Properties of Piezo Cable

R H Brown 30 May 2001

Contents:

Cable formats currently in production

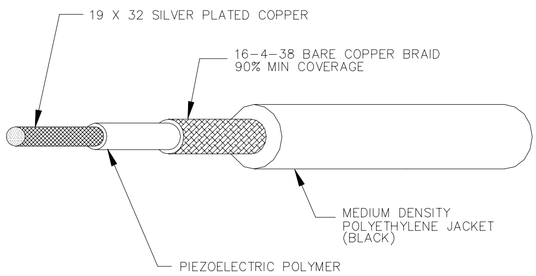
Measurement Specialties, Inc currently produces three different forms of piezo cable, plus an additional sensor similar to cable but with solid brass outer jacket (used for permanent mounting in road surface as an axle detector).

The three conventional cable forms are broadly similar, in that they share same 20 awg stranded core wire, have a piezoelectric layer, followed by an outer braided shield and a final outer jacket of polyethylene. There are slight differences in outer diameter, but the primary difference between the three is the form and sensitivity of the piezo polymer material, as outlined below:

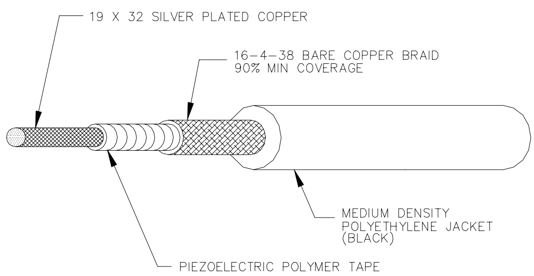
1005646 solid, extruded p(VDF-TrFE) copolymer, high sensitivity

1005801 counter-wound double spiral PVDF tape wrap, high sensitivity

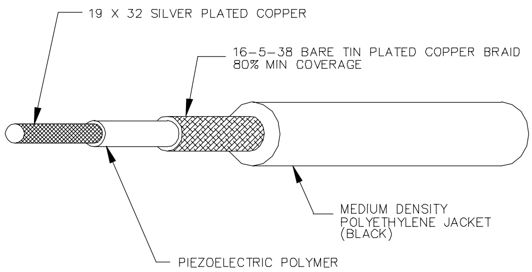
1005845 solid, extruded PVDF homopolymer, low sensitivity



1005646



1005801



1005845

In addition to the above forms, the Sensor Products Division have experience with a wider range of formats, including 24 awg and 16 awg core conductors, solid core wire formats in 24 and 22 awg, polyurethane and Kynar jacket material, and metallised polyester tape-wraps. Variations to the above stocked products may be requested subject to business review.

Typical properties of current production cable

Parameter	1005646 Solid Copolymer	1005801 Spiral PVDF Wrap	1005845 Solid PVDF
Inner Conductor			
Material	silver-plated copper	silver-plated copper	silver-plated copper
Construction	20 awg stranded (19/32)	20 awg stranded (19/32)	20 awg stranded (19/32)
Diameter	1 mm (0.040") nom	1 mm (0.040") nom	1 mm (0.040") nom
Electrical resistance	31 Ω/km	31 Ω/km	31 Ω/km
Piezo Polymer			
Material	extruded copolymer	counter-wound double spiral PVDF tape wrap	extruded PVDF homopolymer
Outer diameter	1.5 mm (0.059")	1.2 mm (0.047")	1.7 mm (0.067")
d(33) coefficient	> 15 pC/N	>15 pC/N	>1 pC/N
Braid			
Material	bare copper	bare copper	tin-plated copper
Construction	16-4-38	16-4-38	16-5-38
Electrical resistance	47 Ω/km	47 Ω/km	
Shielding	90% (min) coverage	90% (min) coverage	90% (min) coverage
Outer Jacket			
Material	MD polyethylene	MD polyethylene	MD polyethylene
Colour	black	black	Black
Wall thickness	(TBC)	(TBC)	(TBC)
Hardness	(TBC)	(TBC)	(TBC)
Overall Cable Characteristics			
Diameter	2.8 ± 0.1 mm	2.6 ± 0.1 mm	3.2 ± 0.1 mm
Capacitance	650 ± 150 pF/m	950 ± 150 pF/m	590 ± 150 pF/m
Dissipation factor	0.015 @ 1 kHz (1 m)	0.016 @ 1 kHz (1 m)	0.017 @ 1 kHz (1 m)
Sensitivity	20 ± 5 pC/N @ 0.1 N	20 ± 5 pC/N @ 0.1 N	>=1 pC/N @ 0.1 N
Weight	17 kg/km	(TBC)	(TBC)
Tensile strength	>200 N (50 lbf)	>200 N (50 lbf)	>200 N (50 lbf)

Cable piezo sensitivity

Piezo cable has a very wide dynamic range, and customers have deployed it in situations ranging from very weak acoustic stimuli (remote footsteps detected by cable buried underground) to high level force (10 ton axle crossing a cable embedded in EPDM strip in road surface). In order to investigate cable performance over such a wide range of force, various test methods have been devised:

Berlincourt d_{33} test

Used to check the sensitivity of the actual piezo polymer material (requires disassembly of small sample of cable). A small portion of the polymer is inserted between two metal spheres, which serve both as electrodes, and to apply a vibrating force. The applied force is monitored by a reference transducer, and the charge output of the sample is presented on a display, calibrated in pC/N. This test is used extensively on piezo film and cable production samples, but is not suitable for online testing, and does not indicate the performance of the final cable construction.

Hydrostatic testing

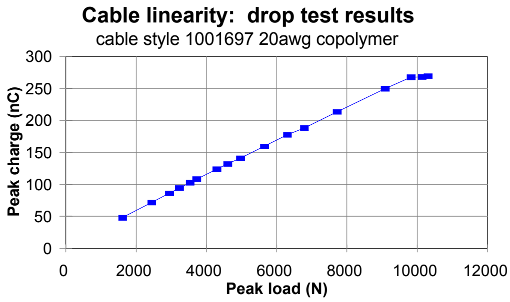
Used primarily for testing hydrophone transducers. A small sample is placed inside an oil-filled chamber, and subjected to a pressure pulse. The charge output of the sample under test can then be calibrated in terms of pC/Pa, but more often expressed in log voltage terms (dB, re 1 V/μPa). Assuming that the active surface area is known, the output can be evaluated in terms of pC/N, when it is desginated d_h. This test has been used for cable samples, but is destructive, not suitable for online testing, and may not reflect accurately the performance of a cable used in different mode.

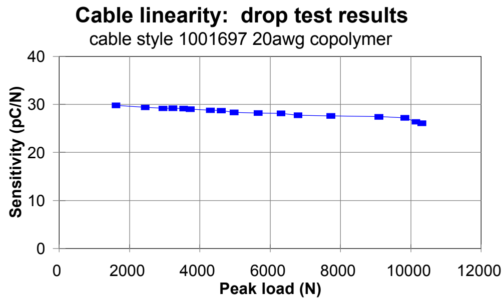
An alternative test arrangement, using a 12-inch diameter loudspeaker as part of a sealed, air-filled cavity, has been used to apply pressure pulses of up to 1 kPa to longer samples (approx 400 mm) of piezo cable. In this case, the output waveform from the cable was found to differ from the recorded pressure pulse, as detected by a high-intensity calibrated microphone. The difference (significant activity following after the main pulse) was attributed to mechanical motion of the cable sample, even when held flat under layers of foam rubber. Due to the discrepancy between input and output waveforms, this test has not been widely used.

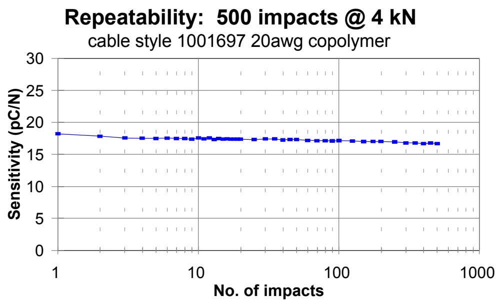
Drop tests

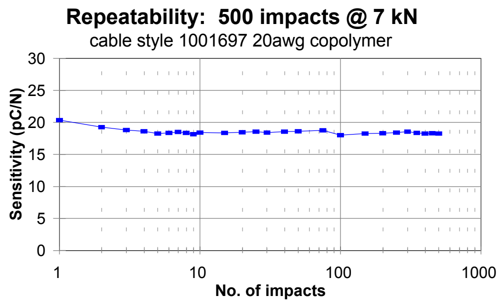
A guided falling mass impacts the cable, with force being applied between two rigid flat plates. An accelerometer on the falling mass is used to calculate applied force from the peak deceleration. The fixture used by the author between 1992 and 1996 allowed a 2 kg mass to be dropped from heights up to 700 mm, and delivered peak force in the range of 1 kN to >20 kN. Forces in excess of about 10 kN were considered potentially destructive (caused permanent deformation of the cable). By arranging a series of increasing drop heights, the linearity of the cable response at high force levels could be determined. Also, by applying multiple impacts at high force, progressive changes in the cable output could be investigated. For each data point, the sensitivity (charge output divided by input force, Q/F) could be determined. Although not a true piezo coefficient (may vary with cable construction), this quantity was designated d_c by the author.

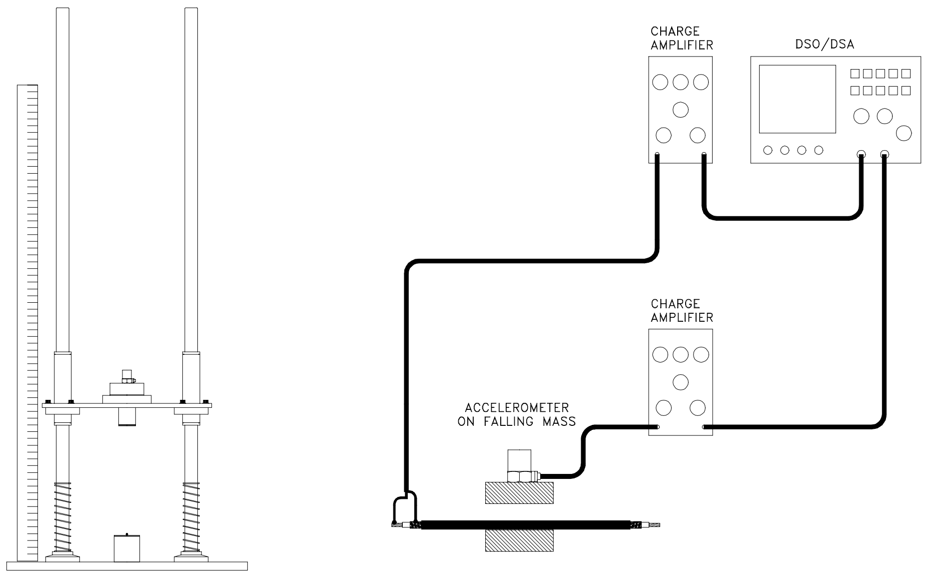
Examples of linearity tests, and repeatability tests, made using an earlier version of 20 awg copolymer cable (style 1001697, which included a metallised polyester tape wrap outside the braided shield, and had polyurethane outer jacket) are shown below (data from March 1992):











Drop-test arrangement: outline drawing

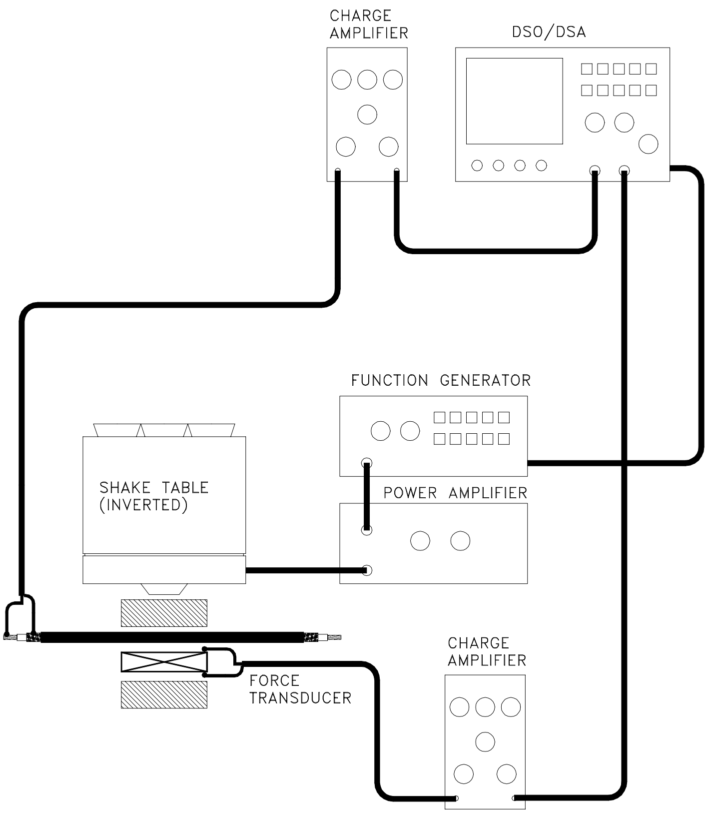
Note: because the drop-test apparatus was discarded in 1997, no data is available for current production cable styles.

Low force measurements

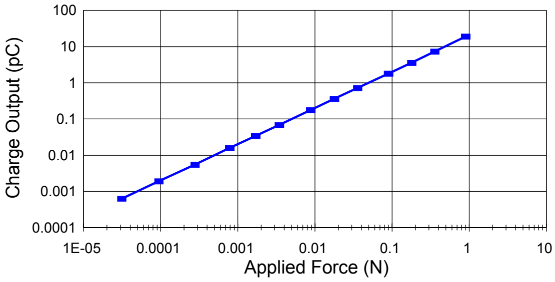
The cable sample under test is compressed between two parallel rigid surfaces. A reference transducer (slab of piezoelectric polymer of known sensitivity) has been placed below the sample under test, and the charge outputs of the sample and the reference are measured and compared. A slight preload is exerted (approx 2.5 N/mm), and dynamic force is applied using an electromechanical vibration exciter to the upper block. The frequency and amplitude of vibration may be varied over a very wide range. Both impulsive and continuous sine excitation may be applied. Linearity measurements have been made over 5 decades of amplitude of applied dynamic force.

The plots on following page show results from testing of current cable production styles. Note that the use of logarithmic axes. The apparent non-linearity at high force levels (>0.1 N/mm) is believed to be an artefact, arising when the exciter head begins to lift off from the cable under continous sine excitation. A frequency-response plot (for copolymer cable 1005646) is also presented, showing quite flat broad-band characteristic, with slight peak at around 2.1 kHz (mechanical resonance of cable structure).

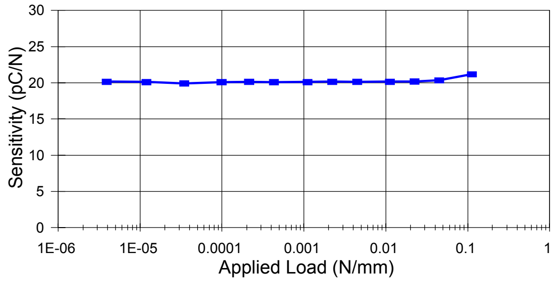
This method has not been extended to higher force levels, since a stronger pre-load would be required to maintain contact with the cable.



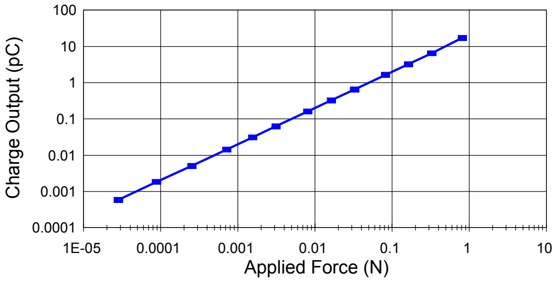
1005646 Cable: Linearity



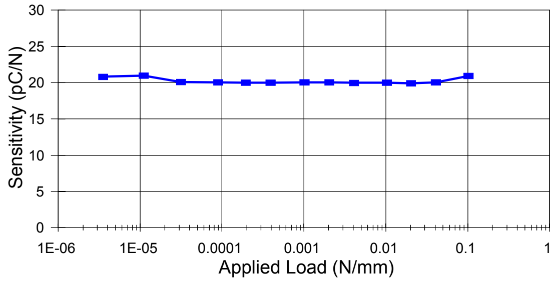
1005646 Cable: Sensitivity



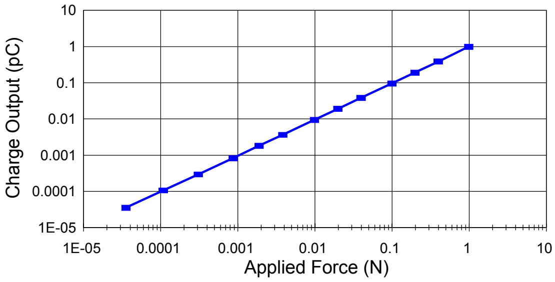
1005801 Cable: Linearity



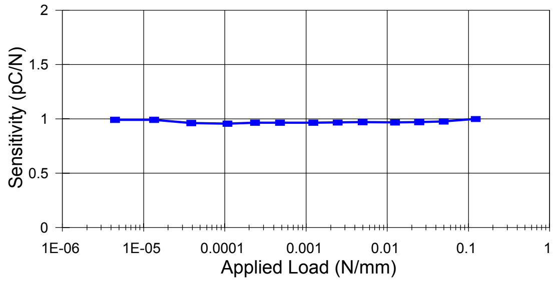
1005801 Cable: Sensitivity



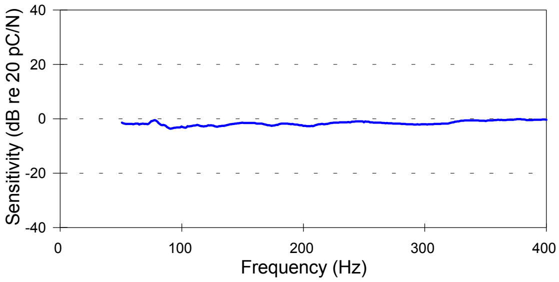
1005845 Cable: Linearity



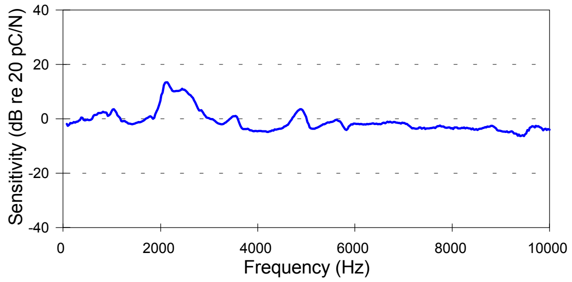
1005845 Cable: Sensitivity



1005646 Frequency Response - LF



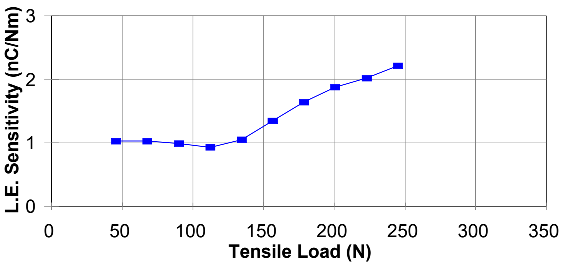
1005646 Frequency Response - HF



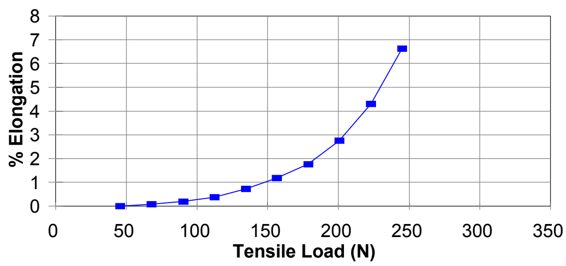
Length Extension Mode

Sections of current production cable are prepared and mounted on an Instron tester, with nominal gauge length of 150 mm. A dynamic force of approx 22 N is applied, while static force is incremented in steps up to break point. Sensitivity to dynamic tensile strain is expressed in nC/Nm, and generally increases at strain levels of >1% (except for solid-core PVDF cable style 1005845), as illustrated below:

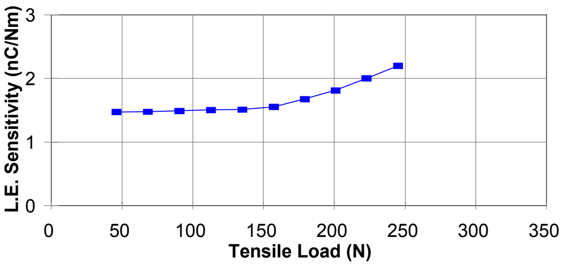
Length Extension Sensitivity vs Load
1005646 Cable (copolymer)



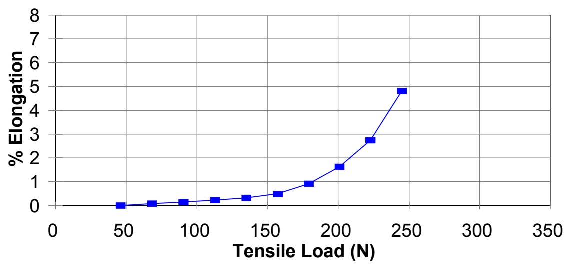
Strain vs Tensile Load
1005646 Cable (copolymer)



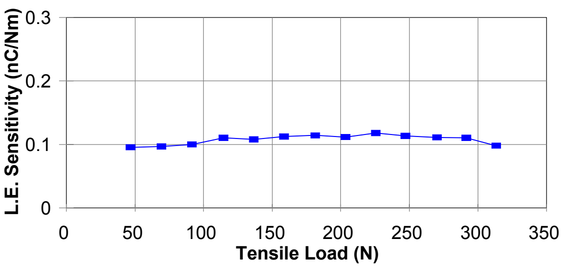
Length Extension Sensitivity vs Load
1005801 Cable (spiral-wrap PVDF)



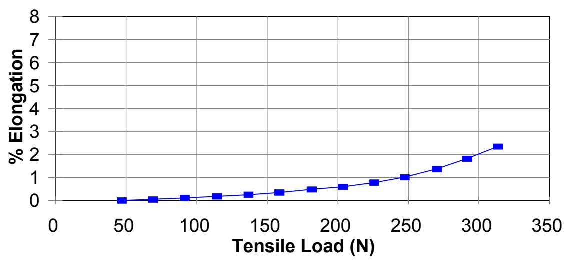
Strain vs Tensile Load
1005801 Cable (spiral-wrap PVDF)



Length Extension Sensitivity vs Load
1005845 Cable (solid PVDF)



Strain vs Tensile Load
1005845 Cable (solid PVDF)



Cable thermal transient sensitivity

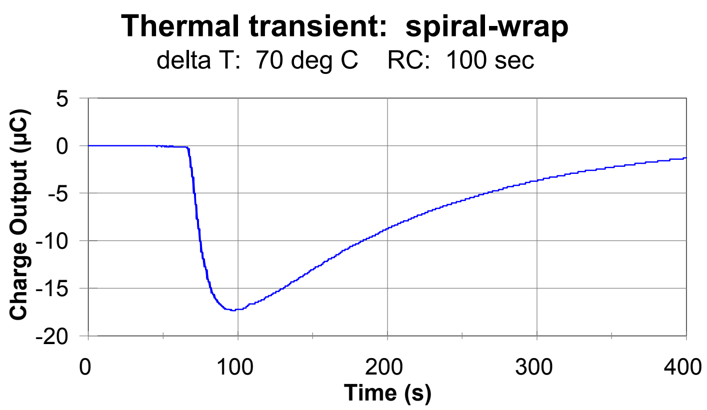
Samples of 3 different production cables were taken from room temperature and plunged into water near boiling point. The resulting charge output was measured (using network with electrical time constant of 100 seconds, equivalent to low-frequency limit of 0.0016 Hz), and effective open-circuit sensitivity to temperature transients calculated. Results ranged from -41 to –297 V/°C open-circuit voltage sensitivity.

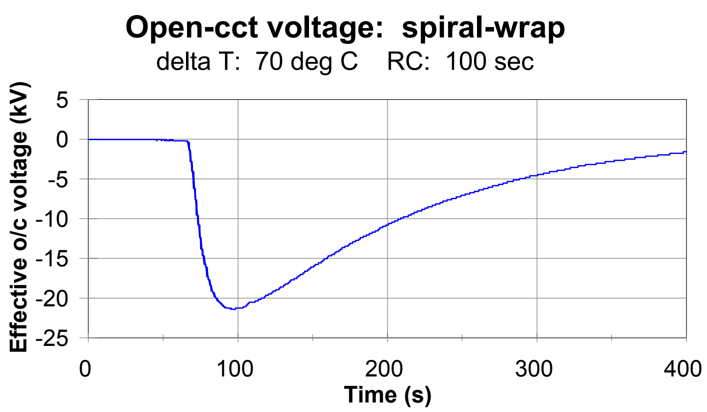
Summary of results:

Parameter	1005646 copolymer	1005801 spiral PVDF	1005845 solid PVDF
Capacitance pF/m	675	955	561
Charge S (nC/m °C)	-87.6	-283	-23.3
Voltage S (V/°C)	-130	-297	-41.6
Thermal TC (s)[1]	9	11	13

Note 1: Thermal time constant from waveform data taken as approx time to reach 63% of peak amplitude from time of immersion, and applies to thermal transient (temperature step) of around +70 °C . Error may be +/- 2 s, from estimation of closest data points and moment of immersion.

An example of the measured charge and calculated open-circuit voltage output of a spiral-wrap sample is shown below:





All three cables demonstrate very high open-circuit voltage sensitivity to thermal transients, although the long thermal time constant would prevent such sensitivity being observed in normal circuits with much shorter electrical time constant. Differing jacket material and thicknesses, and different mounting configurations, will significantly affect the actual thermal time constant observed in a given detection situation.

The absolute value of the thermal (pyroelectric) sensitivity for each cable style may be higher than those quoted above, because the thermal rise time observed from the waveforms, although significantly shorter than the electrical time constant of the measurement, cannot be ignored. Charge leakage into the 100 M probe may have reduced the peak amplitude by up to 30% of true coefficient.

Note that the spiral-wrap PVDF and copolymer cables are known to have virtually identical piezo sensitivity, but the spiral-wrap cable shows more than three times higher thermal sensitivity (in charge mode).

Cable thermal stability

Many of the parameters affecting the response of piezo cable to impact or vibration exhibit temperature dependence. These include the basic piezoelectric coefficients of the sensing element, the dielectric constant and dissipation factor of the piezo material, and the compliance of the piezoelectric and jacket materials. The figures shown in the following pages illustrate experimental data obtained from early samples of piezoelectric material, although it must be pointed out that such curves may vary according to the specific production processes employed during manufacture. In particular, higher temperature stability has recently been observed for thin PVDF films tested up to 100 °C.

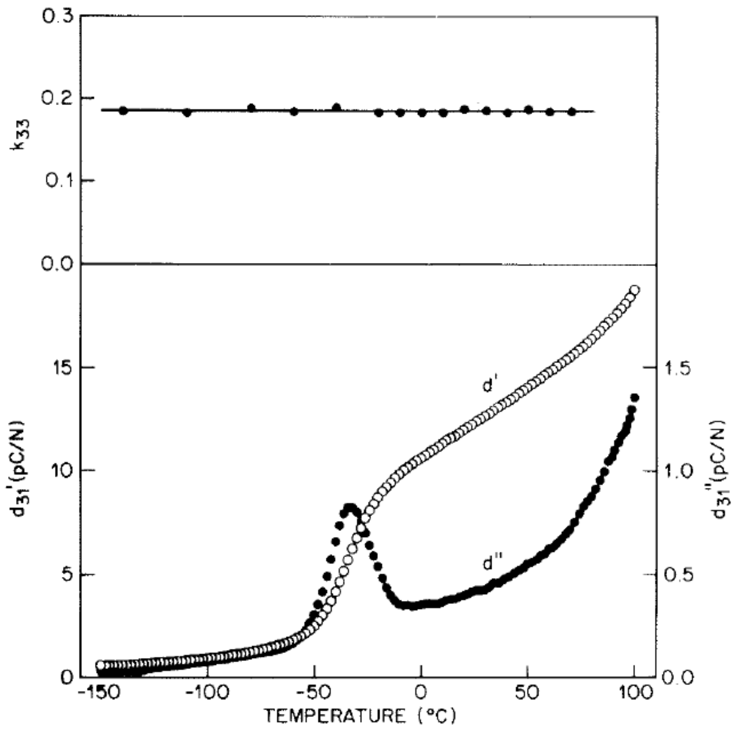


Figure 5.27 Plots of complex piezoelectric constant d^*_{31} and electromechanical coupling factor k_{33} of PVDF as a function of temperature.

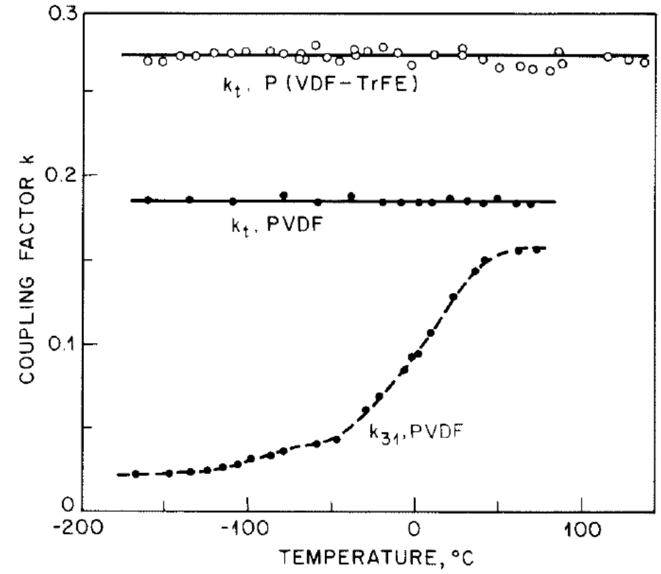


Figure 11.8 Temperature dependence of electromechanical coupling factors k_t and k_{31} for PVDF and P(VDF-TrFE) (75/25) [14, 28].

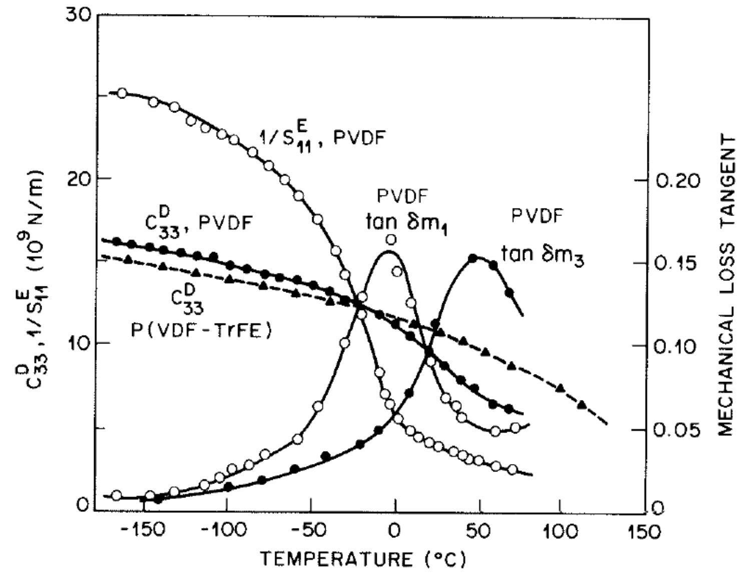


Figure 11.7 Temperature dependence of mechanical properties of PVDF and P(VDF-TrFE) (VDF/TrFE = 75/25). Redrawn and adapted from *J. Appl. Phys.* **47** (1976) 949.

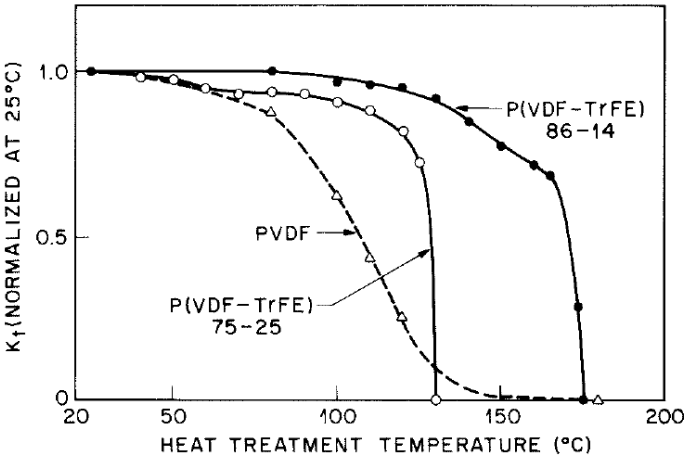


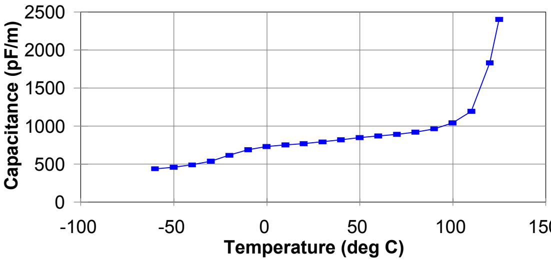
Figure 11.9 Thermal stability of piezoelectric activity in PVDF and P(VDF-TrFE); the value of the coupling factor k_t measured at room temperature after annealing is plotted as a function of annealing temperature. Annealing was carried out for 10 min at every temperature. Redrawn and adapted from H. Ohigashi, *Japan J. Appl. Phys.* **24** *Suppl.* **24-2** (1985) 23.

(the above 4 figures are extracts from *The Applications of Ferroelectric Polymers*, ed. T T Wang, J M Herbert and A M Glass, Glasgow: Blackie, 1998, and are reprinted here with kind permission from Kluwer Academic Publishers)

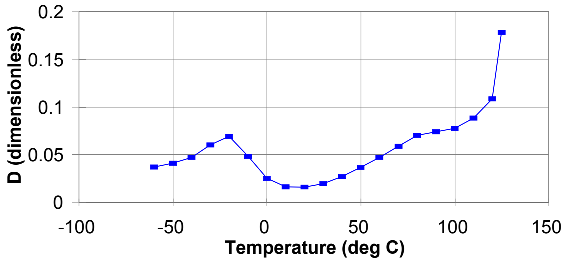
Notice from these plots that, in general, the coupling factor in the thickness direction k_t appears to be virtually constant, while the equivalent coefficient in length direction varies over a much wider range. As noted above, these data were obtained from tests made on thin film alone, and some care must be taken in the interpretation of these results in relation to piezo cable. Generally, it is assumed that piezo cable will receive excitation primarily in the form of compression applied to the outer jacket. In this case, the thickness-mode parameters should predominate. In the case of spiral-wound PVDF cable, compression of the assembled cable will still result in compression of the polymer film. Elongation of the assembled cable may create both thickness and length changes in the active sensing polymer.

At the same time, changes in the dielectric properties of the piezo polymer may influence the final observed output. Specific measurements of the change in dielectric constant, and dissipation factor, have been carried out at a range of frequencies and temperatures for all current cable formats. A summary, showing only results of 1 kHz measurements, is shown below:

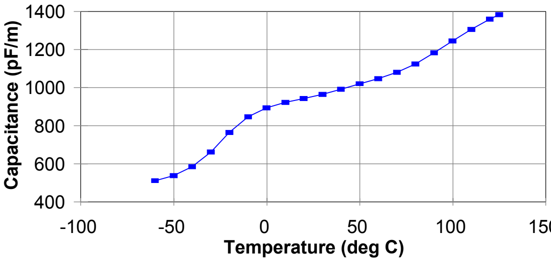
Capacitance vs Temperature
1005646 Cable (copolymer) @ 1 kHz



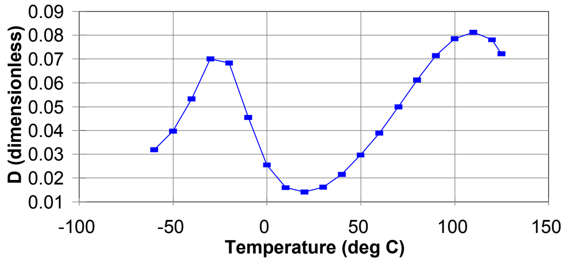
Dissipation (D) vs Temperature
1005646 Cable (copolymer) @ 1 kHz



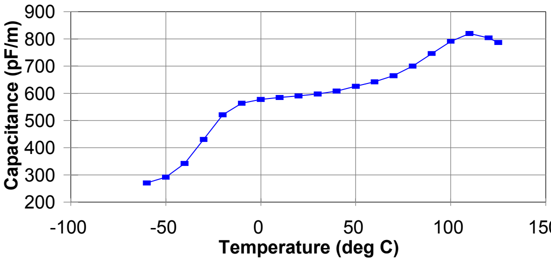
Capacitance vs Temperature
1005801 Cable (spiral-wrap) @ 1 kHz



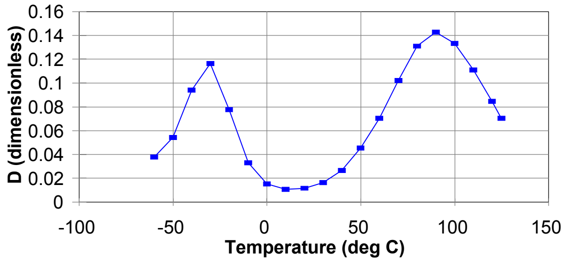
Dissipation (D) vs Temperature
1005801 Cable (spiral-wrap) @ 1 kHz



Capacitance vs Temperature
1005845 Cable (solid PVDF) @ 1 kHz



Dissipation (D) vs Temperature
1005845 Cable (solid PVDF) @ 1 kHz



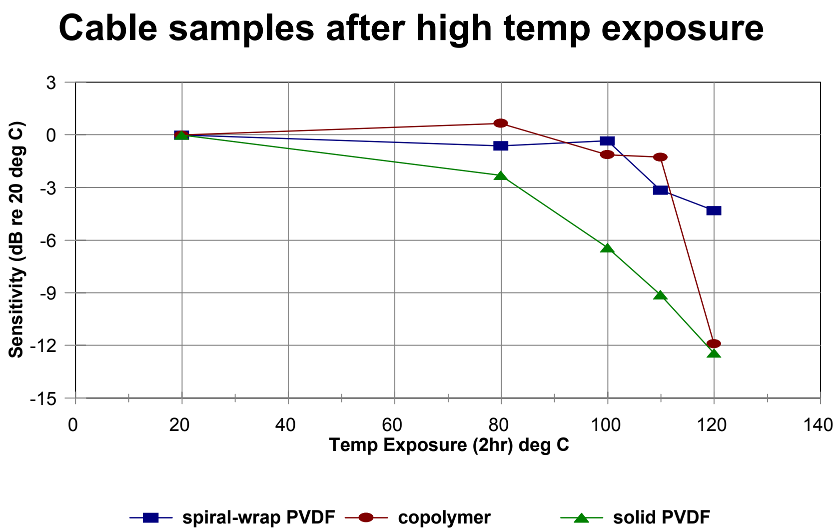
Note that capacitance generally rises with increasing temperature. In cases where a long cable length is employed, of which only a portion receives mechanical excitation, then the output voltage will be affected by the capacitance of the inactive cable. At higher temperatures, the voltage sensitivity of the cable will be higher, but also the additional capacitive loading of the inactive film. Therefore, a degree of self-compensation (in voltage mode only) is expected to occur.

The dissipation curves show a pronounced minimum in the region of 0 to 50 °C. At around –30 °C and around 100 °C, the two PVDF forms show maxima in dissipation. At these temperatures, the effective shunt resistance of the cable will be lower than at normal room temperature, and therefore electrical noise seen at the output of a voltage amplifier may increase.

True performance testing of piezo cable at low and high temperatures has not been carried out. Different applications of cable utilise different modes of excitation, and therefore specifically-designed experiments are required for each application.

Low force excitation (see Cable piezo sensitivity: ways of applying mechanical stimulus, (e) Low force measurements above) has been applied to various cable samples after 2-hour exposure to elevated temperature. Analysis of the cable jacket material (medium-density polyethylene) has shown a melting point in the region of 127 °C, and so results beyond 100 °C may have been affected by partial flow of the jacket material into the braided shield.

Of particular interest in the following plot is the retention of piezo activity in the spiral-wrap cable at 100 °C and beyond, relative to the fall-off seen in the solid-core PVDF material:



Limits of performance: thermal and mechanical

The practical upper limit of temperature exposure depends upon the acceptable permanent drop in piezo activity which can be tolerated in the application. As can be seen above, exposure to 110 °C for 2 hours resulted in a few dB drop in activity on both copolymer and spiral-wrap forms, but a 9 dB drop for the solid-core PVDF form. More detailed studies, using longer soak periods, may be required to determine suitability for use in specific applications. Alternative jacket materials may be required, if prolonged exposure at high temperatures is expected.

Repeated compressive forces of up to 70 N/mm have been applied up to 500 times in quick succession without causing failure in one particular construction, as shown above. Forces of >100 N/mm were liable to cause damage, with 200 N/mm generally crushing the construction with risk of core-to-screen short-circuit.

A tensile force of 150 to 170 N was sufficient to cause 1% elongation of both copolymer and spiral-wrap cables. Break occurred at about 250 N (copolymer and spiral-wrap) or 315 N (solid-core PVDF).

Flexural testing of the cables has not been performed. Core samples (stranded conductor, with applied piezo polymer) are regularly examined for flexibility, and may be tightly wound around an 8 mm diameter mandrel without cracking or splitting. The stranded centre conductor was specifically selected for improved flexibility and fatigue resistance.

Water and chemical resistance

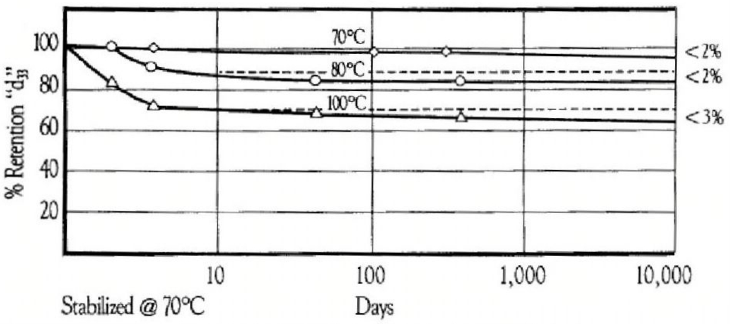
The piezo polymer materials used in the construction of piezo cable are extremely inert. PVDF resin (in non-piezoelectric form) is used extensively in industries where superior chemical and environmental resistance is required (lining of chemical storage vessels, conduit for plenum wiring, coatings for architectural steel panels, UV-stable labels, etc). The inner and outer conductors (silver-plated copper, and pure copper), however, must be protected from water and chemical attack.

The MDPE (medium density polyethylene) jacket material shows water absorption in the region of 0.01%, and has been found by experiment to offer excellent stability of electrical resistance when samples of jacketed cable are immersed in water for >100 hours (no resistance change detectable, measured from braid of cable to probe immersed in water, at 100 V dc potential).

Chemical resistance of MDPE is generally good (data sheet available). Specific applications may require alternate materials or modified properties.

Life expectancy

Piezoelectric polymers show very good retention of piezo activity over time, after an initial drop within hours of production. Storage temperature affects retention, as illustrated below. The example shows performance of film, previously annealed for 70 °C stability, after storage at this and higher temperatures. After an initial drop in sensitivity within a few days of exposure to higher temperature, the film re-stabilises and shows thereafter a logarithmic change of less than 1% per decade of time (measured in days, after first 10 days).



It should be noted that the storage temperature required to bring about a complete depolarisation of piezoelectric PVDF has been estimated as 200 °C, which is above the melt temperature for the crystalline beta-phase (180 °C).

Samples of some of the earliest piezoelectric PVDF sheets ever produced by the researcher (Kawai) who discovered the effect in this polymer have been retested in recent years. The change in piezoelectric activity, if any existed, was less than the uncertainty in the equipment calibration.

Depolarisation (or reversal of the polarisation direction) of previously poled material is possible, although unlikely to occur accidentally. Field strengths greater than 1 MV/cm, or 100 V/µm of polymer thickness, are required to create significant effects. Typical thickness of piezo material used in cable construction is 100 µm (spiral-wrap) to >200 µm (solid-core forms), and so a potential of at least 10kV between core and screen of the cable would be required. In practice, repolarisation generally requires several cycles of a hysteresis loop to be performed at a controlled rate.

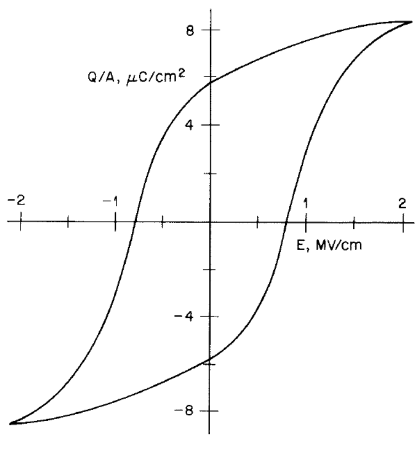


Figure 4.12 Typical hysteresis loop between electric displacement (Q/A) and electric field (E) for ferroelectric polymer.

A form of piezo cable is used to make Measurement Specialties BL traffic sensors. In place of a braided outer shield, a solid brass tube is tightly crimped around the piezo polymer. Sensors are produced to suit various lane widths, and are embedded into narrow slots cut into the roadway. Mounting depth is approx 10 mm below the road surface. The slots are filled with encapsulation resin, and are left flush. Charge output from the BL sensor is linear with axle load. Around 5 nC peak charge is developed from the passage of a car axle, while large trucks may generate >50 nC. Each sensor may see several million heavy axles per year.

One German customer, in an installation campaign totalling more than 3,500 sensors to date, has reported no sensor failures after up to 4 years of use. Generally, the sensors only require replacement after road re-surfacing or accidental cutting of the feeder cables. More than 40,000 such sensors have been supplied worldwide over the past 5 years.

Many instrumentation manufacturers recommend BL axle sensors in conjunction with their counter/classifier hardware. No problems are reported in the setting of a trigger threshold, suitable for accurate detection of both light and heavy axles, throughout winter and summer. Weigh-in motion systems using these sensors have been reported, reaching accuracy classes of A(5) (5% confidence interval width, gross vehicle weight).

Copolymer piezo cable (1005646) has been supplied for use in replaceable axle sensors, where the cable is embedded within a narrow EPDM strip. The strip inserts into a rugged channel mounted into the road surface, with approximately 2.5 mm of the strip protruding above the road surface. Each axle crossing therefore creates significant impacts to the EPDM and thence the cable. This sensor style has been deployed for about 12 years by the UK Dept of Transport, although it has largely been superceded by the flush-mounting MSI BL sensor. The replaceable style has found success also at tolls. Life expectancy of this style of sensor is somewhat lower than the flush-mounting BL sensor, although >3 years (at several million axle impacts per year) has been reported.

Piezo cable, buried at shallow depth underground in a wide variety of soil conditions, has been used for many years as an acoustic sensor for perimeter security, with no reported sensor failures (with one exception: an installation where the cable had been chewed through by rabbits). Similarly, fence-mounted installations use piezo cable, either as supplied, or mounted within flexible conduit, to detect vibrations due to climbing or cutting of the fence. Measurement Specialties, Inc has supplied more than 100 km of cable into the security market over the past 6 years, and similar products have been deployed for at least 9 years.

Cylindrical sections of extruded piezoelectric copolymer, with conductive ink electrodes on inner and outer surfaces, form the hydrophone sensor elements for Lockheed Martin's TB-29 Thinline Towed Array Sonar. TB-29 is currently deployed from Los Angeles class attack submarines.

We may conclude, therefore, that there is no natural or spontaneous degradation of the piezoelectric effect, and that, except for the influence of high storage temperature described above, the material properties remain stable indefinitely.

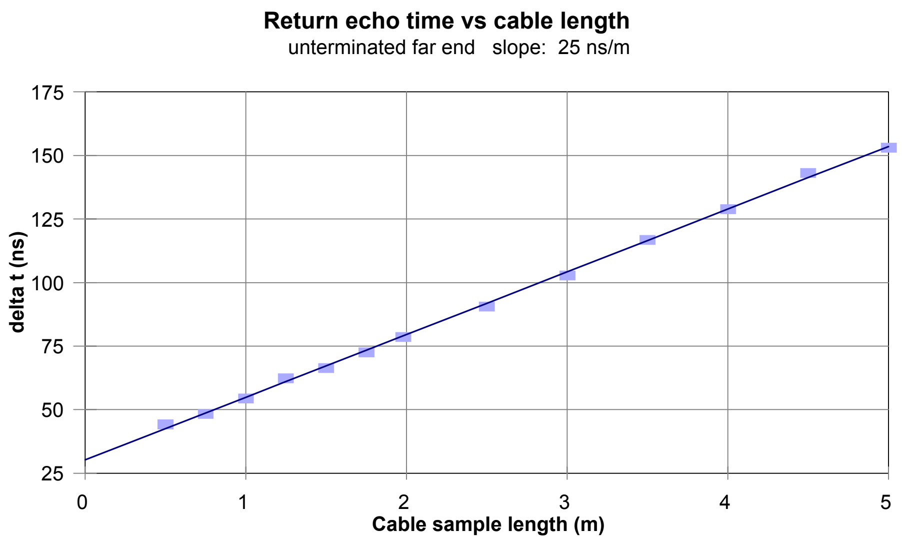
Self-test

In some applications of piezo cable, it is desirable to determine whether the cable has become damaged. For example, in a buried perimeter security system, several kilometers of cable may be deployed, in circumstances that make visual inspection impossible. Target signals may be very infrequent. Although full checking of the piezoelectric function along a continuous length is difficult, it may be sufficient to check for gross cable faults (short-circuited cable caused by severe crushing or wiring fault, or open-circuit caused by disconnection or severing of the cable).

A simple solution is to connect a high-value resistor across the end of the cable farthest from the instrumentation. A small DC current may be passed through the loop, which can easily be filtered out for analysis of dynamic target signals.

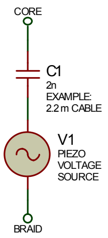
Use of a terminating resistor may not be suitable for a charge-mode preamplifier, since part of the function of the preamplifier is to maintain zero potential difference across the cable. In this case, an alternative solution is to use a capacitor as the far-end termination. Presence or absence of this capacitor may be detected using an oscillator network, set up to operate at a frequency well outwith the frequency range of the target signal. Additional capacitances may be connected at the instrumentation end, to enable all possible fault conditions to create unique oscillator frequencies.

Other, more complex systems are also possible. The principle of time-domain reflectrometry (TDR) has been demonstrated, whereby a very short electrical impulse is launched into the cable and reflects from the unterminated far end. An example of measurements made down to 0.5 m is shown below. Although this method requires high-speed electronics and either high drive voltage or high receiver gain, these requirements are becoming steadily less difficult to meet with practical, cost-effective devices.



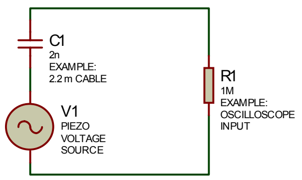
Electronic modelling

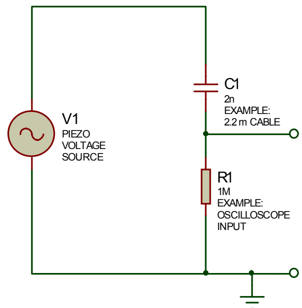
Piezo materials develop a potential difference, or charge imbalance, between their electrodes when subjected to mechanical stress. We may model this situation as a voltage source connected in series with a passive capacitance, or as a charge source connected in parallel with a passive capacitance. Both charge and voltage are directly proportional to the stress applied, but any load connected across the piezo element will create an electronic network that may affect the observed result.



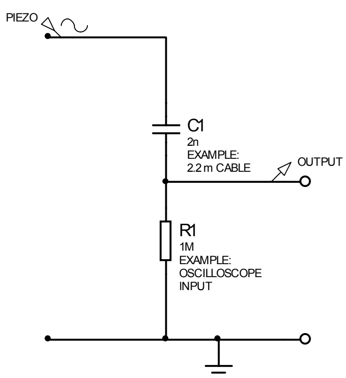
A charge source is not commonly encountered in electronic circuit theory. The piezo element may be modelled as a current source in parallel with a passive capacitance, but in this case the magnitude of the current (rate of change of charge) is not directly proportional to mechanical stress applied, but varies with the rate of change of stress. For this reason, it is easier to model piezo elements as a voltage source in series with a passive capacitance, as shown in the diagram at left.

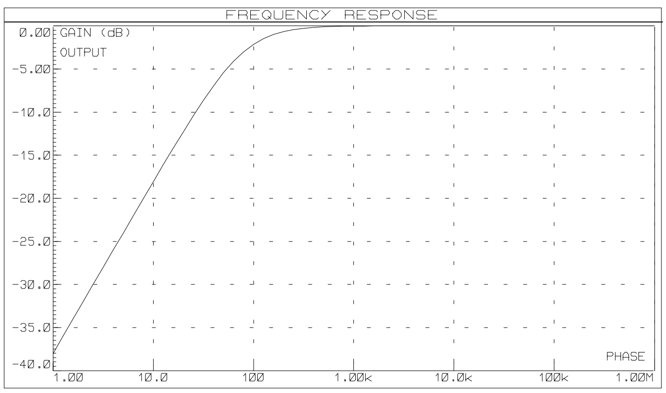
Connection of this arrangement to a resistive load (for example, the input of an oscilloscope) will create a first-order high-pass filter, with a cut-off frequency determined by $1/2\pi RC$. The connection may be redrawn to clearly show the R-C potential divider, as illustrated below:





An active model can be produced, where the voltage source V1 in the diagrams above is replaced by a sine generator, and a frequency response curve generated by comparing the output observed across the 1 M resistor with the input:

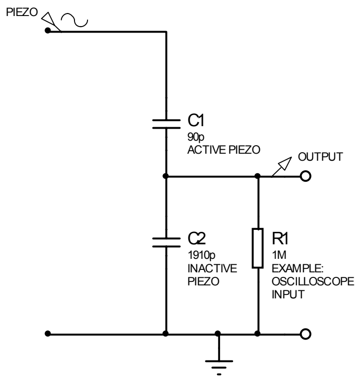


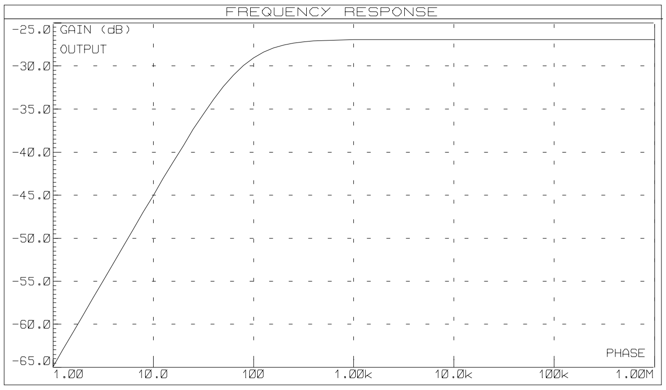


In this case, for a 2.2 m long section of cable with capacitance 2.0 nF, the cut-off frequency (to –3 dB, or to 0.71 of peak value) lies at 79 Hz.

Note that the above model assumes that all of the cable length is generating signal. In reality (and especially when longer cable lengths are employed), only a portion of the cable may be producing charge. In this case, we may represent the inactive cable as a further capacitive load, in parallel with the active segment.

If the active length is assumed to be only 10 cm, with 2.1 m of inactive "load", then we may re-simulate the above example as follows:





The cut-off frequency remains unchanged at 79 Hz (because the total circuit capacitance is the same), but the "gain" has reduced to –27 dB in the flat region of the curve. In other words, the true voltage developed by the active segment in isolation from any load is reduced by a factor of 22 (which is the same as the ratio of active to total length).

Note that the input resistance may be selected by the user, and therefore any practical value of cut-off frequency used. The high thermal sensitivity described in earlier section may become apparent if a very low cut-off frequency is chosen. If a high cut-off frequency is used, then the output voltage will appear proportional to the rate of change of stress applied to the cable. This occurs when the majority of the frequency spectrum of applied force falls below the cut-off frequency (where the slope of the curve is 20 dB/decade, and the network acts as a differentiator).

Example of charge preamplifier interface

Preamplifier design may be based on charge or voltage detection. The term "charge amplifier" is commonly used to describe a stage that converts an input charge into an output voltage. It does not amplify charge. A voltage amplifier, however, may indeed amplify a small input voltage. In either case (charge or voltage mode), the primary function of most piezo interface circuits is to convert a signal generated by a very high impedance source into an output signal which may drive a much lower load impedance. In many cases, actual gain may not be required.

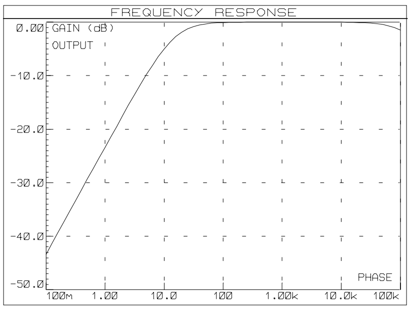
A charge amplifier is useful when examining signals from piezo cable, and especially so when the total length and capacitance of the system may vary between installations. The gain of the circuit is independent upon the capacitive load presented to the input (although the upper frequency limit of the circuit will be affected).

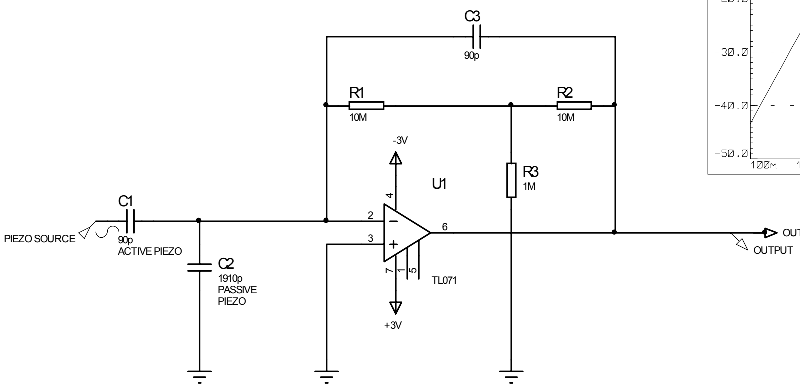
In the schematic shown below, C1 represents the capacitance of the active section of cable which is impacted or generating charge. C2 represents an additional capacitive load (for example, a length of piezo cable not receiving stimulus, or a length of passive interconnecting cable).

The charge amplifier formed around op-amp U1 comprises a feedback capacitor C3, and a T-network of resistors (R1, R2 and R3). This resistor network allows a very high effective value of resistance to be placed across C3, without actually requiring high value components. Reducing R3 increases the effective value of the network.

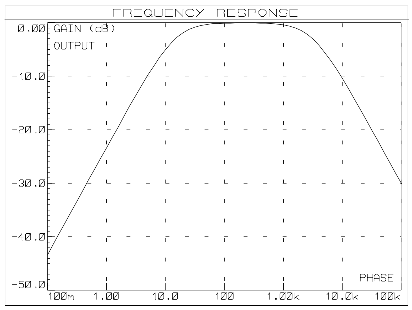
In operation, the op-amp U1 maintains zero potential between the inverting and non-inverting inputs. All charge developed across C1 appears across the feedback capacitor C3, and so its value determines the sensitivity, and the low frequency response of the system is governed by C3 and the resistive T-network.

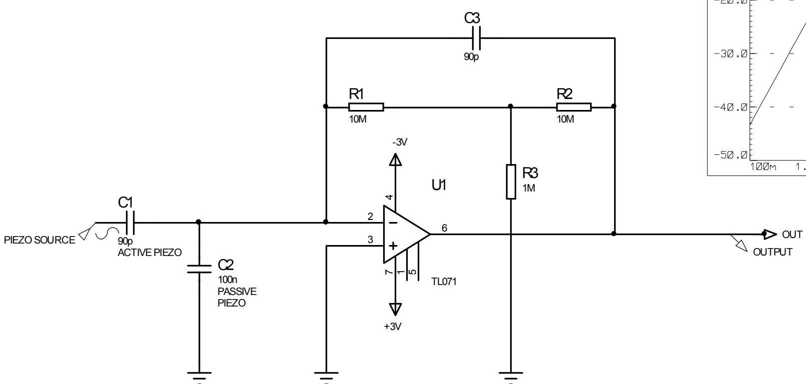
When the feedback capacitor C3 is chosen to be the same value as the active source C1, then the overall gain is unity. This means that the output voltage of the circuit is exactly that which would be seen across the source, under open-circuit conditions. Gain or attenuation can be adjusted by altering C3.





To illustrate the insenstivity of the circuit to capacitive load on the input, the simulation is run again below, changing the value of C2 from 1910 pF (as used in above examples) to 100 nF (equivalent to around 111 m of cable). Note the effect on higher frequencies.





Applications of Piezo cable

A full discussion of existing and possible applications of piezo cable is beyond the scope of this document (see MSI document "Applications of Piezo Cable", filename "Piezo_Cable.pdf", 135 Kbytes, at http://www.msiusa.com/piezo_download_listing.htm#Piezo_Cable.pdf for detailed examples).

Guitar and musical instrument pickups – a customised form of cable sensor is mounted within the bridge of stringed instruments and converts string vibration into high quality audio output signal (*Note: Measurement Specialties, Inc is restricted by legal contract from supplying piezo cable for acoustic guitar pickup applications*)

Traffic sensors – conventional HDPE-jacketed piezo cable is embedded in EPDM extrusions, and mounted permanently or in U-shaped channels in slots cut into road surface for speed detection, and vehicle counting/classification.

Traffic sensors – brass-jacketed piezo cable is directly embedded into slots in road surface using polyurethane encapsulation adhesive, for speed detection, counting/classification and weigh-in-motion

Step switch – cable is placed underneath steel plate to detect arrival of a person at start of moving walkway

Fence-mounted perimeter security – cable is mounted directly to chain-link or rigid fencing, and used as an acoustic sensor to detect climbing or cutting of the fence

Buried sensor perimeter security – cable is buried at shallow depth in soil or sand, and can detect remote footsteps (up to 20 m distant, depending upon ground conditions), also distinguishes between wheeled and tracked vehicles

Personnel presence detection – cable is embedded into a seat (e.g. automotive), and can detect presence or absence of a person by virtue of continuous quasi-random physiological activity (*Note: current safety regulations for airbag systems require discrimination of occupant weight, which this system does not detect*)

Personnel presence detection – cable is embedded below concrete paving slabs at pedestrian crossings. Waiting pedestrians are detected as above; system ignores presence of inert objects. Approved for demand monitoring by UK DoT (avoids unnecessary red light delays for road traffic)