A History of Piezoelectricity

DISCOVERY AND INSIGHTS - 1880 - 1882

The first experimental demonstration of a connection between macroscopic piezoelectric phenomena and crystallographic structure was published in 1880 by Pierre and Jacques Curie. Their experiment consisted of a conclusive measurement of surface charges appearing on specially prepared crystals (tourmaline, quartz, topaz, cane sugar and Rochelle salt among them) which were subjected to mechanical stress. These results were a credit to the Curies' imagination and perseverance, considering that they were obtained with nothing more than tinfoil, glue, wire, magnets and a jeweler's saw.

In the scientific circles of the day, this effect was considered quite a "discovery," and was quickly dubbed as "piezoelectricity" in order to distinguish it from other areas of scientific phenomenological experience such as "contact electricity" (friction generated static electricity) and "pyroelectricity" (electricity generated from crystals by heating).

The Curie brothers asserted, however, that there was a one-to-one correspondence between the electrical effects of temperature change and mechanical stress in a given crystal, and that they had used this correspondence not only to pick the crystals for the experiment, but also to determine the cuts of those crystals. To them, their demonstration was a confirmation of predictions which followed naturally from their understanding of the microscopic crystallographic origins of pyroelectricity (i.e., from certain crystal asymmetries).

The Curie brothers did not, however, predict that crystals exhibiting the direct piezoelectric effect (electricity from applied stress) would also exhibit the converse piezoelectric effect (stress in response to applied electric field). This property was mathematically deduced from fundamental thermodynamic principles by Lippmann in 1881. The Curies immediately confirmed the existence of the "converse effect," and continued on to obtain quantitative proof of the complete reversibility of electro-elasto-mechanical deformations in piezoelectric crystals.

A LABORATORY CURIOSITY - A MATHEMATICAL CHALLENGE - 1882 - 1917

At this point in time, after only two years of interactive work within the European scientific community, the core of piezoelectric applications science was established: the identification of piezoelectric crystals on the basis of asymmetric crystal structure, the reversible exchange of electrical and mechanical energy, and the usefulness of thermodynamics in quantifying complex relationships among mechanical, thermal and electrical variables.

In the following 25 years (leading up to 1910), much more work was done to make this core grow into a versatile and complete framework which defined completely the 20 natural crystal classes in which piezoelectric effects occur, and defined all 18 possible macroscopic piezoelectric coefficients accompanying a rigorous thermodynamic treatment of crystal solids using appropriate tensorial analysis. In 1910 Voigt's "Lerbuch der Kristallphysik" was published, and it became the standard reference work embodying the understanding which had been reached.

During the 25 years that it took to reach Voigt's benchmark, however, the world was not holding its breath for piezoelectricity. A science of such subtlety as to require tensorial analysis just to define relevant measurable quantities paled by comparison to electro-magnetism, which at the time was maturing from a science to a technology, producing highly visible and amazing machines. Piezoelectricity was obscure even among crystallographers; the mathematics required to understand it was complicated; and no publicly visible applications had been found for any of the piezoelectric crystals.

The first serious applications work on piezoelectric devices took place during World War I. In 1917, P. Langevin and French co-workers began to perfect an ultrasonic submarine detector. Their transducer was a mosaic of thin quartz crystals glued between two steel plates (the composite having a resonant frequency of about 50 KHz), mounted in a housing suitable for submersion. Working on past the end of the war, they did achieve their goal of emitting a high frequency "chirp" underwater and measuring depth by timing the return echo. The strategic importance of their achievement was not overlooked by any industrial nation, however, and since that time the development of sonar transducers, circuits, systems, and materials has never ceased.

FIRST GENERATION APPLICATIONS WITH NATURAL CRYSTALS - 1920 - 1940

The success of sonar stimulated intense development activity on all kinds of piezoelectric devices, both resonating and non-resonating. Some examples of this activity include:

Megacycle quartz resonators were developed as frequency stabilizers for vacuum-tube oscillators, resulting in a ten-fold increase in stability.

A new class of materials testing methods was developed based on the propagation of ultrasonic waves. For

the first time, elastic and viscous properties of liquids and gases could be determined with comparative ease, and previously invisible flaws in solid metal structural members could be detected. Even acoustic holographic techniques were successfully demonstrated.
Also, new ranges of transient pressure measurement were opened up permitting the study of explosives and internal combustion engines, along with a host of other previously unmeasurable vibrations, accelerations, and impacts.

In fact, during this revival following World War I, most of the classic piezoelectric applications with which we are now familiar (microphones, accelerometers, ultrasonic transducers, bender element actuators, phonograph pick-ups, signal filters, etc.) were conceived and reduced to practice. It is important to remember, however, that the materials available at the time often limited device performance and certainly limited commercial exploitation.

SECOND GENERATION APPLICATIONS WITH PIEZOELECTRIC CERAMICS - 1940 -1965

During World War II, in the U.S., Japan and the Soviet Union, isolated research groups working on improved capacitor materials discovered that certain ceramic materials (prepared by sintering metallic oxide powders) exhibited dielectric constants up to 100 times higher than common cut crystals. Furthermore, the same class of materials (called ferroelectrics) were made to exhibit similar improvements in piezoelectric properties. The discovery of easily manufactured piezoelectric ceramics with astonishing performance characteristics naturally touched off a revival of intense research and development into piezoelectric devices.

The advances in materials science that were made during this phase fall into three categories:

1. Development of the barium titanate family of piezoceramics and later the lead zirconate titanate family
2. The development of an understanding of the correspondence of the perovskite crystal structure to electro-mechanical activity
3. The development of a rationale for doping both of these families with metallic impurities in order to achieve desired properties such as dielectric constant, stiffness, piezoelectric coupling coefficients, ease of poling, etc.

All of these advances contributed to establishing an entirely new method of piezoelectric device development - namely, tailoring a material to a specific application. Historically speaking, it had always been the other way around.
This "lock-step" material and device development proceeded the world over, but was dominated by industrial groups in the U.S. who secured an early lead with strong patents. The number of applications worked on was staggering, including the following highlights and curiosities:

Powerful sonar - based on new transducer geometries (such as spheres and cylinders) and sizes achieved with ceramic casting.
Ceramic phono cartridge - cheap, high signal elements simplified circuit design
Piezo ignition systems - single cylinder engine ignition systems which generated spark voltages by compressing a ceramic "pill"
Sonobouy - sensitive hydrophone listening/radio transmitting bouys for monitoring ocean vessel movement
Small, sensitive microphones - became the rule rather than the exception
Ceramic audio tone transducer - small, low power, low voltage, audio tone transducer consisting of a disc of ceramic laminated to a disc of sheet metal
Relays - snap action relays were constructed and studied, at least one piezo relay was manufactured

It is worth noting that during this revival, especially in the U.S., device development was conducted along with piezo material development within individual companies. As a matter of policy, these companies did not communicate. The reasons for this were threefold: first, the improved materials were developed under wartime research conditions, so the experienced workers were accustomed to working in a "classified" atmosphere; second, post war entrepreneurs saw the promise of high profits secured by both strong patents and secret processes; and third, the fact that by nature piezoceramic materials are extraordinarily difficult to develop, yet easy to replicate once the process is known.

From a business perspective, the market development for piezoelectric devices lagged behind the technical development by a considerable margin. Even though all the materials in common use today were developed by 1970, at that same point in time only a few high volume commercial applications had evolved (phono cartridges and filter elements, for instance). Considering this fact with hindsight, it is obvious that while new material and device developments thrived in an atmosphere of secrecy, new market development did not - and the growth of this industry was severely hampered.

JAPANESE DEVELOPMENTS - 1965 - 1980

In contrast to the "secrecy policy" practiced among U.S. piezoceramic manufacturers at the outset of the industry, several Japanese companies and universities formed a "competitively cooperative" association, established as the Barium Titanate Application Research Committee, in 1951. This association set an organizational precedent for successfully surmounting not only technical challenges and manufacturing hurdles, but also for defining new market areas.

Beginning in 1965 Japanese commercial enterprises began to reap the benefits of steady applications and materials development work which began with a successful fish-finder test in 1951. From an international business perspective they were "carrying the ball," i.e., developing new knowledge, new applications, new processes, and new commercial market areas in a coherent and profitable way.

Persistent efforts in materials research had created new piezoceramic families, which were competitive with Vernitron's PZT, but free of patent restrictions. With these materials available, Japanese manufacturers quickly developed several types of piezoceramic signal filters, which addressed needs arising in television, radio, and communications equipment markets; and piezoceramic igniters for natural gas/butane appliances.

As time progressed, the markets for these products continued to grow, and other similarly valuable ones were found. Most notable were audio buzzers (smoke alarms, TTL compatible tone generators), air ultrasonic transducers (television remote controls and intrusion alarms) and SAW filter devices (devices employing Surface Acoustic Wave effects to achieve high frequency signal filtering).

By comparison to the commercial activity in Japan, the rest of the world was slow, even declining. Globally, however, there was still much pioneering research work taking place as well as device invention and patenting.

SEARCH FOR HIGH VOLUME MARKETS - 1980 - Present

The commercial success of the Japanese efforts has attracted the attention of industry in many other nations and spurred a new effort to develop successful piezoceramic products. If you have any doubts about this, just track the number of piezo patents granted by the U.S. Patent Office every year - there has been a phenomenal rise. Another measure of activity is the rate and origin of article publication in the piezo materials/applications area - there has been a large increase in publication rate in Russia, China and India.

Solid state motion is presently the single most important frontier. The technical goals of the frontier are to obtain useful and reasonably priced actuators which are low in power and consumption and high in reliability and environmental ruggedness; or, more simply stated, "solenoid replacements," or "electrostatic muscles."

The search for perfect piezo product opportunities is now in progress. Judging from the increase in worldwide activity, and from the successes encountered so far in the last quarter of this century, important economic and technical developments seem certain.

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Piezo Systems, Inc.
617-547-1777 Fax: 617-354-2200
Cambridge, MA 02139 USA

Purchasing

Do you have a minimum order?
Do you have free samples?
Do you have university/educational discounts?
What methods of payment do you accept?

Physics

Why is there piezoelectricity?
What is electric field?
What is strain?
What is elastic modulus (or Young's Modulus)?
What is tensile strength?
What is poling/depoling in piezoceramic materials?
What is damping?
Can piezoceramic actuators be used at cryogenic temperatures?
What is the pyroelectric effect?

Handling & Preparation

How do I cut up a sheet of piezoceramic into the size I want?
How do I bond/attach piezoceramic sheet to a structure like an aluminum beam?
Can I just use "superglue?"
Are piezoceramic sheets fragile and easy to break?
How do I make electrical contact to the side of the piezoceramic that is bonded down?
How do I attach wire leads to the piezoceramic?
How far can I stretch a sheet before it breaks?
How far can I bend a bimorph before it breaks?

PURCHASING QUESTIONS

Q. Do you have a minimum order?
A. No minimum order. If it is in the catalog you can buy just one.

Q. Do you have free samples?
A. No. There is a large selection of piezoceramic materials and an even larger number of part sizes and shapes appropriate for piezo applications. Supplying samples on request would be prohibitive.

Q. Do you have university/educational discounts?
A. We have volume discounts only.

Q. What methods of payment are accepted by Piezo Systems?
A. Purchase orders from universities and large institutions; personal and corporate checks; Master Card and Visa; and COD. Accounts may be opened with banking information and three vendor references; terms are net 30 days.

PHYSICS QUESTIONS

Q. Why is there piezoelectricity?
A. Because some atomic lattice structures have as an essential unit (or "cell") a cubic or rhomboid cage made of atoms, and this cage holds a single semi-mobile ion which has several stable quantum position states inside the cell. The ion's post ion state can be caused to shift by either deforming the cage (applied strain) or by applying and electric field. The coupling between the central ion and the cage provides the basis for transformation of mechanical strain to internal electric field shifts and vice versa.

Q. What is electric field?
A. An electric field is always associated with the presence of electric charges. It fills the space around the charge and is the mechanism of interaction between charges. A test particle with small known charge (Q) placed near a charge concentration will experience an accelerating force (F) due to the field. The value of the electric field (E) at that location is the ratio F/Q (a vector).

Q. What is strain?
A. When a solid object like a rod of length (L) is stretched to a new length (L + delta L), the strain in the rod is defined as the ratio (delta L)/(L). This is a dimensionless measure of stretching or compression often stated as "inches per inch", "millimeters per meter", or "microns per meter (microstrain)" for convenience of visualization.

Q. What is elastic modulus (or Young's modulus) ?
A. A material property of all elastic solids, Young's modulus (Y) is used to describe "stiffness" of materials. When rod or plate of cross section (A) and length (L) is pulled with force (F) resulting in an elongation (delta L), the Young's modulus can be computed as follows: Y = (L/A)*(F/deltaF)
In piezo applications Y is frequently used to estimate the equivalent spring constant of a rod or a plate of material (i.e. that quantity (F/deltaF) that is in contact with a piezo actuator).

Q. What is tensile strength?
A. Tensile strength is the stress (measured in Newtons/m^2 or psi) at which a sample of solid material will break from tension.

Q. What is poling/depoling in piezoceramic materials?
A. The piezoelectric property of ceramics does not arise simply from its chemical composition. In addition to having the proper formulation the piezoceramics must be subjected to a high electric field for a short period of time to force the randomly oriented micro-dipoles into alignment. This alignment by application of high voltage is called "poling". At a later time, if an electric field is applied in the opposite direction it exerts a "dislodging stress" on the micro-dipoles. Low level applied fields result in no permanent change in the polarization (it bounces back upon removal). Medium fields result in partial degradation of the polarization (with partial loss of properties). High applied fields result in repolarization in the opposite direction.

Q. What is damping?
A. 'Damping' is the term used for the general tendency of vibrating materials or structures to lose some elastic energy to internal heating or external friction.

Q. Can piezoceramic actuators be used at cryogenic temperatures?
A. Yes. All piezo actuators continue to function right on down to zero degrees Kelvin. This may seem counter-intuitive at first; however, you must remember that the basis for the piezoelectric effect is inter-atomic electric fields, and electric fields are not affected by temperature at all. Quantitatively, the piezo coupling of most common piezoceramics does decrease as temperature drops. At liquid helium temperatures, the motion of most materials drops to about half that measured at room temperature.

Q. What is the pyroelectric effect?
A. The tendency of some materials to exhibit a change in internal electrical polarization state in response to a change in

temperature. If the materials are equipped with electrodes on two surfaces, a voltage will arise between the electrodes in response to temperature shifts.

HANDLING & PREPARATION QUESTIONS

Q. How do I cut up a sheet of piezoceramic into the size I want?
A. Ceramic is best cut using a special diamond saw. Small prototype parts can be cut from piezoceramic sheet stock by using a razor blade and a straight edge to score the piezo surface and then making a controlled break. Even with practice this method does not yield straight-sided parts or repeatable cuts. Use at your own risk.

Q. How do I bond/attach piezoceramic sheet to a structure like an aluminum beam?
A. Good quality long lasting bonds can be achieved with a number of adhesives and are invariably determined by the application. We suggest that you contact several epoxy manufacturer and discuss the application, being sure to include:

1. The metal surfaces to be joined
2. Temperature of operation
3. Any unusual shear stress requirements

Q. Can I just use 'superglue'?
A. Good quality temporary bonds may be made with cyanoacrylate (e.g. "super glue"). An added benefit of cyanoacrylate bonds is that the bond easily achieves electrical contact. The length of time the bond will last will be application dependent, from seconds to years. For a short time the performance of the part is very close to that achieved using the best bonds, which makes it useful for exploratory work.

Q. Are piezoceramic sheets fragile and easy to break?
A. Yes, they are very fragile! Single sheet piezoceramic should always be handled with great care. Dropping them almost always results in a shattered part.

Q. How do I make electrical contact to the side of the piezoceramic that is bonded down?
A. The most common method is to make a conductive bond between a metal substrate and the piezo part. Then one electrical lead is attached to the substrate, and one to the outward face of the piezoceramic sheet. In cases where a conductive bond is not possible (i.e. when the substrate is glass or plastic), a wire must be soldered to the "down" side of the ceramic at some location and a corresponding 'dish', 'cutout', or 'overhang' must be used to allow room for the wire when bonding the piezo sheet to the substrate.

Q. How do I attach wire leads to the piezoceramic?
A. All of the PSI piezoceramic parts come with a thin metallic electrode already on the ceramic. Wire leads can be soldered (use ordinary 60/40 resin core solder) anywhere on the electrode to suit the application/experiment. Most PSI ceramics have nickel electrodes and require the use of an additional liquid flux for uniform results.

Q. How far can I stretch a sheet before it breaks?
A. A sheet can be stretched to a strain of approximately 500 microstrain (micrometers per meter) in regular use. Higher surface strains can be achieved, but the statistics of survival get worse. Proceed with caution.

Q. How far can I bend a bimorph before it breaks?
A. If a bender is cantilevered to a distance of one inch, the tip can be pushed a distance of 0.055 inch before the bender is heard to "snap".

APPLICATION QUESTIONS

Q. What is the frequency limit of piezoceramic sheet?
A. There is no inherent frequency limit for a piezoceramic sheet. In practice the frequency limits of signal applications are usually determined by resonances associated with the shape and/or size of the transducer design. A typical sheet of PSI-5A material has a thickness mode vibration in the neighborhood of 13 MHz and a planar dilatation mode at around 14 kHz. At ultrasonic frequencies large surface area parts draw considerable current and resistive heating of the electrodes becomes the limiting factor.

Q. How do I hook up a bender element so it works?
A. This depends on how the two piezoceramic plates are polarized. If the plates are poled for series operation (i.e. poling arrows anti-parallel) then a wire is attached to each of the outer electrodes of the bender. ±180 volts is then applied between the wires. If the plates are poled for parallel operation (i.e. poling arrows parallel, pointing in the same direction) then the two outer electrodes are shorted together forming one lead, and a wire is attached to the center metal shim forming the second lead. ±90 volts may be applied between these leads. (See Tutorial)

Q. What is the highest voltage that I can drive a piezoceramic sheet to?
A. For low frequency operation (0 to 5 kHz) a conservative recommendation for applied bi-polar voltage for a single sheet of PSI-5A ceramic is ±90 volts. Voltage applied in the poling direction only can be raised up to 250 volts. Use caution!

Q. How much mechanical power can I get out of one sheet?
A. In theory, one standard PSI-5A sheet (1.5" x 2.5" x .0075") used as an "extender" can do .00035 joules of work on the outside world in a quasistatic cycle (i.e. a slowly executed sinusoidal cycle). When operated just under its first longitudinal resonance of 15 kHz, the theoretically available output power from the sheet would be around 5 watts. In practice it is difficult to collect more than 10% of this work. Resonant designs can be considerably more efficient.

Q. How much electrical power can I get out of one sheet?
A. Assuming that we stretch a PSI-5A 1.5" x 2.5" x .0075" sheet to ±500 microstrains quasistatically at a frequency just below its fundamental longitudinal resonance of 15 kHz, and that we collect 100% of the stored electrical energy at its height twice per cycle we would get approximately 9 watts of electrical power from the sheet. The mechanical energy input under these assumptions would be in excess of 100 watts. Resonant designs can be considerably more efficient.

Q. Can piezoceramic sheet be used to pick up vibrations in machinery?
A. Yes. Almost any size or shape of piezoceramic element will give off a measurable signal when fastened somewhere on machinery. See 'strain gages'.

Q. Can piezoceramic sheet be used as a strain gage?
A. Yes. Piezoceramic is one of the most sensitive strain gage technologies existent, and it is the only one which is self-powered.

Q. How repeatable are the voltage outputs from a piezo strain gage?
A. Outputs from piezoceramics which are 'following' surface vibrations are generally very repeatable and stable. If the sensor is initially calibrated it can be trusted for years of accurate service.

Q. How repeatable is the motion of a piezo actuator?
A. A piezoceramic actuator which is cyclically driven at a constant cycle time between the same two points will perfectly repeat its path every time. However, if the cycle time or either endpoint is changed, hysteresis and creep effects cause non-repeatable motions.

Q. What are the effects of temperature on piezoceramic transducers?
A. Temperature changes cause a voltage to appear across the electrodes of any piezo transducer. This is due to the pyroelectric properties of piezoceramic. Temperature also affects every property of piezoceramics (elastic, dielectric and piezoelectric coupling). There is no general trend. Each dependence must be looked up or better yet measured in the context of your experiment. (See Tutorial).

Q. What is the resonant frequency of a piezoceramic sheet?
A. There is no one 'resonance'. There are many resonances. The number of them and their location in the frequency spectrum depend on the shape and thickness of the part. For a flat sheet as shipped, three obvious resonances are the ones associated with the length, width, and thickness of the sheet.

Q. Can I drive a piezo transducer with a 'square wave' ?
A. The answer is application dependent. We always say "If you can hit your transducer with a hammer you can drive it with a square wave".

PIEZO TECHNOLOGY QUESTIONS

Q. Where in everyday life do I find piezo devices?
A. All 'watch beepers' are piezoceramic audio transducers, most battery operated smoke detector alarms, fish finders, some cigarette lighters, many gas grill igniters.

Q. How are piezoceramics used in vibration cancellation?
A. Two piezoceramic sheets can be bonded directly to the surface of a structure (such as a strut, or beam) close to one another at a site where unwanted bending occurs. One is used to sense surface strain. The output from the strain sensor is fed into a "smart box" (which can be anything from a simple op-amp to an elaborate DSP (Digital Signal Processing) computer) which in turn controls a power amplifier that drives the other piezoceramic sheet. Ideally the resulting mechanical contractions of the second piezo sheet inject a vibration into the structure which is equal and opposite of the initially detected one so that the net vibration is canceled.

Q. Will piezo technology replace magnetic technology?
A. No. Fundamentally, magnetic technology is based on a force which arises 'at a distance', without physical contact. Piezo technology is based on physical contact and elastic coupling. On an application by application basis one is usually better than the other. Take solenoid actuators as an example. Piezo actuators can be designed to replace almost any solenoid but they always come out bulkier and often heavier so it is unlikely that full scale replacement will ever occur. On the other hand, they always take much less power to operate; so in any application where power consumption is an issue, piezo actuators are preferred.

Recommended Reading About Piezoelectricity

If you haven't found enough information about piezoelectricity online, we have come up with the following publications to further your knowledge. If you know of any materials that are not listed here but should be, please mail to us the author, full title, publisher, and year published .

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Thanks to all who continue to add to this resource.

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PIEZO SYSTEMS, INC.
Cambridge, Massachusetts, U.S.A.
Tel: 617-547-1777 Fax: 617-354-2200

INTRODUCTION TO BENDING TRANSDUCERS

Bending Motors

The piezoceramic bender is a versatile low power electro-mechanical transducer. As a motor, electrical excitation (voltage and current) leads to a mechanical response (motion and force).

The application of an electric field across the two layers of a bender causes one layer to expand while the other contracts. The net result is a curvature much greater than the length or thickness deformation of the individual layers.

A simple bender is actually a nine layer device consisting of four electrode layers, two piezoceramic layers, and a center shim. In order to produce laminated parts with consistently high performance, it is necessary to monitor the crucial electro-mechanical properties of individual sheets utilized for multilayer parts. Without such attention, parts will show wide variability in performance, thermal distortion, and lamination integrity. Piezo Systems ships parts to performance specifications, not merely to dimensional tolerance.

Bending Generators

As a generator (or sensor), mechanical excitation (motion and force) leads to an electrical response (voltage and current).

When a piezoceramic bender is forced to flex, one layer will be in tension while the other is in compression. The stresses in each layer will produce electrical outputs which will simply be the summation of the outputs in each layer.

Benders may be used as strain gauges for easy and rapid determination of the characteristics of dynamic strains in structures. They exhibit extremely high sensitivities, in the order of 50 times that of wire strain gauges, and are small enough that on most structures they will not materially affect the vibrational characteristics of the structure.

"Smart" Devices

Piezo devices are ideal for use as "smart" devices. That is, part of the piezo volume is able to sense its surroundings and the other part is able to respond as necessary. Each layer of a bender may be used for each purpose.

Bending Configurations

The common bending configurations, piezoceramic materials, bender thicknesses, and methods of mounting are shown below.

CANTILEVER CONFIGURATION

SIMPLE BEAM CONFIGURATION

"S" BEAM CONFIGURATION

Piezoceramic Material

Typically, PSI-5A piezoceramic is the first choice of most designers. 5A is the most temperature insensitive and offers the widest temperature range. PSI-5A achieves motion similar to PSI-5H if higher voltage is available. PSI-5H is recommended only when low voltage operation is essential.

Center Shim Materials

Center shim materials are available for enhancing strength (stainless steel), thermal endurance, non-magnetism (brass), and economy (brass). Specially designed center shims promote unique composite properties.

Series & Parallel Operation

Series operation refers to a bender with voltage applied across both piezoceramic layers. It is a two electrode device. Parallel operation refers to a bender with voltage applied across each ceramic layer individually. It is a three electrode device and the metallic center shim must be accessed. A bender polarized for series operation requires twice as much voltage as a bender poled for parallel operation.

Non-Magnetic

Totally non-magnetic piezo transducers are specially fabricated using non-magnetic electrode and center shim materials.

High Temperature

High temperature piezo actuators are specially constructed to operate up to 150 degrees Celsius.

Cryogenic
Cryogenic piezo actuators are specially constructed to operate below 4.2 degrees Celsius. Motor performance is reduced by ~1/5 at 77 degrees K and ~1/7 at 4.2 degrees K. However, much higher voltages may be applied to the bender, thereby recovering lost performance.

Vacuum
Vacuum compatible piezo actuators are constructed to be baked-out up to 150 degrees Celsius and have a low cross-section for outgassing.

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PIEZO SYSTEMS, INC.
Cambridge, Massachusetts, U.S.A.
Tel: 617-547-1777 Fax: 617-354-2200

MAGNETOSTRICTIVE TRANSDUCERS

The phenomenon of magnetostriction refers to magnetically induced constriction or expansion in ferromagnetic materials. The change in length in response to an applied magnetic field in materials such as nickel is sometimes called the Joule effect (1847). This can be the basis for making an ultrasonic transmitter using the extensional mode. A twisting deformation is attributed to Wiedemann (1862) and is the basis of torsional transducers.

The reverse of the Joule effect was reported some eighteen years after the Joule effect, by Villari (1865). The Wiedemann effect, like the Joule effect, is also reciprocal, and so can be used for transmission or reception.

From these dates it is seen that at least three of these magnetostrictive effects have been known for longer than the phenomenon of piezoelectricity. Yet magnetostriction remains a relatively obscure transduction mechanism, far behind piezoelectricity in number and types of applications.

What is magnetostriction good for? Why is it less-often used than piezoelectricity? A nickel for our thoughts on this subject?

Panametrics got started with magnetostrictive transducers in 1963. We were doing research for the Office of Naval Research at that time, and were looking for ways of measuring the elastic properties of materials at elevated temperature, 1000 deg C or higher. This is way over the Curie point of the ferroelectrics or piezoelectrics available at that time, and represents a formidable challenge even today, despite the availability of lithium niobate (Curie point ~1210 deg C).

We were primarily using momentary contact as a way to beat the heat, i.e., operate transducers or couplants well over their rated maximum temperatures. One of Panametrics' founders, E. H. Carnevale, came across the work of Professor J. F. W. Bell of the Royal Naval College, UK. Bell had developed another way to beat the heat. Bell used a wire delay line between a magnetostrictive transducer and the remote specimen. The specimen, in the form of a wire, could be easily soldered to another wire made of Permendur or nickel. Bell used separate transmitter and receiver coils; we later found they could be combined in one coil and placed at the very end of the wire assembly.

This arrangement allowed waves of the extensional or torsional modes to be generated at f = 100-kHz and to be coupled easily to specimens. The diameters of all the components had to be kept small compared to wavelength, but this is easily accomplished when the wavelength is around 25 to 50 mm (one to two inches). Specimen diameters around 1 mm to 3 mm were readily tested. (Panametrics' Ken Fowler and Jim Bradshaw eventually found ways of testing glass fibers smaller than 25 micrometers in diameter, and also bundles of carbon fibers). Bell showed (more than forty years ago!) in his 1957 publication in Phil. Mag. that measuring the speed of extensional (c_ext) and torsional (c_tors) modes yielded the Young's (E) and shear (G) moduli, respectively. These waves travel nondispersively in slender waveguides, at speeds equal, respectively, to the square root of (E or G) divided by density. From E & G one obtains Poisson's ratio sigma = E/2G -1. By introducing a reflective shoulder in the specimen, perhaps 50 mm or so from its end, two echoes were generated, one at the shoulder, one at the end. By keeping track of the time between these echoes as temperature increased (part of the "lead-in" and the end portion of the specimen were placed in an oven, to do this) Bell measured E and G up to rather high temperatures. Easy as baking a pie!

The reader interested in how Bell and his colleagues measured time between 100-kHz echoes to fractions of a microsecond, in 1957, may find the answer in his publications and some Dragon Project reports of the 1957-1962 era. Hint: double pulses.

Bell and his colleagues kindly shared much of their knowledge and equipment with Panametrics, and set us on a course of obtaining clean echoes and then timing them accurately. B. Gordon and colleagues at the Gordon Engineering Company are to be credited with working out ways, in the mid-1960s, of using 10- and later 20-MHz clocks to automatically measure time between the centerlines of selected echoes to plus or minus 100 nanoseconds and plus or minus 50 nanoseconds, respectively.

A simple schematic of such a waveguide measuring system looks something like this:

A number of graduate students used waveguide experiments in their doctoral theses, and specifically, they used components from the Panametrics Waveguide Experiments Kit KT-55. The papers cited at the end of this mini-tutorial by Kim and Bau, Kim et al. and by Collard and McLellan are examples of work conducted in the 1989-1993 period.

Readers interested in more details are referred to passages on magnetostriction and references cited in the 1989 book by Lynnworth, <<Ultrasonic Measurements for Process Control>>, ISBN 0-12-460585-0, available from Academic Press.

The foregoing brief historical introduction brings out several basic features of magnetostriction:

Useful for measuring elastic properties of solids at elevated temperature
Convenient for studying specimens of small cross-section
Transducers can be made by do-it-yourself individuals using Ni + a coil or two
Time can be saved, by starting with a Kit
Most applications seem to be limited to sub-MHz ultrasonic frequencies.

Now there are some questions and other advantages or features of magnetostrictive transducers that some readers will find interesting.

The "transducer" and the lead-in can be the same material, making for a perfect impedance match. What do you think this does for the bandwidth of the echo?
What diameter change makes for equal-amplitude echoes A&B? The answer is not the same, for extensional and torsional waves. For a given diameter change, the B/A ratio can be used to track relative attenuation. With echoes A, B and C (second round trip) the attenuation and reflection coefficients can be separated from one another. This might lead to a way to monitor viscosity or curing of a resin, by embedding a sensor in a material being cured. (Harrold & Sanjana, 1987, cited in above book).
Extensional waves gradually leak into water. This effect can be used as a way of sensing water level in the laboratory. How? Hint: Two parallel waveguides, 25- to 50-mm apart. Measure amplitude of the wave leaking from one to another.
Torsional waves slow down about 15% in a noncircular SS (stainless steel) waveguide, when the waveguide is immersed in water. [Noncircular typically means a diamond cross section, aspect ratio = 3. This leads to another way of sensing water level, or the level of other liquids. (US patent no. 4,893,496, January 16, 1990.)] Caution: if the fluid is capable of delivering microbubbles to the waveguide surface, the expected delay of 15% probably won't be observed (Kim et al, 1993).
The 15% delay is for water, density = 1000 mg/cm cubed. The delay is proportionately more or less, to the density, for inviscid fluids. This leads to possible applications in measuring density. If the fluid is viscous an additional delay is observed and must be compensated. Solutions include using two different cross sections, e.g., diamond cross section and a threaded cylindrical sleeve. This yields two different delta t's, allowing one to solve for the two unknowns: density and viscosity. See Kim or Kim et al. (1989-1993).
The sudden decrease in sound speed as the torsional guided wave enters the submerged section of waveguide, means that an echo must be generated at that interface. It is small but detectable. This is one of the ways this waveguide can be used to measure liquid level. Usually, however, the increase in transit time to the end is used as the indicator of liquid level, provided the density of the liquid is known well enough, or can be measured in a reference zone near the bottom of the sensor. (Kim et al, 1993).
Bell's colleagues and Bell himself worked for a number of years on relating the

sound speed in special refractory waveguides, to the average temperature of the sensor portion. Panametrics did likewise, and, like some of our customers, added multiple notches to obtain temperature profiles (Chap. 5 in abovementioned book). Student experiments are readily conducted with the KT55...examples are in Sachse, 1975, cited in list at end. Propagation experiments can explore the limits of dispersion-free operation; attenuation; effects of rotating the waveguide within the coil (commutatorless sensing); mode conversion; ablation simulation by melting away or abrading the tip of the waveguide remote from the coil; effects of temperature; of immersion in viscid or inviscid fluids.
The waveguide can be used as a point source, simulating acoustic emissions (Fowler, 1971; Papadakis and Fowler, 1972).
The waveguide is also a point receiver (Villari effect) and can be used to scan the relative sound pressure on the radiating face of 100-kHz piezoelectric transducers whose face is rugged enough to withstand such mechanical scanning. Data obtained this way, obtained by D. Xiao, is shown in Lynnworth et al., 1997. Remembering Bell's 1957 active (transmit/receive) work at high temperature, it should be no surprise that the magnetostrictive waveguide is adoptable to passive high temperature acoustic emission applications.

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J. O. Kim and H. H. Bau, On-Line Real-Time Densimeter - Theory and Optimization, J. Acoust. Soc. Am. 85 (No. 1), pp. 432-439 (Jan. 1989).

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J. O. Kim, H. H. Bau, Y. Liu, L. C. Lynnworth, S. A. Lynnworth, K. A. Hall, S. A. Jacobson, J. M. Korba, R. J. Murphy, M. A. Strauch, and K. G. King, Torsional Sensor Applications in Two-Phase Fluids, IEEE Trans. UFFC 40 (5), pp. 563-576 (September 1993).

K. A. Fowler, Materials Research and Standards, MTRSA, 11 (3), pp. 35-36 (March 1971).

K. A. Fowler, and E. P. Papadakis, "Observation and Analysis of Simulated Ultrasonic

Acoustic Emission Waves in Plates and Complex Structures, Acoustic Emission, ASTM STP 505 (American Society for Testing and Materials), pp. 222-237 (1972).

L. C. Lynnworth, Ultrasonic Measurements for Process Control, 720 pp., Academic Press [ISBN 0-12-460585-0] (1989).

L. C. Lynnworth et al., Acoustically-Isolated Air Transducers, IEEE Trans. UFFC, 44 (5) 1087-1100 (September 1997).

W. Sachse, Experiments in Mechanical Vibrations and Acoustics, esp. Ch. 3, Cornell University (1975).

What does the KT55 kit include? One extensional transducer, one torsional transducer, metal waveguides of circular and noncircular cross section, and one booklet of approx 100 waveguide experiments. The booklet may be purchased separately for USD15. including postage and handling. Make out checks to Panametrics, Inc. @ 221 Crescent Street, Waltham MA 02154-3497 USA, Attn: Mr. Matt Capobianco, PCI R&D Division.

How to Order: Contact PCI R&D Division, Mr. Matt Capobianco, and ask for KT55 Waveguide Experiments Kit price and delivery information. As a budgetary guideline, assume the kit price is on the order of 70 to 100 times the booklet price.

You will also need a pulser/receiver (NDT Division) or a function generator, and an oscilloscope, to conduct the experiments outlined in the booklet. In some cases one of the PCI Division's ultrasonic flowmeters can be adapted to measuring the time between selected echoes. Collard used this solution to obtain data for his dissertation. However, because of the special nature of magnostrictive transducers and their applications, readers seeking technical information are advised to consult the references listed or contact the PCI R&D Division, Mr. Matt Capobianco, at (781) 899-2719, or fax (781) 894-5785.

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ULTRASONICS - CASE STUDIES

At the Department of Energy's Y-12 nuclear weapons plant in Oak Ridge, Tennessee, ultrasonic cleaning with aqueous detergents has replaced about 95% of the vapor degreasing with chlorinated solvents. The Y-12 plant has many small ultrasonic cleaners and five large automated systems. The initial cost of these systems ranged from $10K to $150K. Martin Marietta Energy Systems, Inc., who manages the Y-12 plant, found that ultrasonic cleaning with aqueous detergents works as well or better than vapor degreasing with chlorinated solvents. NST (Oakite Products Inc., Berkeley Heights, NJ) is used for nonferrous materials cleaning. Micro (International Products Corp., Burlington, NJ) is used for cleaning ferrous parts. While most ultrasonic cleaners operate at 40 kHz, Martin Marietta has found that 20-kHz ultrasonics is more effective at removing tenacious oils. Aqueous detergent can usually be discharged to the sewer where it readily biodegrades.

Vaccari, John. 1993. Ultrasonic Cleaning with Aqueous Detergents; a Government Plant has Almost Entirely Replaced the use of Chlorinated Solvents, and Cleaning Performance is at Least as Good as Before, American Machinist, 137(4):41-42.
A Connecticut manufacturer of precision steel components needed to eliminate the use of two 1,1,1-trichloroethane (TCA) vapor degreasers. The degreasers were centrally located and used to clean parts at various stages of the production process. After evaluating the cleaning needs of the factory, several changes were made. Cleaning was eliminated for parts that were in transit from one machining process to the next. Cleaning was decentralized, allowing alternate methods for a department's specific needs to be developed. Aqueous methods were substituted for the TCA vapor degreasers in 95% of the cleaning applications. Several systems were developed using emulsifying alkaline solutions, nonemulsifying alkaline solutions, rust inhibitors, ultrasonics, and immersion cleaning. Some of the clients of this manufacturer required lubricants that could not be removed by aqueous chemistries. A small TCA degreaser was kept for this fraction (5%) of "special" cleaning.

Elliott, Bradley T. (Capsule Environmental Engineering). 1991. Solvent Waste Reduction Through Process Substitution. Presented at the Environmental Technology Expo '91, Chicago, Illinois, April.

The Ross Gear plant in Greeneville, Tennessee, manufactures fluid power components that are extremely sensitive to contamination. To remove the soils produced during the lapping operation, Ross Gear had been using a trichloroethylene vapor degreaser. Ross Gear discontinued the use of trichloroethylene in the Greeneville plant in 1987. The plant now cleans with an aqueous system using an alkaline solution and ultrasonics. The plant eliminated health hazards associated with trichloroethylene use, reduced overall hazardous waste by 50%, and realized significant savings in material and waste disposal costs.

Hartman, Frank and Rad Clanton (TRW Ross Gear Division). 1988. The Elimination of a Trichloroethylene Vapor Degreasing Operation. Tennessee Governor's Award for Excellence in Hazardous Waste Management, WRATT, University of Tennessee.

Digital Equipment Corporation (DEC) has replaced chlorofluorocarbon (CFC) cleaning systems at its Colorado Springs, Colorado, and Kaufbeuren, Bavaria, Germany, facilities. The alkaline aqueous system it installed at these locations consists of one cleaning, three rinsing, and two drying stations. The cleaning station consists of a heated ultrasonic tank filled with an alkaline detergent-surfactant. Cleaning is followed by a rough spray rinse, immersion in a high-purity water ultrasonic tank, and finally a spray rinse with high-purity water. Drying is accomplished in two stages. First, excess water is blown off the parts using pressurized clean, dry air. Infrared radiation then heats the parts surface to 160øF to speed up evaporative drying. The system incorporates a water purification and reclamation system. Wastewater is nonhazardous and can be sent directly to sewer, provided the parts being cleaned contain no hazardous contaminant. The aqueous system surpasses the CFC system in removing particles and is at least equal to the CFC system in overall efficiency.

Vosper, Fred C. and David J. Vickers. 1992. Developing Precision Aqueous Cleaning of Hard-Disk Electromechanical Components. Microcontamination, 10(10):31-34.

In a joint research effort, the U.S. EPA and APS Materials, Inc., have investigated the use of a limonene cleaner to replace TCA and methanol. APS Materials, Inc., is a metal finishing company that plasma coats parts for use in hostile environments. In the biomedical parts division, cobalt/molybdenum and titanium parts are coated with a porous titanium layer for use as orthopedic implants. APS Materials has converted to the terpene cleaner as a result of the investigation. Cleaning efficacy is excellent with a slight increase in bonding strength for the limonene-cleaned parts. Changing to the aqueous required the addition of rinse and dry stations. The new system cost $1,800 to install with annual operating expenses of $850. Net savings are $4,800 per year.

Brown, Lisa M. (EPA), Johnny Springer (EPA), and Matthew Bower (APS Material, Inc.). 1992. Chemical Substitution for 1,1,1-Trichloro- ethane and Methanol in an Industrial Cleaning Operation. Journal of Hazardous Materials, 29:179-188.

Torrington Bearing in Newington, CT has implemented a phase out of all solvents. A new aqueous ultrasonic cleaning system installed to clean turbine engine bearings allows better detection of micro cracks in the bearing surface. The cost of the new cleaning system was less than the annual solvent expense for the old vapor degreaser. Torrington Bearing has also eliminated the use of a petroleum based rust inhibitor, replacing it with an aqueous alternative.

Paulhus, Jack/Lewis Corporation, Source Reduction: Aqueous Replacement of Solvent Cleaning Systems, Third Annual Workshop on Solvent Substitution, Phoenix, Arizona, December 8-11, 1992.

Since 1988, Allied-Signal Aerospace in Kansas City, Missouri has used a volatile aqueous cleaner for wiping work surfaces of laminar flow work stations, finger cots, latex gloves, and fixtures to remove light soils and particulates. The volatile aqueous cleaner consists of 12.5% isopropyl alcohol, 0.82% surfactant, and the remainder is deionized water. The solvent removes both organic and inorganic soils. The previous solvent, CFC-113, was consumed at the rate of 2000 lb/month and has been completely eliminated for wiping. The volatile aqueous cleaner is also used in ultrasonic baths to clean complicated machined assemblies. Allied-Signal Aerospace reports better cleaning and lower cost, about $1.00/gallon.

Hand, Tom and Bohnert, George/Allied-Signal Aerospace, Case Study #3: Development and Use of a Volatile Aqueous Cleaner, EPA/ICOLP Eliminating CFC-113 and Methyl Chloroform in Aircraft Maintenance Procedures, EPA-430-B-93-006, October 1993, pp. 161-162.

PROCESS UNIQUE INFORMATION

Economics for this alternative and related process equipment.
Environmental information concerning regulations and disposal.
General information concerning the process and its uses.
References containing information related to this alternative.
Safety information on operator/process issues.

OTHER INFORMATION

GLOSSARY || STATE INFORMATION || PROCESS CONVERSION CHECKLIST

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sagemaster@clean.rti.org

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