Interfacing Considerations
Interference

Chapter 3

In the first two chapters, it is easy for the reader to get the (correct) impression that transducer interface circuitry often involves the ability to deal with small signals. Whether one is simply seeking to resolve signals that are inherently small or to accurately handle signals with a wide dynamic range (or both!), one must pay attention to some factors that are not shown on a professionally drawn schematic diagram. These matters are sufficiently important to warrant discussion here before any further consideration of circuit elements, circuits, or system applications.

One can classify interference problems roughly in these three areas:

Problems generated locally (e.g., unwanted thermocouples)
Problems communicated within a subsystem (e.g., via grounds)
Problems originating in the outside world (e.g., power-frequency interference)

Causes and cures of a few of the most-frequently encountered problems will be discussed here. Several useful publications (two of which are available from Analog Devices without charge) will be found in the Bibliography. They should be part of the working library of anyone concerned with low level signals or performing precision measurements in the face of great odds.

LOCAL PROBLEMS

In low-level measurements, strict attention must be given to the materials used (or found) in the signal path. As Figure 1-5b shows, the combinations of solder, wire, binding posts, etc., found in a simple circuit can generate substantial thermal emf's. Since they usually occur in pairs, it is useful to go to pains to keep such pairs at the same temperature, and in general, to seek to minimize thermal gradients by thermal shielding, heat-sinking, alignment along isotherms, and separation of high- and low-power circuitry. Even such innocuous practices as joining stranded wires from two different manufacturers can produce 200nV/°C, or twice the hard-won drift level of a chopper-stabilized amplifier.

Sockets permit convenient replacement of electrical components and subassemblies, but a poor one can introduce contact resistance, thermal potentials, or both, and can be a source of failure if exercised more than a few times. Because a good mechanical switch can be quite expensive, every effort should be expended to eliminate the requirement for high-performance switches by judicious choice of the point in the circuit at which switching takes place. For example, in an op amp circuit, gain-switching terminals should be wired to the high-level output, rather than to the summing point.

In general, the price for the convenience provided by switches, relays, connectors, and sockets is increased uncertainty of resolving low-level signals, i.e., somewhat poorer resolution and accuracy, increased noise, and lower reliability than might be attained in a direct-wired system. Since the electronics is a small element of cost in many of the ultimate applications for which transducers are required, it usually pays to obtain the best-quality hardware available. There are available specialized connectors designed for signal-carrying applications, with excellent electrical characteristics. Very often, the transducer manufacturer will specify or provide such a connector. Such switches as the Leeds & Northrop Type 34 are quite good with respect to contact potentials and resistance.

Banana jacks are the best connector generally available for low-level dc and are in common use in standards laboratories. For heavy-duty use, barrier strips with screw-type terminals are widely employed. It's not a good idea to use BNC-type connectors for low-level dc measurements, though they are optimal for high-frequency ac work.

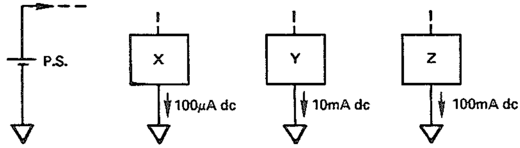
As Figure 1-5b shows, even solder can become a culprit at low levels, because of the thermal emf's generated in solder joints. Special low-thermal solders, such as Kester Type 1544, should be used at the inputs to microvolt-level circuits. There are instances where it may be necessary to deliberately cut and re-splice (with solder) a connection in a line, in order to counterbalance a thermal emf introduced by a splice or solder connection in another line. Needless to say, one should seek to keep both connections at the same temperature.

SUBSYSTEM PROBLEMS

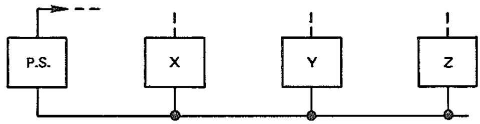
The lines drawn on a schematic drawing do not usually resemble the circuit wiring that is actually desired; Unlike the circuit wiring, the lines on a drawing are assumed to be free of resistance, inductance, and capacitance. Since they are, they may go to any lengths for purposes of clarity, pleasing appearance, or minimum drafting effort. For clarity, wires that go to many locations–such as power-supply leads, and "grounds"–may simply be terminated in tags, such as V_S, or ⏚ ; it is assumed that when the device is built, all such points will be at equal potential. But how equal is "equal" when we're processing signals in which microvolts may be significant? The two functions that suffer the greatest abuse due to lack of care in thinking and drawing are *grounding* and *bypassing.*

There is perhaps no more-misused word in electrical engineering today than "ground". Marconi and the Edison Company intended that grounded parts of the circuit be connected to rods that were literally "earthed", or driven into the ground. And today there are parts of electrical circuits for which the term "ground" is still validly used because of a solid tie to Earth (however, the electrical properties of Earth differ a great deal from place to place). The term has come to include a variety of other forms of common connection, including "grounding" to a metal chassis or housing, "grounding" to the low side of a power supply, and "grounding" to the common connection for input and output signals–in all cases, with very tenuous (if any) relationships with the Earth.

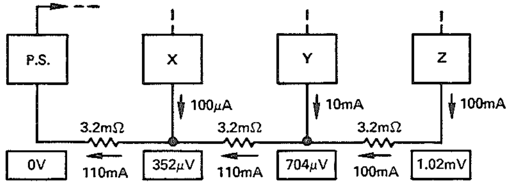
A consequence of the careless use of the "ground" concept can be seen in Figure 3-1. In (a), we see the lower end of several parts of a circuit, and the power supply, as drawn by the engineer, who intends that all the ground symbols be at the same potential. In (b), the circuit is redrawn, following the general configuration of (a), but with a (presumably equipotential) line connecting the "grounded" points, In (c), the circuit has been wired in approxi-



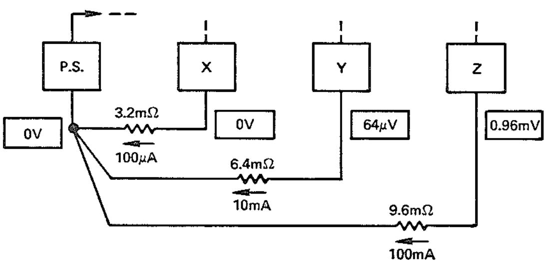
a. Basic circuit



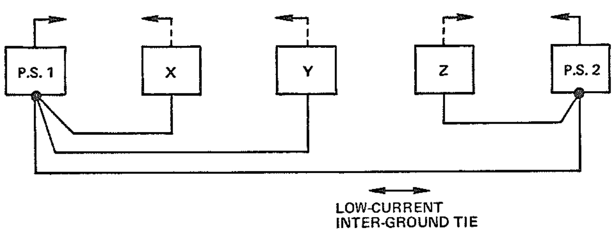
b. Circuit as drawn



c. Circuit wired with 6" lengths of #18 wire. Voltages at each "ground" point are shown.



d. Circuit wired to single-point ground



e. Separate supply for Z

Figure 3-1. A grounding example

mately the same configuration as (b) with #18 wire; the resistance of the 6″ lengths is about 3.2 milliohms (mΩ). The low end of circuit Z is at about 1mV, and the low end of low-power (and perhaps small-signal) circuit X is at 352μV. If, for example, X were an op amp, with its + input tied to the local ground point, the summing point would effectively be at an offset of 352μV with respect to a signal source referenced to the power supply. It is worth noting that the #18 wire specified here is perhaps somewhat heavier than the usual #20 or #22 wire used in electronic wiring; it would have even larger voltage drops.

One approach to improvement of the situation is shown in (d); a separate lead is run from each circuit to the low end of the power supply. The offset at circuit X is now negligible, the offset at circuit Y has been reduced by more than 90%, but the offset at Z is still about 1mV. Further improvement for Z, if necessary, could be gained by using heavier wire for its return, or perhaps by interchanging X and Z physically, if other considerations permit, or even by the use of a separate supply (e).

The circuit of (d) has essentially achieved the objective of (a), i.e., to return all of the circuit low points to a single common "ground" point and avoid the sharing of voltage drops in long leads. Note that each line is returned separately, and that no mixing of ground currents is permitted. In practice, the single-point ground may be an actual block of metal, to provide the lowest possible resistance at the common point.*

The common may be a *heavy* bus, just so long as interference is kept at a satisfactorily low level. Such a bus might be a suitable common connection for digital circuitry; it would then be connected to the analog common point to establish the basic system common.

Systems involving multiple power supplies and multiple chassis require more thought. Often, returning all lines, regardless of which supply they originate from, to the common point, and then tying the system common terminals together there will work. In other systems, such as (e), all +5V loads are returned to +5V common, all +15V loads returned to +15V common, and a final line is run between the common terminals to tie them together. In

*If power-supply voltage drops must be minimized, the "high" leads may be wired in a similar manner.

multiple-supply systems, intelligent experimentation may be needed to achieve the best compromise.

Digital ground lines are usually quite noisy and have large current spikes. All analog common leads should be run separately from the digital common leads and tied together at only one point (Figure 3-2).

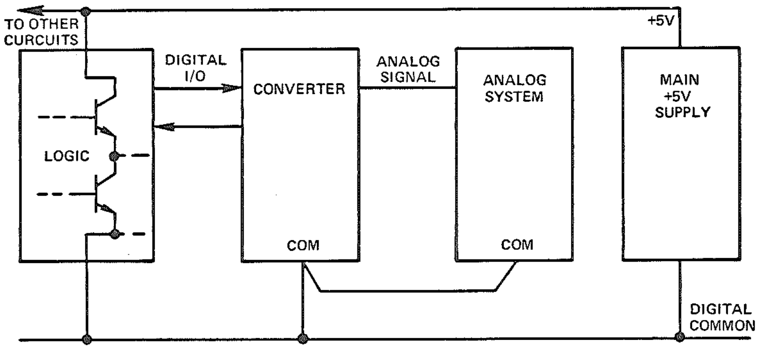


Figure 3-2. This connection minimizes common impedance between analog and digital (including converter digital currents)

In some cases, grounding problems can be solved by using instrumentation amplifiers as buffers at critical locations, converting the ground voltage into a common-mode voltage, which is rejected by the amplifier's differential input Figure 3-3. If very high-level and very low-level circuits must be used together, it may be desirable to float the circuits and transfer digital information via opto isolators and analog information via isolation amplifiers.

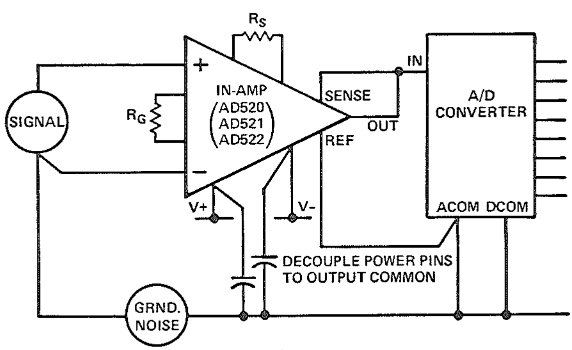


Figure 3-3. Use of instrumentation amplifier to interface separate ground systems

Besides the dc and low-frequency ground problems, there is also potential coupling of fast ac and transient signals from high-level circuits to low-level circuits through common power-supply and wiring impedances. Another way such signals can be coupled is a result of the fact that many internally compensated IC operational amplifiers do not have a dynamic connection to common; instead the reference for the output integrator is connected to one side of the power supply, and the output is subject to its perturbations, even if ground is as steady as a rock (Figure 3-4).

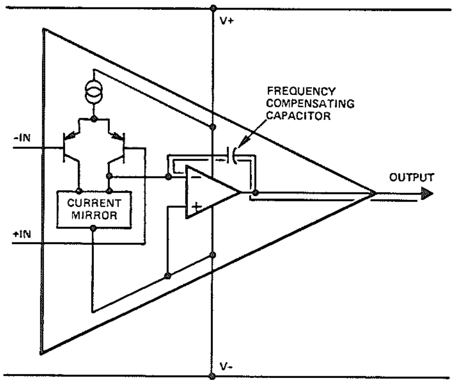


Figure 3-4. Typical op-amp circuit architecture. Reference for output integrator is V–.

Both situations call for *bypassing* of high-frequency signals around slower analog circuitry by the use of judiciously placed capacitors. The capacitors are connected *directly* from amplifier power-supply terminals to the low-impedance common point.

Figure 3-5 illustrates this technique, as applied to decoupling the

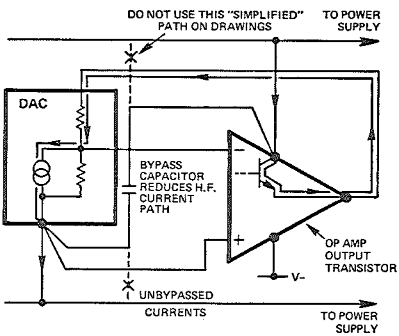


Figure 3-5. Bypassing power supplies for virtual-ground applications. Arrows show unbypassed current flow.

noisy digital drive of a d/a converter from the analog output op amp. Note that if the bypass capacitor is drawn randomly as a straight connection between the two supply buses, and if it is physically connected in the same way, it will serve no useful purpose. Indeed, it can be harmful, by providing a low-impedance ac path for noise to go from a dirty ground to a previously clean V_S.

OUTSIDE AND LOCAL INTERFERENCE

AC signals at high power and high frequency can be coupled to low-level analog circuitry via stray capacitance and inductance. High dc voltage can be coupled to high-impedance input terminals via leakage conductance. Proper layout, shielding, and guarding are the defenses against these sources of interference. Elements of proper layout include keeping as much distance as possible between high-energy and low-energy circuits, and between digital and analog circuits, and as *short* a distance as possible between destinations of low-level wiring.

Both electrostatic and electromagnetic shielding are warranted in many cases. Power-supply transformer fields (especially from small modular supplies) are notorious sources of seemingly inexplicable problems. Simple approaches are either to use shielded types, or to mount the supply remotely from sensitive circuits. Paradoxically, the same circuit that requires the center tap of a transformer to be close by to achieve a high-quality grounding scheme may be disturbed by the intensity of the transformer's magnetic field. Often, it is necessary to experiment in order to determine the most suitable layout. For example, one can connect a simple R.F. choke across an oscilloscope probe to determine the presence and relative strength of high-frequency fields; this procedure will be found helpful in preliminary layout assessment.

Electrostatic and electromagnetic interference from the ubiquitous 50-60Hz power line can be brought under control by minimizing areas of wire loops, use of twisted pairs, shielding, and bandwidth limiting in low-frequency circuits. Battery-powered circuits, despite their isolation from the mains, are still susceptible to 60Hz pickup. A few picofarads of capacitance to ground can seriously degrade the performance of an ill-prepared battery-powered amplifier.

Often, small, shielded houses will have to be constructed around an amplifier or an assembly to prevent interference from fields or energy-radiation within the system itself. Another form of shielding that must be considered is *thermal* shielding against hot spots and gradients. Consider the relationships between placement of high-dissipation and low-level portions of a system. Make sure components are not exposed to drafts and unequal temperature distributions.

Guarding is a technique used to prevent ac and dc leakage currents from degrading circuit performance. Guards are conductive surfaces usually placed close to inputs or other points in a circuit that are sensitive to stray currents. The guard is driven at low impedance to a potential that is very close to (nominally equal to) the voltage being protected. If the guard is properly placed stray leakage current will be absorbed by the guard. Since the guard is at the same potential as the protected point, no leakage current will flow between them. Figure 3-6a shows a simple application of a guard to a high-impedance unity-gain follower input. Another advantage of the guard is in reducing the input capacitance of the circuit. Stray capacitance from the outside world is to the guard, not the

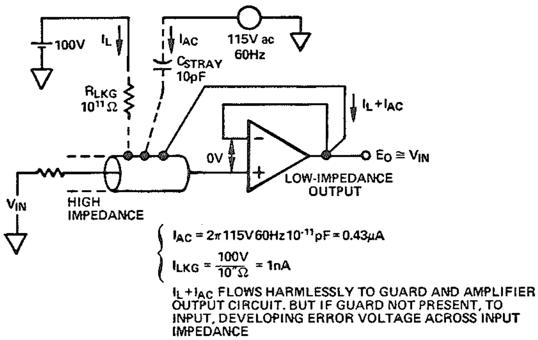
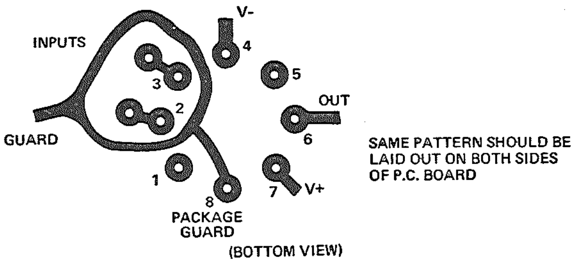


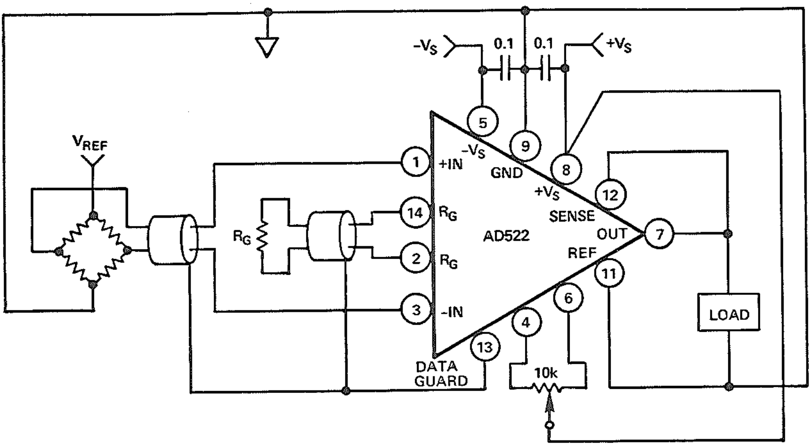
Figure 3-6a. Example of guard circuit—follower-connected op amp

input terminal; again, since the guard and the input terminal are at about the same potential, very little displacement current flows between them, hence, the effective capacitance is virtually nil. In circuit-board work, a guard ring should completely enclose the protected point, and a jumper should be used for interconnections (Figure 3-6b). This technique is particularly important at dc when low bias-current op amps are used.

Additional discussions of the necessity and techniques for reducing appropriate forms of interference will be found in descriptions of a number of applications in the Applications section.



b. Board layout for guarding inputs of AD515 with guarded TO-99 package



c. Use of the AD522 instrumentation amplifier's guard terminal to guard both the input connections and connections to a remote gain-setting resistor

Figure 3-6. Guarding

ANALOG FILTERING

Despite the best of efforts to reduce interference, the signal may include too much noise to ignore. Indeed, this may not be the fault of the designer of the signal-conditioning circuitry; the noise may have been present in the signal itself, or if the input information is modulating an ac signal, demodulation and filtering must take place. For most of the transducers discussed in this book, the information is fairly slow, with typical bandwidths of the order of 10Hz maximum; filtering of these signals is relatively easy.

Again, it is important to observe that no filter, however well-intended or crafted (or cheap) is justifiable as a substitute for proper attention to wiring, layout, and shielding techniques; rather, it is an adjunct to them. Every effort should be expended to keep noise out of the system. Low-level leads (especially those at high impedance levels) should be shielded or guarded and run away from noise-generating sources. Such sources can include motors, transformers, fluorescent and carbon-arc lamps, induction heaters, and—in general—any source of electromagnetic radiation. It is poor practice to allow any form of noise into a system *carte blanche* on the premise that "filtering will take care of it." Once the interface system has been tightened against noise, the filtering may be added to clean up any remaining undesired signals, especially those present in the original signal.

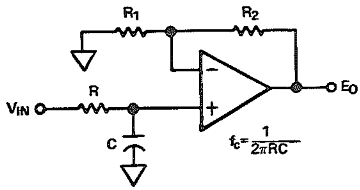
Besides reducing noise, filtering is also used to reduce bandwidth so that any frequency components at greater than 1/3 to 1/2 the sampling rate in sampled-data systems are negligible, to prevent aliasing.

In this chapter, we shall describe some easily understandable and accessible filtering techniques. For those interested in deeper understanding of filter design, references to useful sources of information are provided in the Bibliography. For those interested in treating filters as "black boxes", names of manufacturers and their specialties may be found in industry Buying Guides. Filters are quite often found in commercially available signal conditioners.*

For the applications discussed here, the most useful form of filtering is the *low-pass* filter, which responds perfectly to very low-frequency signals and has a great deal of attenuation at high frequencies. Since the phenomena we are concerned with are primarily low-frequency phenomena and much of the noise that is picked up, whether line-frequency, radio frequency, or carrier frequency, tends to be at higher frequencies, this form of response is widely used. The simplest low-pass filter consists of a resistor and a capacitor. Figure 3-7 shows three ways (active filter circuits) in which it is commonly implemented. The first of these, (a), can be used wherever the output of the filter drives a high-impedance

*For example, the Analog Devices 2B30 and 2B31 signal-conditioning modules contain 3-pole Bessel filters with 2Hz cutoff frequency. Higher cutoff frequencies are available by the use of 3 external resistors. The *modified Bessel* filter's amplitude and phase response are designed for optimum time-domain step response: fast rise time and minimum overshoot.

load, such as the input of an instrumentation amplifier or an op-amp connected as a follower. (b) and (c) are inverting-op-amp versions; c shows how two independent time constants can be achieved, forming a second-order low-pass filter.

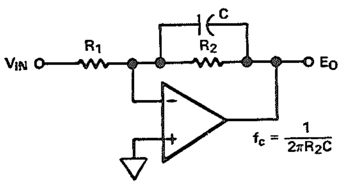


$$f_c = \frac{1}{2\pi RC}$$

$$\frac{|E_O|}{|V_{IN}|} = \frac{1+\frac{R_2}{R_1}}{\sqrt{1+(f/f_c)^2}}$$

FREQUENCY AMPLITUDE RESPONSE		STEP RESPONSE	
f/f_c	E_O/V_{IN}	t	%
0.1	1.00	RC	63
0.2	0.98	2RC	86
0.5	0.89	3RC	95
1.0	0.71	4RC	98
2.0	0.45	5RC	99.3
5.0	0.20	6RC	99.8
10.0	0.10	7RC	99.9
100.0	0.01		

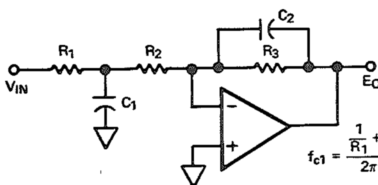
a. First-order RC low-pass filter unloaded by follower. Gain is set independently of time constant (RC).



$$f_c = \frac{1}{2\pi R_2 C}$$

$$-\frac{|E_O|}{|V_{IN}|} = \frac{R_2}{R_1}\,\frac{1}{\sqrt{1+(f/f_c)^2}}$$

b. Inverting op amp as first-order RC filter. Gain is set by R_2/R_1, time constant by R_2C. For independent setting, fix R_2, adjust C for cutoff frequency, R_1 for gain.



$$-\frac{|E_O|}{|V_{IN}|} = \frac{\frac{R_3}{R_2+R_1}}{\sqrt{1+(f/f_{c1})^2}\,\sqrt{1+(f/f_{c2})^2}}$$

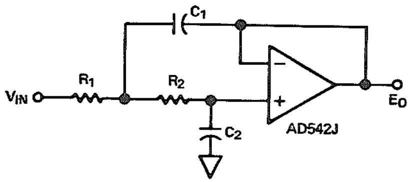
$$f_{c1} = \frac{\frac{1}{R_1}+\frac{1}{R_2}}{2\pi C_1}$$

$$f_{c2} = \frac{1}{2\pi R_3 C_2}$$

c. Adapting (b) as a second-order filter with two independently adjustable time constants

Figure 3-7. Simple RC active low-pass filters

Figure 3-8 shows the basic circuit architecture for second- and third-order low-pass filters, using a single follower-connected op amp. By tailoring the values of capacitance and resistance, a variety of response characteristics can be achieved, for a given cutoff frequency, e.g., three equal time constants, maximal flatness in the pass band, lowest phase shift, fastest settling time to a given



$$\frac{|E_O|}{|V_{IN}|} = \frac{1}{\sqrt{(1-4\pi^2 f^2 R_1 R_2 C_1 C_2)^2 + (2\pi f C_2 (R_1+R_2))^2}}$$

IF $R_1 = R_2 = R$, $C_2 = 2C_1$

$$f_C = \frac{1}{\sqrt{2}\pi R C_1}$$

DAMPING: 0.71 CRITICAL, K=2

$R_1 = R_2 = R$, $C_2 = C_1 = C$

$$f_C = \frac{0.66}{2\pi RC}$$

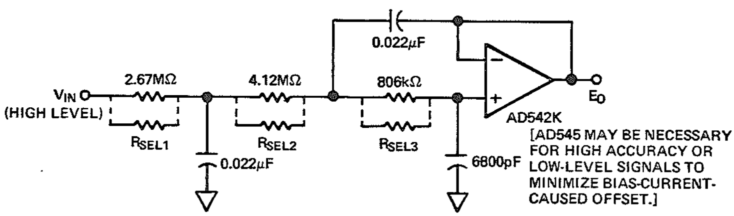
CRITICAL, K=4

$$\frac{|E_O|}{|V_{IN}|} = \frac{1}{\sqrt{\left[1-\left(\frac{f}{f_c}\right)^2\right]^2 + K\left(\frac{f}{f_c}\right)^2}}$$

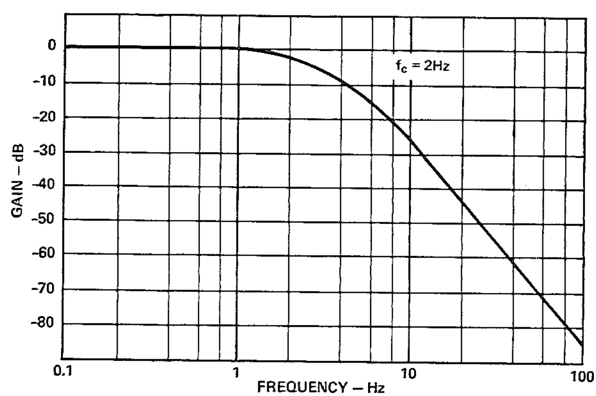
FREQUENCY AMPLITUDE RESPONSE (COMPARE FIG. 3-7a)

f/f_C	E_O/V_{IN}	E_O/V_{IN}
0.1	1.00	1.00
0.2	1.00	0.98
0.5	0.97	0.90
1.0	0.71	0.70
2.0	0.24	0.36
5.0	0.04	0.08
10.0	0.01	0.02
100.0	0.0001	0.0002
	0.7 CRITICAL DAMPING	CRITICALLY DAMPED

a. 2nd order filter—0.7 critically damped and critically damped



f_c (Hz)	R_{SEL1} (kΩ) (Pin 1 to 9)	R_{SEL2} (kΩ) (Pin 9 to 8)	R_{SEL3} (kΩ) (Pin 8 to 6)
2	Open	Open	Open
5	1270	2050	383
10	523	806	154
50	90	137	26.7
100	44.2	68.1	13.3
500	8.66	13.3	2.61
1000	4.32	6.65	1.30
5000	0.866	1.33	0.261



b. 3rd order filter—modified Bessel response

Figure 3-8. 2nd and 3rd order RC low-pass active filters input step level, minimum frequency difference for a given accuracy in the pass band and rejection in the stop band.

Low-pass filter responses may have many *poles* (corresponding to the *order*, or number of energy storage elements having a lagging effect), and the transfer functions of cascaded filters may be multiplied together to produce a response typical of a higher-order filter. Conversely, a complicated transfer function can be factored into unit lags and second-order responses. The choices of time constants, natural frequencies, and damping for these filter elements determine the composite response of the filter. For example, a 3-pole filter (the equivalent of a two-pole and a one-pole) may be combined with a two-pole filter to form a 5-pole filter, which will have an ultimate rolloff rate of 100dB per decade. Typical standardized sets of filter parameters (corresponding to distribution of poles in the complex domain—but enough of that!), such as Butterworth, Bessel, Chebyshev, Paynter, etc., provide fast rolloff, aperiodic transient response, linear phase shift with frequency, etc.

The values indicated for the circuit in Figure 3-8b are for a modified 3-Pole Bessel response (used in the 2B31 signal conditioner) with a 2Hz cutoff frequency (the frequency at which the amplitude response is 3dB down, to 71% of the low-frequency value). Its amplitude response can be seen to be rolling off at 60dB per decade (i.e., down by a factor of 1000 for every tenfold increase in frequency). The table indicates a set of 1%-tolerance resistance values that are connected externally in parallel with the filter's resistors to modify it for several commonly used cutoff frequencies. To predict the nominal response, move the curve to the right until the response is –3dB at the new cutoff frequency.

Low-pass filtering should be used as close to the front end as possible in a system. Theoretically, one can filter at any stage of a linear system—but not all systems are linear. If any noise is present ahead of a nonlinearity, its effects may be hard to get rid of at a later stage. Filter cost is minimized if the capacitance can be kept small; but the amplifier's bias current and any leakages develop voltage across the resistors in the filter, which establishes the upper limit to the resistance. Capacitors should generally be high-quality units having low leakage and low dielectric hysteresis—polystyrene, Teflon, mica, and polycarbonate are typical useful materials for the smaller sizes. For high capacitance, tantalum is a good choice. If electrolytic types are used, one should be careful about polarity.

If, despite the best efforts of the designer, interference of a single frequency (e.g., line frequency) is present, a narrow-band-elimination (*notch*) filter may be desirable. A popular configuration is the twin-tee, shown in Figure 3-9. The values given are ideal component values for rejecting 60Hz interference. The notch frequency and depth are sensitive to component values; the components should be well-matched and trimmed. The highest frequency of interest in the signal should be considerably lower than the notch frequency, since the notch is broad. This filter is generally used with a low-pass filter to minimize transmission of noise at higher frequencies, since the notch filter has unity gain at high frequency. The notch can be made sharper by feedback[1] but will require components having considerably greater stability.

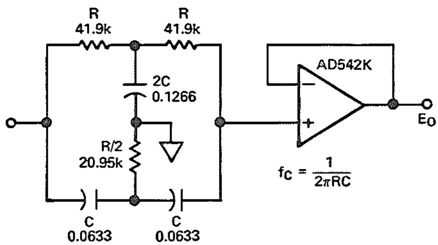


Figure 3-9. Twin-tee notch filter tuned to 60Hz. Typical components might be TRW MARG resistors and Arco type PT capacitors.

Another type of filter that is a useful building block is the *state-variable* filter. It consists of integrators in a feedback loop solving a differential equation. For example, a second-order state-variable filter has two integrators. Enough amplifiers are included to provide damping, sign inversion, and linear combinations to make use of this filter's versatility, since it can be used as a high-pass, low-pass, bandpass, or band-elimination filter, with adjustable Q, depending on how it is connected. It can also be used as an element of a complex multi-pole active-filter cascade. And it can be used with coefficients controlled by analog multipliers or multiplying DAC's

[1] Jung, Walter G., *IC Op-Amp Cookbook*, Howard W. Sams & Co., Inc., 1974, pages 338-340

to provide externally programmable parameters. An example of such a filter is shown in Figure 3-10.

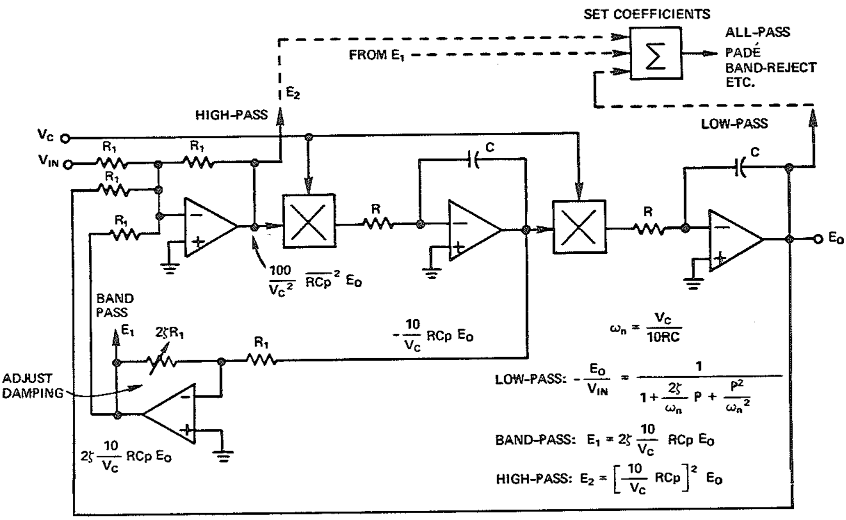


Figure 3-10. Second-order state-variable filter with multiplier-controlled natural frequency

Because the foregoing filter blocks employ op amps for unloading or driving or for actual contributions to the filter transfer function through feedback, they are known as *active* filters. *Passive* filtering (resistors, capacitors, inductors in circuits requiring no external energy source) is used for fairly simple transfer functions, and where either amplification will be provided or the impedance and signal levels are sufficient to enable the output of the filter to drive the subsequent circuit elements (such as analog meters, recorders, etc.)

Specialized Filter Circuits

A simple way of significantly reducing both noise and high-frequency common-mode errors in instrumentation-amplifier circuitry is the use of a capacitor connected between the differential instrumentation amplifier's input terminals. This is useful in two ways. First, with the source resistances of the inputs, it serves to form an RC filter for the differential signal. Second, it tends to reduce any unbalance between the common-mode capacitances from both sides of the input to ground because of its cross-coupling effect. Figure 3-11 is a example that illustrates how it works.

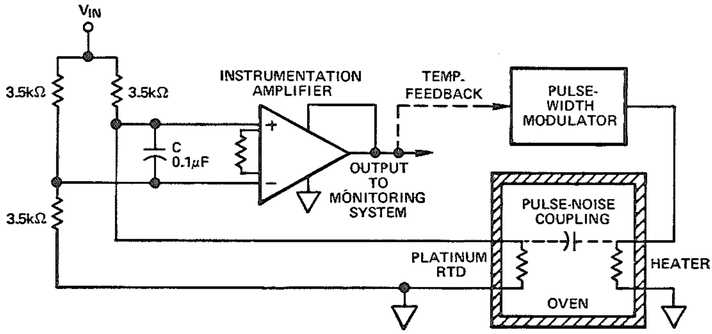


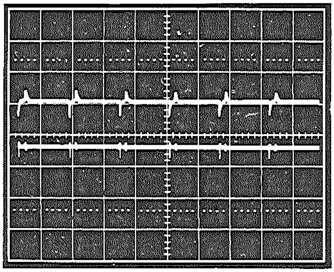
Figure 3-11. Reduction of unbalanced pulse noise in a temperature-monitoring system by the use of a shunt capacitor at the instrumentaion-amplifier input.

Here, a differential instrumentation amplifier is used to monitor the temperature of an oven. The platinum sensor resides within the oven, while the other resistors that make up the bridge circuit are located near the amplifier on the circuit board. The oven uses a pulse-width-modulator-driven transistor switch to control the power into the heater. While this circuit is efficient, it also generates noise, which is picked up by the platinum sensor, due to its proximity to the heater. The problem is aggravated by the inductance of the sensor, which is wirewound. Pulse noise could lead to erroneous readings in a monitoring DPM or multiplexed data-acquisition system.

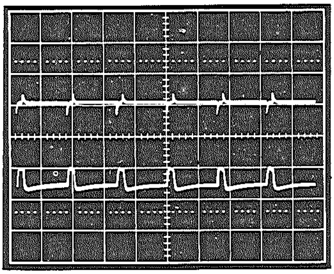
Figure 3-12a shows the waveforms that are seen at the two inputs of the instrumentation amplifier. The transducer side of the bridge picks up substantially more noise than does the resistance divider (note that the resistance-divider trace has a 10X more sensitive scale factor).

In the absence of the capacitor, the amplifier's output reflects this unbalance (b). The lower trace shows the amplified difference between the two input signals (upper trace), which includes the amplified noise waveform.

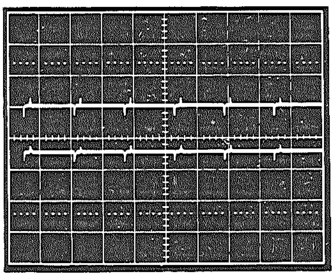
With the 0.1μF capacitor connected between the amplifier inputs, the two input traces, corresponding to (a), appear very nearly equal, due to the cross-coupling effect of the capacitor for the noise. That they are indeed equal can be seen at the output of the amplifier (d); the noise excursion is well below 1mV (note the scale for the lower trace, compared to the scale for the lower trace in (b).



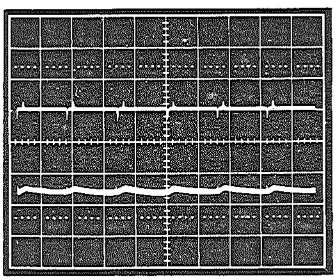
a. Input traces, no capacitor



b. Differential input, and output—no capacitor



c. Input traces with capacitor



d. Common-mode input and output trace with capacitor. Note scale for lower trace.

Figure 3-12. Waveforms in circuit of Figure 3-11

On occasion, unusual filtering problems may arise. For example, consider the case of an instrumentation amplifier and a filter that are shared by the channels of a multiplexed system, which provides programmable gain. If each channel has noise of a known different character, the filter time constant may also be programmable in order to minimize scan time without duplicating hardware.[2] A highly simplified block diagram of such an arrangement is shown in Figure 3-13. In this way, signals having large amounts of low-frequency noise can have sufficient filtering and adequate settling time without slowing down the acquisition of relatively clean signals with mostly high-frequency noise.

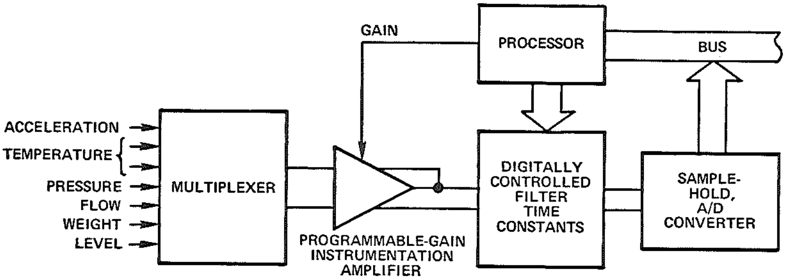


Figure 3-13. Data acquisition system using digitally controlled software-programmed filter

Another unusual application calls for a *derivative-controlled low-pass filter*. This is a filter that settles rapidly in response to a step change of input, then assumes a long time-constant for filtering out the low-level noise. Figure 3-14 depicts the use of such a filter in a rapidly-responding infant weighing scale where the constant motion of the baby would preclude stable high-resolution readings. Details can be found in the Applications section, Figures 15-8 through 15-10.

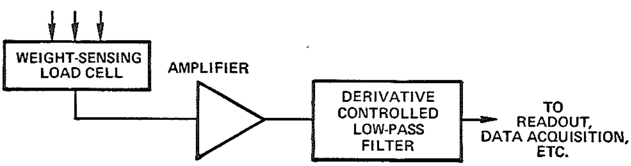


Figure 3-14. Derivative-controlled low-pass filter in a weighing application

[2] Several digitally programmable low-pass filters are described in the Analog Devices *Application Guide for CMOS Multiplying D/A Converters*, 1978.

Synchronous filters, utilizing sample-hold techniques, may be used to filter out noise in an interface. In some systems, noise is a direct consequence of the operating characteristics of components within the system. Switching power supplies, inductors, current surges, etc., often contribute noise which is both characterizable and predictable with respect to frequency and amplitude. In low-level circuitry, transients caused by such noise sources can cause saturation and slow recovery.

One way to minimize the effects of such noise sources is to use a sample-hold circuit in the signal path. The device is commanded to *hold* just before the spike is expected; when the noise is expected to have decayed to an acceptable level, the circuit is allowed to return to the *track* (normal operating) mode. This kind of circuit, which operates in synchronism with the noise bursts, is very similar to "deglitching" circuits used in fast digital-to-analog converters.

In the circuit of Figure 3-15, a synchronous filter is used to gate out the noise caused by ignition of an oil burner. The same command that instructs the oil-burner ignitor is used to gate the sample-hold circuit. During the time of the ignition pulse, the output of the interface remains at the level it had just prior to ignition. After ignition, the interface data is again back to real time. This technique is especially useful where the predictable noise occurs at relatively low duty cycles with respect to the desired system time frame, because the sample-hold action does

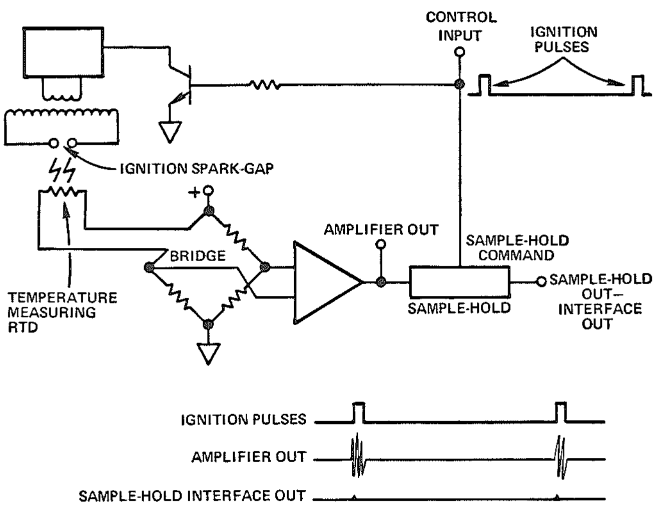


Figure 3-15. Synchronous filtering application

create "holes" in the data stream (but generally smaller and more-uniform ones than would occur if the spikes were allowed to communicate with the low-level circuitry).

Selecting a Cutoff Frequency

It is highly desirable to select as low as possible a cutoff frequency for the transducer interface filtering. The farther away the noise frequencies are from the frequency of interest, the easier it is to filter them out. A good guideline is to select a cutoff frequency which is as low as the desired information from the transducer will permit. For example, if nothing of interest occurs at frequencies above 1Hz, the 3-pole Bessel filter of Figure 3-8b, with a cutoff frequency (–3dB) of 2Hz, will permit measurements of reasonable fidelity at 1Hz, yet have attenuation of 70dB (3000X) at 60Hz.

On the other hand, piezoelectric accelerometers can generate information at considerably higher frequencies, and a higher noise cutoff frequency will usually be appropriate. In addition, circuits employing piezoelectrics (e.g., charge amplifiers) also require attention to *high-pass filtering* to minimize errors due to amplifier bias currents and the high noise gain at low frequencies due to the integrating effect of charge amplifiers.

In multi-transducer systems, where time-domain multiplexing techniques are used to scan between the various transducers, a critical look should be taken at the scan frequency's relationship to transducer frequency response. The scan frequency should be fast enough so that it captures changes occurring at the fastest rate of interest for a given transducer. And the dwell time should be long (short) enough to permit adequate time for settling without discernible changes of data. While the Nyquist criterion must be observed (sampling at about 3—or more—times the highest frequency of interest, and filtering-out of all higher frequencies to avoid aliasing), it may be foolishly redundant to scan a slowly-varying signal thousands of time per second. A useful technique is to group slow and fast signals so that all are scanned at rates appropriate to the actual rate at which their data can change.