TRANSDUCERS

Transducers are devices that convert a signal of one form to another. In physiological applications this usually means converting variations of a physical signal, such as temperature or pressure, into variations in voltage that can then be recorded or manipulated as necessary.

There are many different types of transducers available for physiological recording and they range in their requirements for excitation voltages, amplification and recording techniques as well as mechanical connections. In the past this has required a different amplifier for each transducer type. The introduction of the Axon Instruments CyberAmp, a signal-conditioning amplifier, heralded a new approach to interfacing transducers. A small 15-pin socket on each channel of the CyberAmp provides the excitation voltage, the differential inputs, the offset correction and the filtering required by a wide variety of transducers. This eliminates the need for a dedicated amplifier to suit the transducer type. The AI 400 series probes and adapters can plug into any socket on the CyberAmp. Within the 15-pin probe connector is a small memory device called an EEPROM (electrically erasable programmable read only memory) that stores such information as the transducer type, its scale factor and the offset. When the transducer is plugged into the CyberAmp, this information may be automatically loaded by the acquisition software, thereby making the transducer ready for immediate use.

Temperature Transducers for Physiological Temperature Measurement

Three types of transducers are suitable for physiological temperature measurement: thermistors, integrated circuit (IC) temperature transducers that produce an output current proportional to absolute temperature, and IC temperature transducers that produce an output voltage proportional to absolute temperature.

Thermistors

Thermistors are resistors whose resistance drops significantly as temperature increases. They are composed of a compressed and sintered mixture of metallic oxides of manganese, nickel, cobalt, copper, magnesium, titanium and other metals. Thermistors exhibit temperature coefficients many times greater than those of pure metals. For most of them, the resistance falls by 4 - 6% per °C with increasing temperature.

The response is exponential with temperature, but can be considered to be linear over a range of a few tens of degrees Celsius. By combining multiple thermistors and some resistors, the useful linear range can be extended to span more than 100 degrees Celsius. The Yellow Springs Instrument Company (Yellow Springs, OH) Series 700 Thermilinear Probes (also manufactured by Omega Engineering Inc. in Stamford, CT) contain a matched pair of thermistors. When connected by precision resistors to an accurate DC excitation voltage, these probes are interchangeable within ±0.15°C over the recommended range of -30 to +100°C. These YSI probes come in a wide range of shapes and sizes for different applications such as esophageal, rectal and surface body temperature measurements, or for immersion in hostile chemical environments. All of these probes can be plugged directly into the AI 413 Temperature Adapter, which contains the appropriate linearization resistors and DC excitation voltage. For even greater accuracy, each temperature probe can be further calibrated using appropriate software. For convenience, accuracy and price, the YSI Series 700 Thermilinear Probes are often the best choice.

The Yellow Springs Instrument Co. produces many other thermistor types as do other manufacturers. These other types can also be interfaced to the CyberAmp via the AI 490 Connector and AI 491 Cable Kits. Several different interface circuits are suggested in the manuals for the CyberAmp series of amplifiers.

IC Temperature Transducers that Produce an Output Current Proportional to Absolute Temperature

The most notable of these temperature-dependent current sources are the Analog Devices, Inc. (Norwood, MA) AD590 with a temperature range of -55 to +150°C and the lower-cost AD592 with a temperature range of -25 to +105°C. These are not available in the wide range of probe configurations provided by thermistor manufacturers. Most often they are supplied in 0.23" (5.8 mm) diameter metal cans or in 0.25" x 0.093" (6.4 mm x 2.4 mm) ceramic flat packs. These need to be connected to wires and must be insulated for special purposes. The only temperature probe available from Analog Devices is the AC2626, which includes an AD590 enclosed in a 4" (102 mm) or 6" (103 mm) long stainless steel sheath with a 3/16" (4.8 mm) outside diameter.

When connected to a DC voltage source (*e.g.,* the +5 V excitation voltage in the CyberAmp) these transducers force the current that flows in the circuit to be equal to 1 µA/°K. The external circuitry required to use the AD590 is very simple and it is easy to configure for minimum and average temperature measurements by placing transducers in series or in parallel, respectively. The absolute accuracy and interchangeability of these probes is inferior to the Thermilinear Probes described above. In their best and most expensive grade, the interchangeability is ±0.5°C at 25°C. The main advantages of the AD590 temperature probes are that the external support circuitry is very simple and that they are suitable for remote sensing applications. Because the output is insensitive to voltage drops, the devices can be used with twisted-pair cabling hundreds of feet in length.

The Analog Devices semiconductor temperature probes can be interfaced to the CyberAmp via the AI 490 Connector and AI 491 Cable Kits, with the user providing the interface design based on the range of application circuits provided by Analog Devices and in the manuals for the CyberAmp amplifiers.

IC Temperature Transducers that Produce an Output Voltage Proportional to Absolute Temperature

Two of the most suitable temperature-dependent voltage sources are the LM35A and the LM135A sensors from National Semiconductor Corporation (Santa Clara, CA). These have absolute accuracies (interchangeability) of ±0.5°C and ±1.0°C, respectively, at 25°C. The LM35A has a zero voltage output at 0°C and a sensitivity of 10 mV/°C. The LM135A behaves as a zener diode with a zero voltage output at 0°C and a sensitivity of 10 mV/°C. These devices are generally cheaper than the AD590 transducers. They are supplied in approximately 0.2" (5 mm) metal cans or plastic packages, but they are not available in ready-to-use probes.

The National Semiconductor temperature probes can be interfaced to the CyberAmp via the AI 490 Connector and AI 491 Cable Kits with the user providing the interface design using the range of application circuits provided by National Semiconductor and in the manuals for the CyberAmp amplifiers.

Temperature Transducers for Extended Temperature Ranges

Two types of transducers are commonly used for temperature measurements beyond the physiological range: thermocouples and resistance temperature detectors.

Thermocouples

Thermocouples are economical and rugged transducers, having the advantage of small size with a very fast response time and a wide temperature range. Thermocouples consist of two dissimilar metals in contact. The offset potential between the metals is proportional to temperature (see Table 7-1). The low sensitivity and broad operating range generally make thermocouples more suitable for industrial applications than for physiological ones. Because of their greater sensitivity, thermistors are more popular than thermocouples for most physiological applications. On the other hand, thermocouples can be fabricated in remarkably small sizes, creating the opportunity for some unusual biological applications. For example, micron-dimension thermocouples that can be inserted into single living cells have been described (Cain & Welch, 1974). Commercially available thermocouples can be obtained with diameters as low as 25 µm and thermal time constants as short as 2 ms (High Temperature Instruments Corp., Philadelphia, PA; Omega Engineering, Inc., Stamford, CT).

ANSI Type	Min Value °C	Max Value °C	Sensitivity at 20°C µV/°C	Material
E	-200	900	60.48	chromel/constantan
J	-200	750	51.45	iron/constantan
K	-200	1250	40.28	chromel/alumel
R	0	1450	5.80	platinum/Pt-13% rhodium
S	0	1450	5.88	platinum/Pt-10% rhodium
T	-200	350	40.28	copper-constantan

Table 7-1. Common Thermocouple Materials

Thermocouples require a reference temperature that traditionally was an ice bath but is more commonly provided by a compensation circuit. Complete signal-conditioning modules, such as the Analog Devices AD594 and 2B50 signal conditioners, exist. They contain the differential amplifiers and the temperature compensation circuitry. Alternatively, voltage-output temperature transducers, such as the LM35A, can be used to derive a compensation voltage to apply to the negative input of the CyberAmp. The Axon Instruments AI 418 Thermocouple Adapter directly accepts type K thermocouples. To interface other thermocouples to the CyberAmp, the user must provide an interface circuit using a temperature transducer for compensation or using the Analog Devices or equivalent conditioning modules. Circuit examples are given in the CyberAmp manuals.

Resistance Temperature Detectors

Resistance thermometers can be made of metals or ceramic-like mixtures. By convention, resistance thermometers made of metals are called Resistance Temperature Detectors (RTD), while the ceramic-like resistance thermometers are called thermistors.

The resistance of most metals increases with increasing temperature. The sensitivity is small, less than 0.4% per °C. The most commonly used metal is platinum because of its wide linear resistance-to-temperature relationship.

Platinum RTD's offer better stability and linearity than thermocouples, but are limited to temperatures below 850°C. Most platinum RTD's have a resistance of 100 Ω at 0°C and a positive temperature coefficient of 0.385% per °C at 0°C.

The simplest way to configure a platinum RTD is to excite it with a small, accurate DC current. Currents of 1 mA or less are used so as to minimize self-heating. A differential amplifier is used to measure the voltage across the RTD. If the excitation current is 1 mA, the sensitivity is 385 µV per °C. To interface RTD's to the CyberAmp, the user must provide an interface circuit. Circuit examples are given in the CyberAmp manuals.

Electrode Resistance and Cabling Affect Noise and Bandwidth

The electrode impedance (resistance), the capacitance of the cable to the electrode, and the amplifier input impedance combine to produce resistive dividers and filters (Figure 7-1) that can substantially degrade the quality of a recorded signal. The easiest solution to these potential problems is to use high-impedance probes (*e.g.*, AI 401, AI 402) and place them as close as possible to the electrodes.

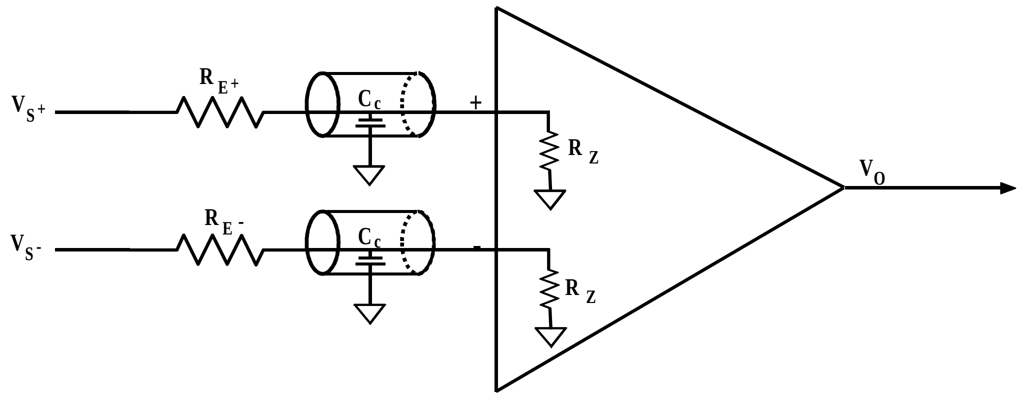


Figure 7-1. Electrode Resistance and Cabling Can Degrade a Signal

The electrode impedances (resistances) R_E combine with the amplifier input impedances R_Z to produce resistive dividers. R_Z also combines with the capacitance of the cable to the electrodes C_C to produce low-pass filters. V_S and V_O are the source and output voltages.

High Electrode Impedance Can Produce Signal Attenuation

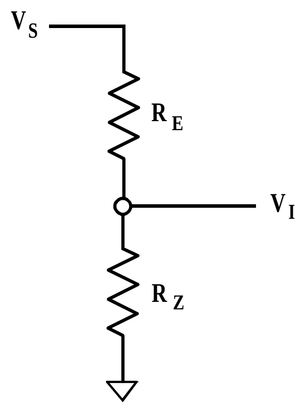
The electrode resistance in series with the amplifier input impedance acts as a voltage divider (Figure 7-2). The CyberAmp has input impedances of 1 MΩ and if the electrode resistance is 1 kΩ, this reduces the signal by only 0.1 %, since

$$V_I = \frac{1\ \text{M}\Omega}{1\ \text{k}\Omega + 1\ \text{M}\Omega} V_s \qquad (1)$$

However, if the electrode resistance is 100 kΩ, the signal would be reduced by about 9.1%, since

$$V_I = \frac{1\ \text{M}\Omega}{100\ \text{k}\Omega + 1\ \text{M}\Omega} V_s = 0.909\ V_s \qquad (2)$$

The solution to high electrode resistance is to use a high-input impedance amplifier. If using a CyberAmp then you should use a high-impedance probe between it and the electrodes. The AI 401 x10 Low-Noise Differential amplifier probe and the AI 402 X50 Ultra Low-Noise Differential amplifier probe both have input impedances measured in the teraohms (10^{12} Ω).



$$V_I = \frac{R_Z}{R_E + R_Z}$$

Figure 7-2. High Electrode Resistance Can Attenuate a Signal and Increase Crosstalk
The resistance of each electrode in series with the amplifier input impedance acts as a pair of voltage dividers. This can reduce the recorded amplitude of the signal. If the electrode impedances are not matched, it will reduce the CMRR leading to amplification of common background signals. R_E and R_Z are the electrode and amplifier impedances. V_S and V_I are the source voltage and input voltage to the amplifier.

Unmatched Electrode Impedances Increase Background Noise and Crosstalk

When making differential measurements such as EMG, EKG and EEG it is important that both electrodes have similar properties. As we have seen above, high electrode impedance can produce signal attenuation. If we apply Figure 7-2 to both inputs of Figure 7-1, we see that we could easily get greater attenuation of the signal at one electrode than at the other. This can substantially degrade the common mode rejection ratio (CMRR) and result in amplification of common background signals that would otherwise be rejected.

For a differential amplifier, the CMRR is the ratio of the response for a signal at just one input to the response for a common mode signal (applied to both inputs) of the same amplitude. The CMRR of the CyberAmp is 100 dB (at high gain). That is, the output voltage with a signal applied to just one input is 100,000 times greater than the output voltage with the same signal applied to both inputs. (The ratio of amplitudes is measured in decibels where $dB = 20 \log_{10}(V_{out}/V_{in})$. A ten-fold increase in the ratio equals a 20 dB increase (see **Chapter 6**).

If the electrode impedance of one electrode connected to a CyberAmp is 1 kΩ and that of the other electrode 10 kΩ, then the CMRR of the system as a whole is reduced 1,000 fold to 41 dB.

Applied to a single channel of the CyberAmp:

$$V_I = \frac{1\ M\Omega}{1\ k\Omega + 1\ M\Omega} V_s = 0.999\ V_s$$

$$V_I = \frac{1\ M\Omega}{10\ k\Omega + 1\ M\Omega} V_s = 0.990\ V_s$$

The difference equals 0.009,

$$\text{CMRR} = 20 \log_{10}(0.999/0.009) = 41 \text{ dB}$$

As for the problem of the signal attenuation, the solution to a mismatch of electrode resistances is to use an amplifier probe with very high input resistance such as the AI 401 and the AI 402. With each of these probes, the electrode impedances used in the example are too small to have any influence on the CMRR of the probes.

If high-input impedance probes are not available, the CyberAmp has a built-in capacity to measure electrode impedances and this should be carried out prior to each recording session to ensure a match. This is a good idea anyway as it can reveal the development of faults such as breaks in the electrodes.

Crosstalk from other body signals can occur for additional reasons, although infrequently. For example, if invasive EMG leads are routed subcutaneously near the heart, the EKG can capacitively couple into the EMG leads. This problem is eliminated by recording differentially using lead pairs that are twisted together, or by not routing the EMG leads near the heart.

High Electrode Impedance Contributes to the Thermal Noise of the System

With an active amplifier the only noise sources encountered are the thermal noise of the electrode, the noise provided by the amplifier itself, and crosstalk from other body signals.

Thermal noise, also called Johnson noise, is a voltage produced across the terminals of all resistive elements (including electrodes) due to the random motion of charge carriers within the element. Thermal noise is proportional to the resistance (R) and absolute temperature (T) of the resistive element (see **Chapter 12**). To minimize the thermal noise contribution, the electrode resistance must be minimized. This is usually accomplished by maximizing the surface area of the electrode and ensuring good electrical contact.

The noise contribution to the signal from the amplifiers is negligible if the amplifier noise is less than the thermal noise of the electrodes. All Axon Instruments amplifiers have very low noise levels. The lowest noise amplifier, the AI 402 x50 differential amplifier probe, has extremely low noise of just 1.1 $\mu V_{p\text{-}p}$ in the DC-10 kHz bandwidth (0.18 µV rms). This is approximately equivalent to the thermal noise of a 250 Ω resistor. This means that for electrodes whose resistance exceeds 250 Ω, the thermal noise of the electrode exceeds the noise of the amplifier.

Cable Capacitance Filters Out the High-Frequency Component of the Signal

The source resistance, together with the capacitance of the cable to the amplifier, act as a simple RC low-pass filter (Figure 7-1). Electrical cables can provide 30 -100 pF capacitance per foot (100 -300 pF per meter). If a cable has a 1,000 pF capacitance and the electrode resistance is 10 kΩ, then the cut-off frequency is about 16 kHz. A 100 kΩ electrode resistance with the same cable would filter the signal at 1,600 Hz. The appropriate solution is to use an active probe as close to the signal source as possible.

EMG, EEG, EKG and Neural Recording

EMG

Electromyograms (EMG) can be recorded in many ways, each with its own special requirements. Surface EMG electrodes have the advantage of being non-invasive but suffer from artifacts or even total loss of signal during movements. They are also not as selective as implanted electrodes.

Implanted electrodes must be capable of remaining in the same location and must be of an appropriate size and separation. EMG electrodes available from Semcos Associates (Heathmont, VIC, Australia) are constructed from gold-plated dental probes with many tiny barbs that hold the electrode in place in the muscle. Bipolar electrodes should be placed in parallel with the muscle fibers to record the maximum signal with an electrode spacing of 2 -10 mm appropriate for most mammalian muscles. This close spacing of electrodes reduces crosstalk from other muscle sites and is therefore appropriate for selective recording from local areas. Low-frequency components of electrical signals propagate for larger distances in body tissues than do high-frequency components. The bipolar electrode configuration acts as a high-pass filter whose cut-off frequency is determined by electrode spacing. Close spacing results in a high cut-off frequency, thus filtering out some of the remaining low-frequency components from distant muscle activity. However, close electrode spacing also reduces the amplitude of the signal in a non-linear fashion. Larger electrodes reduce the impedance (see section on source impedance and noise) but are less selective regarding the site of muscle activity.

The frequency range of the EMG is between 10 - 2,000 Hz, although the electrode configuration and separation will have considerable influence on what frequencies are recorded. The signal size ranges from 5 µV - 20 mV for surface recording and from 50 - 1,000 µV for invasive recording.

Several probes are available for recording EMG with the CyberAmp. These include the AI 401, 402, 404 and 405 active amplifier probes, the AI 417 passive adapter and direct user connection.

EKG

There are probably more books available on electrocardiogram (EKG) recording and analysis than any other electrophysiological topic. The signals are usually of large amplitudes and readily recorded without the need for any amplifier probes. As electrode spacing is reduced, there is an increasing possibility of recording unwanted EMG signals from neighboring muscles. Consequently, the traditional electrode sites are worth considering. The AI 417 Passive 2 mm Adapter provides a single differential EKG channel and plugs directly into the CyberAmp.

The normal frequency range of the mammalian EKG is 0.2-100 Hz; its amplitude size is up to 2-3 mV.

EEG

The electroencephalogram (EEG) ranges from 10 - 300 µV in amplitude and has a frequency range from 0.2-50 Hz. A single differential EEG channel is best recorded with the assistance of one of the low-noise AI 400 series active probes.

Nerve Cuffs

Nerve-cuff recordings have a frequency response to 10 kHz and an amplitude in the low microvolt range. The AI 402, x50 Ultra Low-Noise Differential amplifier probe is designed for this application, with 10 kHz noise of less than 0.18 μV_{rms} (1.1 $\mu V_{p\text{-}p}$) in the 0.1-10 kHz bandwidth.

The nerve cuffs themselves are very simple to make by running bare stainless steel fine wires through a small length of silicone tubing split longitudinally. Any bared wires that are in contact with the outer surface of the cuff can be insulated with silicone adhesive.

Metal Microelectrodes

The impedance of metal microelectrodes may be several hundred kilohms or more. All of the low-noise AI 400 series active probes are suitable for recording from high-resistance microelectrodes. Since the input capacitance of the AI 401 differential amplifier probe is approximately 5 pF, the largest electrode resistance consistent with maintaining a 10 kHz bandwidth is about 3 MΩ.

Bridge Design for Pressure and Force Measurements

Pressure and force transducers are often constructed using strain gauges connected in a Wheatstone Bridge circuit. The basic circuit is shown in Figure 7-3.

The Wheatstone bridge should be considered as two pairs of resistive dividers with the output voltage equaling the difference between the voltages at (A) and (B). The bridge circuit is good for detecting small changes in resistance, and the output is linear in the region of balance, *i.e.*, when the voltage difference is small.

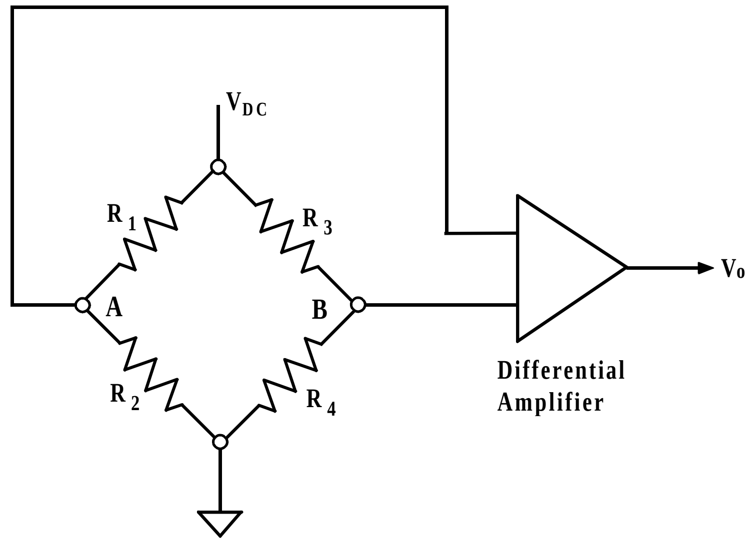


Figure 7-3. Wheatstone Bridge Circuit with Amplifier

The largest output comes from having strain gauges for all four resistive elements, although physical constraints may require the user to have only two or even one "active" element. For applications where only two gauges can be used, they should be placed in positions R1 and R2 and the gauges should be located such that one increases in resistance and the other decreases in resistance during the applied pressure or force. This is usually achieved by placing the elements on opposites sides of the beam under strain. When choosing strain gauges, keep in mind that semiconductor types have outputs ten times higher than metal-film types.

The sensitivity of a bridge circuit decreases with increasing temperature and some applications may therefore require the addition of a temperature compensation circuit that should be placed as close as possible to the bridge in order to experience the same temperature changes.

Pressure Measurements

In the past, high-quality pressure transducers were very expensive and suffered from significant temperature sensitivity. The introduction of semiconductor pressure transducers has greatly reduced the cost, decreased the temperature sensitivity and enhanced the range of transducer devices available.

An important point when measuring very low pressures is to set the height of the pressure transducer to that of the sense location in order to avoid hydrostatic errors introduced by fluid-filled catheters. Pressure transducers should also be kept out of the range of heat sources such as heat lamps to avoid temperature-induced increases in the signal output.

Major producers of semiconductor pressure sensors include SenSym, Inc. (Sunnyvale, CA) and Honeywell, Inc. (Minneapolis, MN). Blood pressure transducers from Cobe Laboratories, Inc. (Lakewood, CO) have a usable range of -50 to +300 mm Hg and can be interfaced to the CyberAmp via the AI 410 Cobe CDX III adapter.

All other pressure transducers are compatible with the Axon Instruments range of amplifiers and signal conditioners and can be interfaced to the Axon Instruments CyberAmp via the AI 490 Connector and AI 491 Cable Kits.

Force Measurements

The requirements for force measurements are so diverse that many people need to make their own force transducer, although some are commercially available (*e.g.*, BLH Electronics, Inc., Waltham, MA; Grass Instruments Company, Quincy, MA). The Axon Instruments AI 411 Grass Transducer adapter is suitable for direct attachment of the Grass Instruments FT03 and FT10 force transducers. Force transducers have some compliance and you must consider this when choosing transducers. For example, with the Grass Instruments FT10, a force of 100 N will stretch the device by 1 mm.

For user-designed force transducers the two main choices are between resistive or semiconductor strain gauges. Resistive gauges are cheaper and generally more rugged while semiconductor strain gauges are smaller and about 10 times more sensitive.

User-designed force transducers can be interfaced to the CyberAmp via the AI 490 Connector and AI 491 Cable Kits. Strain gauges and diaphragms are available from BLH Electronics and Entran Devices, Inc. (Fairfield, NJ). Bonding of the strain gauges to the transducer block can be performed with cyanoacrylate, or for wet environments, Araldite AV138M (CIBA-GEIGY Polymers, Hawthorne, NY).

Acceleration Measurements

Accelerometers from Pennwalt Corporation (Valley Forge, PA) consist of piezoelectric pressure sensors attached to a test mass. They are small enough for physiological experiments and are supported by the Axon Instruments AI 414 Pennwalt accelerometer adapter. These piezoelectric accelerometers have a wide frequency range (1 Hz to 25 kHz) and a wide dynamic range (0.01 - 150 g). Entran Devices, Inc. (Fairfield, New Jersey) manufactures accelerometers consisting of strain gauges attached to a mass. Alternative systems use feedback to prevent the test mass from being displaced; the amount of the applied feedback force represents the output signal.

Length Measurements

Implantable Length Gauges

Length can be measured inside an animal using mercury-filled or saline-filled silicone tubing length gauges (Lemon and Prochazka, 1984). As the tubing is stretched, the impedance of the transducer increases. To avoid the generation of bubbles in the tubing, a high-frequency AC signal is used with an AC bridge circuit. In practice, these gauges have many difficulties and may not be much better than cinematography techniques using markers on the limb joints for measuring muscle lengths.

Linear Potentiometers

Linear potentiometers are available in short and long lengths (at least 4") with linearity to 0.1% (Waters Manufacturing, Inc., Wayland, MA). They are inexpensive and very simple to use but must be perfectly aligned to avoid internal damage. Linear potentiometers can be interfaced to the CyberAmp via the AI 490 Connector and AI 491 Cable Kits.

Linear Variable Differential Transformers (LVDT)

Linear variable differential transformers are used for accurate and stable measurement of linear position and displacement. Rotary variable differential transformers (RVDT) are similarly used to measure rotation. These devices are very rugged and since there is no contact between the core and the body of the LVDT (or RVDT), there is no friction or wear, providing essentially infinite life. Linearity of ±0.25% over the full range is typical (Transicoil, Inc., Plymouth Meeting, PA). Full-scale LVDT ranges are typically limited to ±1 inch or less. Most LVDTs can be connected to the CyberAmp 380 using the AI 419 LVDT adapter.

Self-Heating Measurements

As a result of applying an excitation current or voltage to the temperature measurement sensor, power is dissipated in the sensor. This power dissipation causes the temperature of the sensor to rise above the ambient temperature that is being measured. This phenomenon is referred to as "self heating." For most of the temperature sensors used in physiology, it is necessary to keep the power dissipation to a few milliwatts or less. If this condition is met, temperature changes of less than 0.01°C can be measured.

Other transducers, such as strain gauges, are temperature-sensitive; therefore it is important not to allow self heating in these transducers to cause a temperature rise sufficient to affect the measurement.

Isolation Measurements

In industrial environments, it is common for signal leads from transducers to be run over long distances past machinery that can induce large voltages in the leads. To protect the measurement instrument, isolation amplifiers should be used for each transducer. Induced voltages are not commonly a problem in animal physiology applications and, therefore, isolation is not required.

Note that if measurements are to be made from human subjects, isolated probes that are approved for human use must be used.

Insulation Techniques

Electrodes that are implanted for long-term recording eventually fail either due to the rupture of a solder joint, breakage of wires at points of repeated flexion, or moisture penetration through the insulation. Although teflon-insulated wire is commonly used, when it is connected to the leads of the transducer it is difficult to join the teflon insulation to the insulation on the transducer leads. A solution is to etch the teflon so that it will adhere to the adhesive used to join the two insulations. In practice it is often faster and better to use PVC-insulated wires because it is much easier to make a strong adhesion, even though PVC is more permeable to water over the long term. Also, Araldyte AV138M (CIBA-GEIGY) and Epoxylite #6001 (Epoxylite Corporation, Anaheim, CA) both provide excellent water-resistant insulation for rigid applications.

Special attention should be paid to providing strain relief where wires, and particularly connections, are repeatedly flexed. Sliding a length of silicon tubing over the stress region often reduces this problem.

Suggested Manufacturers and Suppliers of Transducers

Analog Devices, Inc.
Two Technology Way
P.O. Box 280
Norwood, MA 02062-0280
Phone: (617) 329-4700

BLH Electronics
42 Fourth Avenue
Waltham, MA 02154
Phone: 617-890-6700

CIBA-GEIGY Polymers
7 Skyline Drive
Hawthorne, NY 10532
Phone: (914) 785-2000

Cobe Laboratories, Inc.
1185 Oak Street
Lakewood, CO 80215
Phone: 303-232-6800

Entran Devices, Inc.
10 Washington Avenue
Fairfield, NJ 07006
Phone: 201-227-1002

Epoxylite Corporation
9400 Toledo Way
Irvine, CA 92718
Phone: (714) 951-3231

Grass Instrument Company
101 Old Colony Avenue
P.O. Box 516
Quincy, MA 02169
Phone: 617-773 0002

Honeywell. Inc.
Honeywell Plaza
Minneapolis, MN 55408
Phone (612) 870-2294

National Semiconductor Corporation
2900 Semiconductor Drive
Santa Clara, CA 95052-8090
Phone: 408-721-5000

Omega Engineering, Inc.
1 Omega Drive
Stamford, CT
Phone: 203-359-1660

Pennwalt Corporation
Kynar Piezo Film Department
P.O. Box 799
Valley Forge, PA 19482
Phone: 215-666-3500

Semcos Associates
26 Heathwood Street
Heathmont, VIC 3135
Australia
Phone: 613-729-5763

SenSym, Inc.
1255 Reamwood Avenue
Sunnyvale, CA 94089
Phone: 408-744-1500

Transicoil, Inc.
One Apollo Road
Plymouth Meeting, PA 19462
Phone: 215-825-9200

Waters Manufacturing, Inc.
552 Boston Post Road
Wayland, MA 01778
Phone: (508) 358-5460

Yellow Springs Instrument Company
P.O. Box 279
Yellow Springs, Ohio 45387
Phone: (513) 767-7241

Further Reading

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