising materials for prospective "intelligent" applications are composites comprising reactive materials like piezoelectric or shape memory alloys. It is expected to be possible to tailor properties of these materials according to the requirements and needs of particular structure. But before having practical application in engineering these materials need a lot of research work.

## 3. Signal transferring

Transmitting information between different elements of a smart structure can be difficult due to the amount of information to be passed. According to the hypothesis of Wiener, the information must be carried by mass or energy; no information can be transmitted from a source (object of measurement) to a receiver (sensor) without mass or energy transport between them. No example has been found which would oppose this hypothesis. Transmitting a great amount of information can lead to substantial energy loses. As a result, the signal obtained by the receiver can be too weak to be recognised properly. Despite that, the possibility of additional disturbances of the signal should also be taken into account.

At the existing stage of technology the following two ways of signal transportation are the most common: electricity transported via wiring or light transferred via optic fibres. In the second case the signal should be converted to an electrical one to be processed by available computing devices. Fibre optic technology require electronic devices, sometimes very sophisticated, for making information consumable by computers.

The processes which have electric stimulant or electric output signal seem to be the most prospecting for application in adaptive structures. The possibility of converting different forms of energy into electric signal is listed in Table I.

**Table 1**

| Physical effects with electrical output | | | | |
|---|---|---|---|---|
| Domain | Measurand | Stationary | Gradient | Time derivative |
| radiant | intensity<br>frequency<br>polarisation<br>phase | photoelectric<br>photoconductivity | lateral | |
| mechanical | size<br>place | piezoelectric<br>electroaccoustic | place dependence of electrical field | velocity |
| thermal | temperature | Seebeck effect | | |
| magnetic | field intensity<br>magnetoresistance<br>superconductivity<br>Suhl effect | Ettingshausen-<br>-Nernst effect<br>Hall effect | | Faraday-Henry law |
| chemical | concentration<br>crystal structure<br>aggregation | electrical properties | Volta effect | Redox reactions |

Due to a small magnitude of signal only some of these effects can be considered to be feasible in multifunctional elements of intelligent structures.

In adaptive structures the mechanical energy should be generated to change the shape of the structure. These changes are also to be measured to provide information for control systems. So in adaptive structures the effects which couple mechanical and electrical signals are essential.

## 4. Sensors

The task of sensors is to acquire and identify information. To design a smart structure, commercially available sensors (strain gauges of both foil and semiconductor types, fibre optics, thermocouples, etc.) can be applied. The basic requirements imposed on sensor properties cover: high sensitivity to the measured stimulus and linear relation between the stimulus and the signal. For sensors embedded in an adaptive structure, compatibility between sensor material and the host structure is essential.

The result of integration sensors with computing devices are "smart sensors" that have electronics on the transduction element itself (cf Giachino (1987)). These sensors can perform some logic functions, two-way communication, sometimes can recognise the situation and make some type of decision. These features would allow them to perform also more advanced tasks, like, for instance, selfcalibration and multisensing.

Most types of sensor have two parameters that are adjusted during fabrication: offset and gain. The offset is the deviation of output from the desired value when the input is at a minimum. The offset error is independent of the measurand value. The gain defines the difference in a sensor output between the maximum and minimum values of measurand. These parameters can show some changes during the time of operation or under extreme operating conditions. The sensors without the selfcalibration ability have to be removed from service and recalibrated in the case of suspiction of malfunctioning. The sensors with the built-in microprocessor can have the correction functions implemented (e.g., as a piece of software in their memory) which would allow selfcalibration.

To perform the selfcalibration, the ability to determine by the sensor itself whether it is operating properly (i.e. selfdiagnostics) is needed. It could be done via comparison of selected state values (which form the base for correcting changes in offset and gain) with the external measurements. When the array of sensors is applied, the selfdiagnostic ability to recognise whether all sensors work properly is important. It also includes recognising the elements which are still functioning, but for some reasons, they have got a shift in calibration. In the case, when some sensors are out of service, the signal processing procedure would do proper adjustment to the situation. A smart sensor would then recalibrate the individual element and readjust the output of this element, so the overall value of measured signal is correct.

Computational abilities can also be used to obtain devices that utilise different sensitivities of different sensing elements. This would allow to fabricate a sensor of adequate sensitivity, even when none of individual sensing element is selective enough to function in this situation. Some "smart sensors" have already been designed.

For instance, the researchers at the Case Western Reserve University have fabricated a pH sensor consisting of ten "identical" sensing elements on a single silicon chip incorporating signal conditioning electronics (cf Giachino (1987)). By using a microcomputer, they constructed an improved sensor by applying statistics to the signals of sensing element. Computational abilities allow one to obtain the values of average, variance and standard deviations for the set of measurements. If an individual output signal is recognised not to be a member of the set (e.g., it exceeds the confidence interval), it can be discarded. Using such a technique, the sensors can be utilised which contain elements subjected to unexplained shifts in calibration curve, and the device has improved performance and extended life.

Multisensing is the ability of a sensor to measure simultaneously more than one physical or chemical variables.

An example of multisensor, which emphasis the potential of integrated silicon-based devices, is an integrated multisensor chip developed at the Electronics Research Laboratory, University of California, Berkeley (cf Giachino (1987)). This chip, which is $8 \times 9$ mm, contains conventional MOS devices for signal conditioning together with the following on-chip sensor, gas flow sensor, infrared sensing array, chemical reaction sensor, cantilever beam accelerometers, surface-acoustic-wave vapour sensors, tactile sensor array, and infrared charge-coupled device imager.

Selfcalibration, selfdiagnostics, and multisensing capabilities described above can also be obtained by proper procedures of signal processing for sensors of classical type. This possibility should be taken into account, when the number of sensors is high and the probability of failure increases due to operating under extreme conditions.

## 5. Actuators

The main task performed by actuators is changing properties of the structure according to a control signal.

The actuator converts one form of energy into the other in a way opposite to the sensor. In adaptive structures the actuator task is to convert the signal (usually an electrical one) to the mechanical action (strain or displacement) in the structure. For these applications solid state actuators are investigated extensively, due to their design simplicity. The solid state actuators are made of adaptive material embedded into a host structure to produce the actuating strain, which is controllable and does not depend directly on external stress.

The general performance parameters of solid state actuators are: maximal stroke or strain, resolution, bandwidth, linearity of response to a signal, mechanical and dynamic properties. The required output from a solid state actuator is mechanical energy or useful work. The ability to provide it is characterised by actuator force/displacement characteristics. To calculate actuator influence on a host structure, a detailed analysis should be made, taking into account: constitutive relations of the actuator, deformation field caused by local strain, and imposition of equilibrium conditions. Simplified analysis can give us insight into a general performance of an actuator.

As an example, the behaviour of one stroke actuator (cf Janker and Martin (1993)) is considered. The total strain of actuator is a result of a strain due to stress occurring in a host structure and a controllable strain induced by an actuator itself. This can be expressed by the one-dimensional constitutive law in the linear from

$$S = sT + \Delta(P) \tag{5.1}$$

where

| | | |
|---|---|---|
| $S$ | – | strain |
| $T$ | – | stress |
| $s$ | – | compliance constant |
| $\Delta(P)$ | – | strain due to the governing physical quantity $P$. |

It is the simplest form of constitutive equation, extension of which is a multidimensional, tensor formulation.

Usually strain caused by physical effect $\Delta(P)$ is also assumed linear, i.e.

$$\Delta(P) = dP \tag{5.2}$$

As it is illustrated in Fig.4, the actuator free strain can be characterised by the line $AQ$ for a constant value of $\Delta(P_1)$. The energy is transferred to an actuator due to changing the physical effect by $\Delta(P_2)$. Assuming that

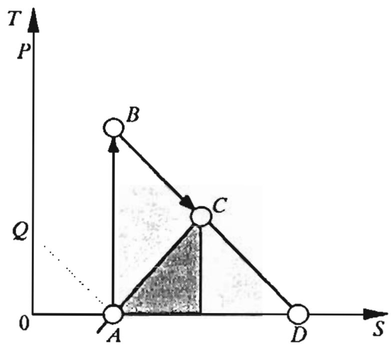


Fig. 4.

actuator is free to deform, changing the value of $P$ transfers the strain of actuator from the state described by the line $AQ$ to the state characterised by the line $DP$.

The specific energy (i.e. the amount of energy relative to the volume of material) of the free strain actuator resulting from the changes of $P$ from $P_1$ to $P_2$ can be calculated as

$$e_0 = \frac{1}{V}\int\limits_A^D T\,ds = \frac{1}{2sV}[\Delta(P)]^2 \tag{5.3}$$

where $V$ is the volume of active material.

This is the energy stored in an actuator due to an external impact and it is available to be transferred into external work. Specific energy for different materials it is given in Fig.5.

The efficiency of material for actuator purposes can be also characterised by coupling factor $\eta$ (or $k^2$) defined as

$$E_0 = \eta E_P = k^2 E_P \tag{5.4}$$

where

$E_0$ – energy available for actuating

$E_P$ – input energy.

The coupling factor depends on internal properties of the material. The values of coupling factor for different materials are given in Fig.6.

In the case when an external load acting on an actuator has also a linear stress/strain relation (line $AC$ in Fig.4), the final stress in the actuator will result from equilibrium of the external and internal loads. The equilibrium

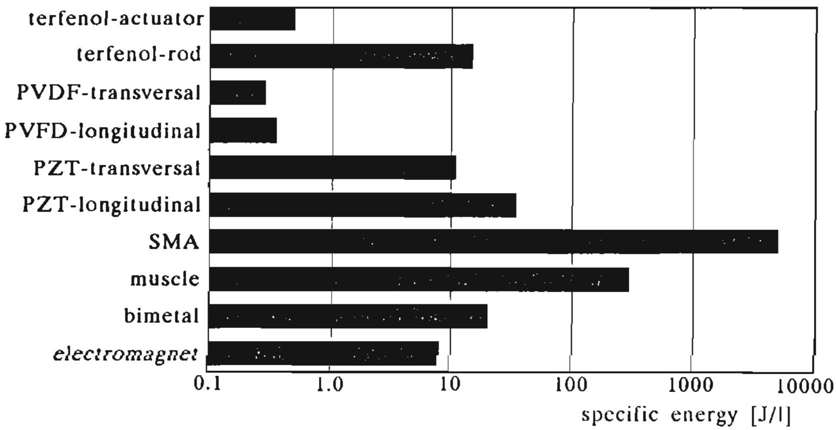


Fig. 5.

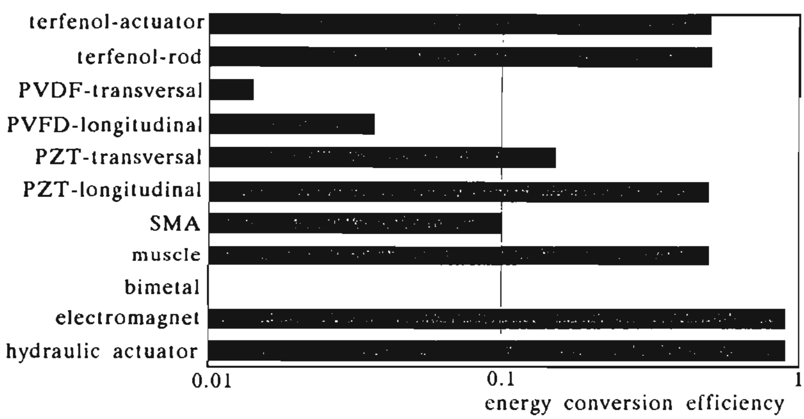


Fig. 6.

state is achieved at the point $C$ (Fig.4) and the useful work is illustrated as the area below the line $AC$. The maximum useful work is available in the case, when mechanical compliance of the actuator and the structure are the same.

The actuator strain which can be converted into the strain in a host structure depends on the way the actuator is placed in the structure, which influences the stress distribution both in the structure and actuator.

Different assumptions of stress distribution in the actuator and the structure are accepted. For beams, plates and shell-like structures, if an actuator is mounted on the surface, it is usually assumed that the strain distribution is uniform in the actuation material and linear throughout the host structure. Other more complex assumption states that the strain is linearly distributed throughout the actuator and host structure, regardless of the actuator is mounted on the surface or embedded in the structure.

For the surface mounted actuators, a bonding layer between the actuator and structure should be included into analysis. To identify a shear lag resulting from a layer between the actuator and the structure, a local shearing in the host structure should be modelled precisely for calculating the strain fields near the active elements.

## 6. Sensor/actuator synthesis

It seems that a device which would perform the sensor and actuation function simultaneously has not been built yet. The main difficulty in its design emerges from properties of existing materials. The piezoelectric (electroscrictive) phenomena seem to be most suitable effects for the sensor/actuator integration activity. For the actuating purposes electrorheological fluids are good candidates. These materials will be analysed in next ssections.

## 7. Piezoelectric materials

The piezoelectric effect was discovered in 1880 by Curie brothers Jacques and Pierre in quartz. In 1968 Kawai (Japan) discovered the piezoelectric effect in polymers (polyvinylide fluoride, PVFD). Commercial piezofilms appeared in 1981.

The name of the effect comes from Greek "piezo" which means pressure. The direct piezoelectric effect is to produce electric potential, when the material is mechanically stressed. There is also the inverse piezoelectric effect, when under the applied electric field the material changes its dimensions.

Piezoelectric materials can be classified as: *natural piezoelectrics* (cane sugar, quartz, Rochelle salt), *piezoceramics* (PZT-lead-zirkonate-titanate, PLZT-lead-lanthanum-zirkonate-titanate, PMN-lead-magnesium-niobate), *piezopolimers* (or piezofoils, PVDF-polyvinylidene fluroide) and *piezogels* (polyacrylamide with barium titanate).

In *ceramics* the piezoelectric effect comes from the rearrangement of spatial distribution and orientation of electric domains under the electric field. The mechanical and electrical properties have orthotropy.

Piezoceramics have large dynamic range of frequencies, quick (almost instantaneous) response to applied voltage, and potential large force authority. Their disadvantages concern durability, and possibility of quick ageing due to the sensitivity to temperature and radiation. The piezoceramic material is brittle with low tensile strain and susceptibility to fatigue breakdown under a high cycle load. It has low energy density and exhibits nonlinear hysteresis effects (Fig.7). To activate it, high voltage is needed which gives weight to supplying equipment. There is the possibility to rise the temperature of material due to electrical power supplied.

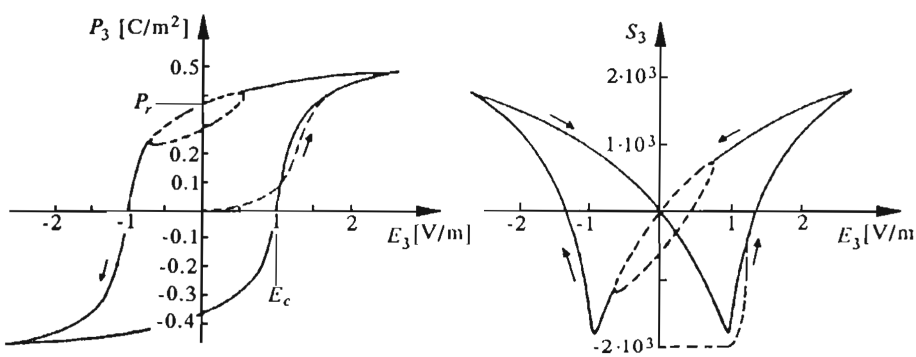


Fig. 7.

Depolarisation of piezoceramics occurs (cf Janocha and Jendritza (1993)):

- mechanically at pressure $20 \div 100$ N/mm (max. strain 0.005% in 3 direction and 0.025% in 1 or 2 direction)

- thermally at the Curie temperature of $120 \div 380$°C.

Working voltage is about 500 V/mm with the operating range: from −1 kV/mm (depolarisation) to 2 kV/mm (saturation).

In *piezopolimers* the polarisation concerns macromolecule chains. The effect is stable up to 90°C. Due to low mechanical strength prospective application of piezopolimers is to sensing or damping elements.

To obtain *piezogels*, polyacrylamide and barium titanate are used in the form of fine powder in 1:1 weight ratio. In the polyacrylamide of other kind, the ingredients are polyacrylamide barium titanate and ferrite in ratio 1:1:0.5 by weight. With the addition of water, the hygroscopic polyacrylamide becomes a solgel with heterogenerously dispersed barium titanate particles. The result is a nonlinear dielectric whose electric polarisation can be significantly controlled by application of the external electric stimulus. The elastic behaviour of the gel with an initially imposed constant electric polarisation is changed dynamically by applying a superimposed alternating electrical field. The stimulation can be done by current or by voltage.

The basic properties of different piezoelectric materials are given in Table 2 (cf Cross (1992))

**Table 2**

| | PZT | PVDF |
|---|---|---|
| $d_{33} \cdot 10^{-10}$ [m/V] | 3.6 | −0.33 |
| $d_{31} \cdot 10^{-10}$ [m/V] | −1.9 | 0.23 |
| $d_{32} \cdot 10^{-10}$ [m/V] | | 0.3 |
| $d_{15} \cdot 10^{-10}$ [m/V] | | 0.03 |
| $g_{33} \cdot 10^{-3}$ [Vm/N] | | −0.339 |
| $g_{31} \cdot 10^{-3}$ [Vm/N] | 11 | 0.126 |
| $e \cdot 10^{-10}$ [F/m] | 150 | 1.062 |
| $K_3$ | 2000 | 12 |
| $V_c \cdot 10^6$ [V/m] | | 1 |
| $K_{33}$ | | 19 |
| $K_{31}$ | 0.35 | 12 |
| $K_p$ | 0.6 | |
| $\rho \cdot 10^3$ [kg/m$^3$] | 7.6 | 1.78 |
| $E_3 \cdot 10^{10}$ [N/m$^2$] | 6.3 | 0.2 |
| $E_1 \cdot 10^{10}$ [N/m$^2$] | | 0.2 |
| $G \cdot 10^{10}$ [N/m$^2$] | 2.6 | 0.077 |
| $T_c$ [°C] | 360 | 90 |

The coefficients used to describe properties of piezoelectric materials (given in Table 2) usually have two indices defining the directions of electrical field polarisation and mechanical load. The first index defines the direction of electric field and the second index the direction of mechanical load (force) in orthogonal coordinate system axes of which are defined by numbers. The 3-axis is usually along the direction of polarisation field. The index 5 describes the shear force. The superscripts usually concern quantities measured as: $T$ – constant stress, mechanically free, $E$ – constant field, short circuit, $D$ – constant electrical displacement, open circuit, $S$ – constant strain, mechanically clamped.

Charge (strain) coefficient $d_{ij}$ is the ratio of the electric charge generated per unit area to the force applied per unit area. The units are [C/m] or [m/V]. The strain induced in a free piezoelectric due to a voltage across the thickness is calculated as

$$\varepsilon_{ij} = d_{ij}\frac{V}{t} \tag{7.1}$$

where
$V$ – voltage
$t$ – thickness.

Voltage coefficient $g_{ij}$ is the ratio of the electrical field produced to the mechanical stress applied [Vm/N]. The voltage obtained for a given load is calculated as

$$V = g_{ij}\frac{F}{t} \tag{7.2}$$

where $F$ is the applied load.

Below the resonant frequency piezoelectric material acts as capacitor, so voltage and charge coefficients are related by the dielectric constant $K_i$ measured relatively to a vacuum, so

$$d_{ij} = K_i\varepsilon_0 g_{ij} \tag{7.3}$$

The value of dielectric constant of a vacuum is $\varepsilon_0 = 8.85 \cdot 10^{-12}\,\mathrm{F/m}$.

Coercive field $V_C$ is the voltage potential per unit thickness required to repole piezoelectric.

Curie temperature $T_C$ is the temperature at which the piezoelectric properties of material disappear.

Coupling coefficient $K_{ij}$ [%] is the electromechanical coupling coefficient defined above. In this case it describes conversion of mechanical energy into the electric one. Subscripts denote the relative directions of electrical and mechanical quantities and the kind of motion involved.

Elastic modulus $E_i$ (Young modulus) is usually different for electrodes opened and for electrodes short circuited (lower in the second case).

There are various "classical" applications of piezoelectric materials in the field of electronic, medicine, computer technology, sport equipment. For application to adaptive structures, piezoelectric elements are considered to be directly mounted or embedded into structure. The difficulties can emerge from the differences between mechanical properties of piezoelectrics and host structure material.

## 8. Electrorheological (ER) fluids

Electrorheological fluids belong to a class of colloidal suspensions of which global characteristics can be controlled by the imposition of an appropriate external electric field upon the fluid domain. Depending on the strength of applied field, the ER fluid changes its viscosity and transfers from fluid to gel and eventually solid state. This transformation happens within hundredths of second. The first ER fluid was patented by W.M. Winslow in 1947.

The ER fluid is composed of solute, solvent, and additives; i.e., activators and dispersing agents. Solute is a dielectric fluid, usually of the oil type. Solvent consists of small particles size $1 \div 100\,\mu$m which make about $30 \div 50\%$ of fluid. Activator is added to intensify the electrorheological effect. Dispersing agent prevents adhesion of particles. Usually the additive is water with some type of alcohol or detergents. The components of some ER fluids are given in Table 3.

**Table 3.** Components of ER fluids

| Solute | Solvent | Additive |
|---|---|---|
| kerosene | silica | water and detergents |
| silicone oils | sodium carboxsymethyl | water |
| cellulose | | |
| olive oil | gelatine | none |
| mineral oil | aluminum dihydrogen | water |
| transformer oil | carbon | water |
| dibuthyl sebacate | iron oxide | water and surfactant |
| mineral oil | lime | none |
| p-xylene | piezoceramics | water and glycerol |
| silicone oil | copper phthalocyanine | none |
| transformer oil | starch | none |
| polychlorinated biphenyls | sulphorpropyl dextran | water and sorbitan |
| hydrocarbon oil | zeolite | none |

The electrorheological properties result from different polarisation of dispersed particles and the host fluid. If there is no electrical field, the particles are randomly distributed in the fluid. When the electric field is imposed the separation of electrical charge of particles occurs and the particles become electrical dipoles. They organise themselves into chains and then join into columns. The change of particle distribution influences mechanical properties of the fluid.

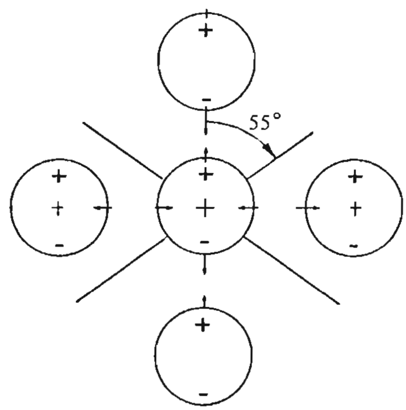


Fig. 8.

The mechanism of chains initiation is explained in Fig.8. The particles which are in a vertical row attract themselves. Particles which are in a horizontal row repel themselves. They can move out, and find themselves in the attraction zone of vertical row and eventually join the chain. The intensity of chain growing depends on the difference between polarizability of the host fluid and particles.

The formation of columns composed of chains was verified experimentally in the silicon oil with glass particle of 40 $\mu$m diameter. The columns in this case have the structure of spatially centred, tetragonal net. The mechanical strength of the fluid increases when the columns become thicker, so it can be expected that the fluid strength will increase during electric field is active.

Activators gather on the surface of solvent particles. Due to some kind of chemical reactions in the activator, they cause the electric charge of particles to increase and make the chains stronger.

Brownian motions, intensified, for instance due to the heat energy supplied, can have various influence of fluid structure. They intensify the motion of particles, which can prevent organising them in chains or can make more particles enter the attraction zone of others, augmenting of growing the chains and organising of columns.

The mechanical properties of the fluid depend also on the polarizability of the host fluid. Application of the electrical field can cause a movement of particles towards the electrodes, which can brake the chains of solvent particles. The greater solvent particles, the higher electrical charge is produced, but this favourable effect can be distorted as greater particles can separate under the gravitational force suppressing the ER effect.

Two explanations of shear mechanism in ER fluids are in Fig.9. One explains the changing the shear stress by breaking the chains of particles, the second by shortening their length and rearranging.

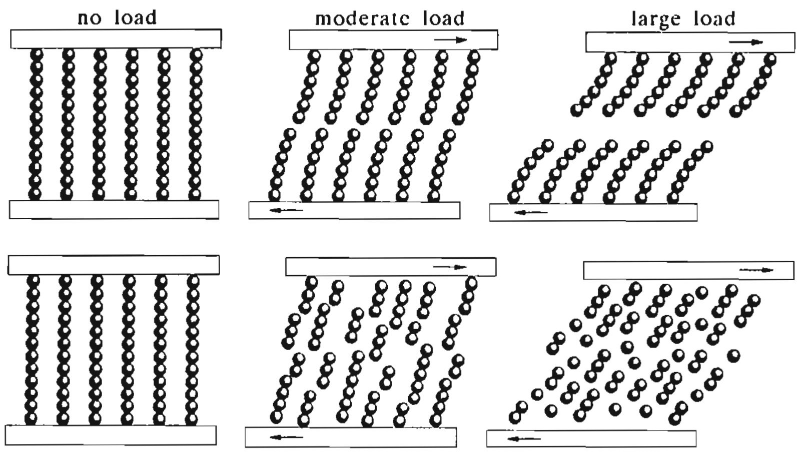


Fig. 9.

The ER fluid properties are non-linearly dependent on temperature, control field amplitude, field frequency and shear rate. They also depend on the components of the ER fluid. It is difficult to draw any conclusions theoretically, so the experimental investigations are essential at the present state-of-the-art.

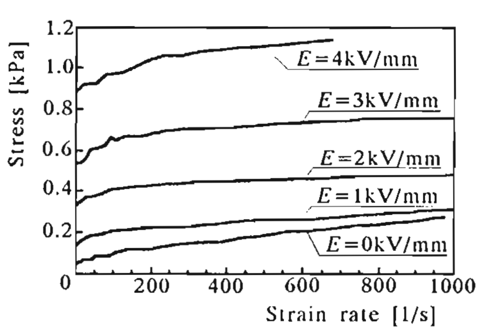


Fig. 10.

The examples of properties of unspecified ER fluid obtained from experimental measurements in viscometer with rotating cylinder are given in Fig.10 (cf Kamath and Wereley (1995)), where the shear stress as a function of shear rate is presented. In this case the constant electric field has been applied. Under shear loads, without and for low control field, the ER fluid behaves like Newtonian fluid. For higher intensity of electric field a yield point appears (depending on the voltage), beyond which the fluid can be modelled as the Maxwell type fluid or linear viscoelastic body (ideal spring and ideal damping element). For higher fields it behaves as the viscoelastic-plastic fluid according to the Bingham model (parallel connection of ideal damping element) and finally as the ideally plastic substance (St.Venant element).

The problems with application of electrorheological fluids rise from the fact that:

- In solid state low stress can be carried, ER fluids are too soft
- Friction effects between fluid and structure can occur in the fluid state
- In higher temperatures there is the possibility separation of chains
- Mechanical properties are time dependent.

## 9. Conclusions

The concept of smart (intelligent) structures stems from the idea to imitate the behaviour of living creatures to react in a reasonable way to the changes in the environment. This idea can be realised as intelligent materials, intelligent passive systems and intelligent active systems. In mechanical engineering the intelligent active systems are investigated in the form of adaptive structures. Putting into practice the concept of multitask sensor/actuator device can make the adaptive structures more efficient. Due to data transmitting and processing the active elements which couple mechanical/electrical effects are the most suitable for this application. Among different materials piezoelectrics and electrostrictives seem to be the most feasible for this purpose.

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## Przegląd możliwości zastosowania materiałów wzbudzanych elektromechanicznie w czujnikach i wzbudnikach układów typu "smart structure"


Streszczenie

W pracy przedstawiono koncepcję układów typu "smart structure". Dokonano analizy warunków jakie powinny spełniać elementy aktywne i pomocnicze tych układów. Przeanalizowano własności materiałów, które mogłyby zostać wykorzystane w układach typu "smart structure". Szczególną uwagę zwrócono na materiały piezoelektryczne oraz płyny elektrologiczne.


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