CHAPTER 15.3
TRANSDUCER-INPUT MEASUREMENT SYSTEMS

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Transducers are used to convert the quantity to be measured into an electric signal. Transducer types and their input and output quantities are discussed in Sec. 8.

TRANSDUCER SIGNAL CIRCUITS

Amplifiers are often required to increase the voltage and power levels of the transducer output and to prevent excessive loading of the transducer by the measurement system. The design of the amplifier is a function of the performance specifications, which include required amplification in terms of voltage gain or power gain, frequency response, distortion permissible at a given maximum signal level, dynamic range, residual noise permissible at the output, gain stability, permissible drift (for dc amplifiers), operating-temperature range, available supply voltage, permissible power consumption and dissipation, reliability, size, weight, and cost.

Capacitive-coupled amplifiers (ac amplifiers) are used when it is not necessary to preserve the dc component of the signal. AC amplifiers are used with transducers that produce a modulated carrier signal. Low-level amplifiers increase the signal from millivolts to several volts. The two-stage class A capacitor-coupled transistor amplifier of Fig. 15.3.1 has a power gain of 64 dB and a voltage gain of approximately 1000. Design information, an explanation of biasing, and equations for calculating the input impedance and various gain values are given in Walston and Miller (see Chap. 15.5). An excellent ac amplifier can be obtained by connecting a coupling capacitor in series with resistor R_1 of the operational amplifier of Fig. 15.3.4. The capacitor should be selected so that $C > 1/2\pi fR_1$, where f is the lowest signal frequency to be amplified. Class B transformer-coupled amplifiers, which are often used for higher power-output stages, are also discussed in Walston and Miller (see Chap. 15.5).

Direct-coupled amplifiers are used when the dc component of the signal must be preserved. These designs are more difficult than those of capacitive-coupled amplifiers because changes in transistor leakage currents, gain, and base-emitter voltage drops can cause the output voltage to change for a fixed input voltage, i.e., cause a dc-stability problem. The dc stability of an amplifier is determined primarily by the input stage since the equivalent input drift introduced by subsequent stages is equal to their drift divided by the preceding gain. Balanced input stages, such as the differential amplifier of Fig. 15.3.2, are widely used because drift components tend to cancel. By selecting a pair of transistors, Q_1 and Q_2, which are matched for current gain within 10 percent and base-to-emitter voltage within 3 mV, the temperature drift referred to the input can be held to within 10 μV/°C. Transistor Q_3 acts as a constant-current source and thereby increases the ability of the amplifier to reject common-mode input voltages. For applications where the generator resistance r_g is

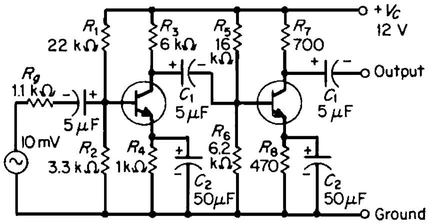

FIGURE 15.3.1 Two-stage cascaded common-emitter capacitive audio amplifier.

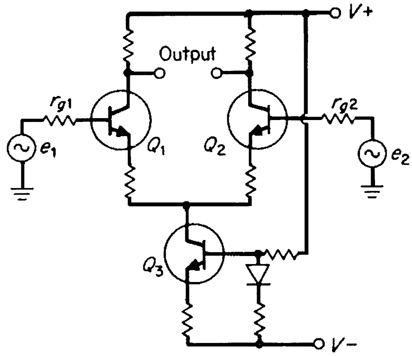

FIGURE 15.3.2 Differential amplifier.

greater than 50 kΩ, current offset becomes dominant, and lower overall drift can be obtained by using field-effect transistors in place of the bipolar transistors Q_1 and Q_2. Voltage drifts as low as 0.4 μV/°C can be obtained using integrated-circuit operational amplifiers (see Table 15.3.1).

Operational amplifiers are widely used for amplifying low-level ac and dc signals. They usually consist of a balanced input stage, a number of direct-coupled intermediate stages, and a low-impedance output stage. They provide high open-loop gain, which permits the use of a large amount of gain-stabilizing negative feedback. High-gain bipolar and JFET transistors are often used in the balanced input stage. The bipolar input provides lower voltage offset and offset voltage drift while the JFET input provides higher input impedance, lower bias current, and lower offset current as can be seen in Table 15.3.1 which compares the typical specifications of three high-performance operational amplifiers. The chopper-stabilized CMOS operational amplifier provides the low offset and bias currents of FET transistors while using internal chopper stabilization to achieve excellent offset voltage characteristics. With input voltages, e_1, e_2, and e_{cm} equal to zero, the output of the amplifier of Fig. 15.3.3 will have an offset voltage E_{os} defined by

$$E_{os} = V_{os}\frac{R_1 + R_2}{R_1} + I_{b1}R_2 - I_{b2}\frac{R_3R_4(R_1 + R_2)}{R_1(R_3 + R_4)}$$

TABLE 15.3.1 Operational Amplifier Comparison

Typical parameter (except where noted)	Temp.	Bipolar input (Harris 5130)	JFET input (Harris 5170)	Chopper-stabilized CMOS (Siliconix 7652)
Input characteristics				
Offset voltage	25°C	10 μV	100 μV	0.7 μV
Maximum offset voltage	25°C	25 μV	300 μV	5 μV
Avg. offset voltage drift	Full	0.4 μV/°C	2 μV/°C	0.01 μV/°C
Bias current	25°C	1 nA	0.02 nA	0.015 nA
Bias current avg. drift	Full	20 pA/°C	3 pA/°C	
Maximum offset current	25°C	2 nA	0.03 nA	0.06 nA
Offset current avg. drift	Full	20 pA/°C	0.3 pA/°C	
Differential input resistance	25°C	30×10^6 Ω	6×10^{10} Ω	10^{12} Ω
Transfer characteristics				
Voltage gain	25°C	140 dB	116 dB	150 dB
Common-mode rejection ratio	25°C	120 dB	100 dB	130 dB

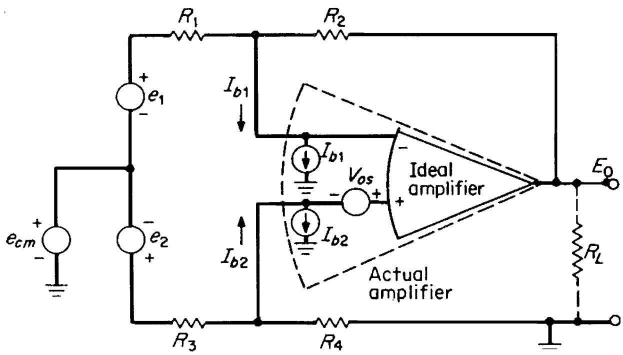

FIGURE 15.3.3 Operational amplifier.

where I_{b1} and I_{b2} are bias currents that flow into the amplifier when the output is zero and V_{os} is the input offset voltage that must be applied across the input terminals to achieve zero output. The input bias current specified for an operational amplifier is the average of I_{b1} and I_{b2}. Since the bias currents are approximately equal, it is desirable to choose the parallel combination of R_3 and R_4 equal to the parallel combination of R_1 and R_2. For this case, $E_{os} = V_{os}(R_1 + R_2)/R_1 + I_{os}R_2$, where the offset current $I_{os} = I_{b1} - I_{b2}$.

In the ideal case, where V_{os} and I_{os} are zero, the output voltage E_0 as a function of signal voltage e_1 and e_2 and common-mode voltage e_{cm} is

$$E_0 = -e_1\frac{R_2}{R_1} + e_2\frac{R_4(R_1+R_2)}{R_1(R_3+R_4)} + e_{cm}\frac{R_4(R_1+R_2) - R_2(R_3+R_4)}{R_1(R_3+R_4)}$$

Maximum common-mode rejection can be obtained by choosing $R_4/R_3 = R_2/R_1$, which reduces the above equation to $E_0 = R_2(e_2 - e_1)/R_1$. The common-mode signal is not entirely rejected in an actual amplifier but will be reduced relative to a differential signal by the common-mode rejection ratio of the amplifier. Minimum drift and maximum common-mode rejection, which are important when terminating the wires from a remote transducer, can be obtained by selecting $R_3 = R_1$ and $R_4 = R_2$.

Where common-mode voltages are not a problem, the simple inverting amplifier (Fig. 15.3.4) is obtained by replacing e_{cm} and e_2 with short circuits and combining R_3 and R_4 into one resistor, which is equal to the parallel equivalent of R_1 and R_2. The input impedance of this circuit is equal to R_1.

Similarly, the simple noninverting amplifier (Fig. 15.3.5) is obtained by replacing e_{cm} and e_1 with short circuits. The voltage follower is a special case of the noninverting amplifier where $R_1 = \infty$ and $R_2 = 0$. The input impedance of the circuit of Fig. 15.3.5 is equal to the parallel combination of the common-mode input impedance of the amplifier and impedance Z_{id} $[1 + (AR_1)/(R_1 + R_2)]$, where Z_{id} is the differential-mode amplifier input impedance and A is the amplifier gain. Where very high input impedances are required, as in electrometer circuits, operational amplifiers having field-effect input transistors are used to provide input resistances up to 10^{12} Ω.

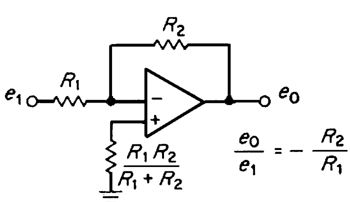

FIGURE 15.3.4 Inverting amplifier.

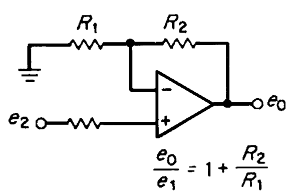

FIGURE 15.3.5 Noninverting amplifier.

An ac-coupled amplifier can be obtained by connecting a coupling capacitor in series with the input resistor of Fig. 15.3.4. The capacitor value should be selected so that the capacitive reactance at the lowest frequency of interest is lower than the amplifier input impedance R_1.

Operational amplifiers are useful for realizing filter networks and integrators. Other applications include absolute-value circuits, logarithmic converters, nonlinear amplification, voltage-level detection, function generation, and analog multiplication and division. Care should be taken not to exceed the maximum supply voltage and maximum common-mode voltage ratings and also to be sure that the load resistance R_L is not smaller than that permitted by the rated output.

The charge amplifier is used to amplify the ac signals from variable-capacitance transducers and transducers having a capacitive impedance such as piezoelectric transducers. In the simplified circuit of Fig. 15.3.6*a*, the current through C_s is equal to the current through C_1, and therefore

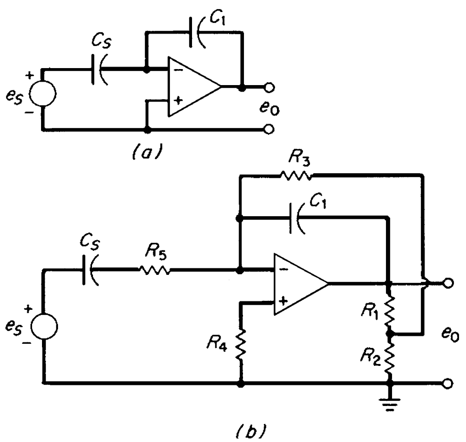

FIGURE 15.3.6 Charge amplifier.

$$C_s \frac{\partial e_s}{\partial t} + e_s \frac{\partial C_s}{\partial t} = -C_1 \frac{de_o}{dt}$$

For the piezoelectric transducer, C_s is assumed constant, and the gain $\delta e_o/\delta e_s = -C_s/C_1$. For the variable-capacitance transducer, e_s is constant, and the gain $de_o/dC_s = -e_s/C_1$. A practical circuit requires a resistance across C_1 to limit output drift. The value of this resistance must be greater than the impedance of C_1 at the lowest frequency of interest. A typical operational amplifier having field-effect input transistors has a specified maximum input current of 1 nA, which will result in an output offset of only 0.1 V if a 100-MΩ resistance is used across C_1. It is preferable to provide a high effective resistance by using a network of resistors, each of which has a value of 1 MΩ or less.

The effective feedback resistance R' in the practical circuit of Fig. 15.3.6*b* is given by $R' = R_3(R_1 + R_2)/R_2$, assuming that $R_3 > 10R_1R_2/(R_1 + R_2)$. Output drift is further reduced by selecting $R_4 = R_3 + R_1R_2/(R_1 + R_2)$. Resistor R_5 is used to provide an upper frequency rolloff at $f = 1/2\pi R_5 C_s$, which improves the signal-to-noise ratio.

Amplifier-gain stability is enhanced by the use of feedback since the gain of the amplifier with feedback is relatively insensitive to changes in the open-loop amplifier gain G provided that the loop gain GH is high. For example, if the open-loop gain G changes by 10 percent from 100,000 to 90,000 and the feedback divider gain H remains constant at 0.01, the closed-loop gain $G/(1 + GH) \approx 99.9$ changes only 0.011 percent.

If a high closed-loop gain is required, simply decreasing the value of H will reduce the value of GH and thereby reduce the accuracy. The desired accuracy can be maintained by cascading two or more amplifiers, thereby reducing the closed-loop gain required from each amplifier. Each amplifier has its own individual feedback, and no feedback is applied around the cascaded amplifiers. In this case, it is unwise to cascade more stages than needed to achieve a reasonable value of GH in each individual amplifier, since excessive loop gain will make the individual stages more prone to oscillation and the overall system will exhibit increased sensitivity to noise transients.

Chopper amplifiers are used for amplifying dc signals in applications requiring very low drift. The dc input signal is converted by a chopper to a switched ac signal having an amplitude proportional to the input signal and a phase of 0 or 180° with respect to the chopper reference frequency, depending on the polarity of the input signal. This ac signal is amplified by an ac amplifier, which eliminates the drift problem, and then is converted back into a proportional dc output voltage by a phase-sensitive demodulator.

The frequency response of a chopper amplifier is theoretically limited to one-half the carrier frequency. In practice, however, the frequency response is much lower than the theoretical limit. High-frequency components in the input signal exceeding the theoretical limit are removed to avoid unwanted beat signals with the chopper frequency.

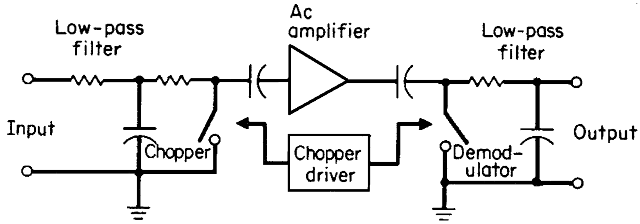

FIGURE 15.3.7 Chopper amplifier.

The chopper amplifier of Fig. 15.3.7 consists of a low-pass filter to attenuate high frequencies, an input chopper, an ac amplifier, a phase-sensitive demodulator, and a low-pass output filter to attenuate the chopper ripple component in the output signal. The frequency response of this amplifier is limited to a small fraction of the chopper frequency.

The frequency-response limitation of the chopper amplifier can be overcome by using the chopper amplifier for the dc and low-frequency signals and a separate ac amplifier for the higher-frequency signals, as shown in Fig. 15.3.8. Simple shunt field-effect-transistor choppers Q_1 and Q_2 are used for modulation and detection, respectively. Capacitor C_T is used to minimize spikes at the input to the ac amplifier.

A CMOS auto-zeroed operational amplifier, which contains a built-in chopper amplifier, has typical specifications of 0.7 μV input offset voltage, 0.01 μV/°C average offset voltage drift, and 15 pA input bias current (see Table 15.3.1).

Modulator-demodulator systems avoid the drift problems of dc amplifiers by using a modulated carrier which can be amplified by ac amplifiers (Fig. 15.3.9). Inputs and outputs may be either electrical or mechanical.

The varactor modulator (Fig. 15.3.10) takes advantage of the variation of diode-junction capacitance with voltage to modulate a sinusoidal carrier. The carrier and signal voltages applied to the diodes are small, and the diodes never reach a low-resistance condition. Input bias currents of the order of 0.01 pA are possible. For zero signal input, the capacitance values of the diodes are equal, and the carrier signals coupled by the diodes cancel. A dc-input signal will increase the capacitance of one diode while decreasing the capacitance of the other and thereby produce a carrier imbalance signal which is coupled to the ac amplifier by capacitor C_2. A phase-sensitive demodulator, such as field-effect transistor Q_2 of Fig. 15.3.8, may be used to recover the dc signal.

The magnetic amplifier and second-harmonic modulator can also be used to convert dc-input signals to modulation on a carrier, which is amplified and later demodulated. Mechanical-input modulators include ac-driven potentiometers, linear variable differential transformers, and synchros. The amplified ac carrier can be converted directly into a mechanical output by a two-phase induction servomotor.

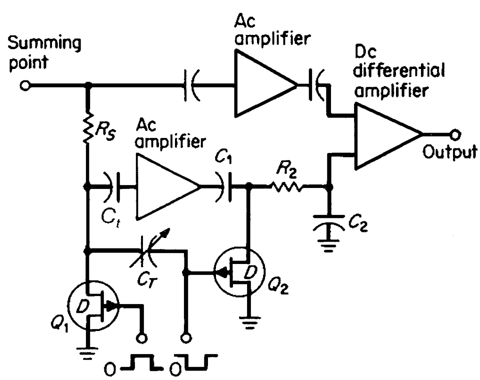

FIGURE 15.3.8 Chopper-stabilized dc amplifier.

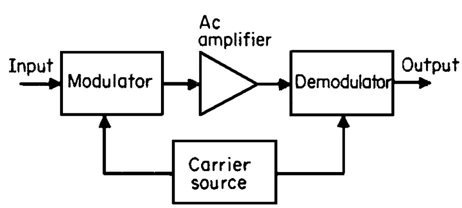

FIGURE 15.3.9 Modulator-demodulator system.

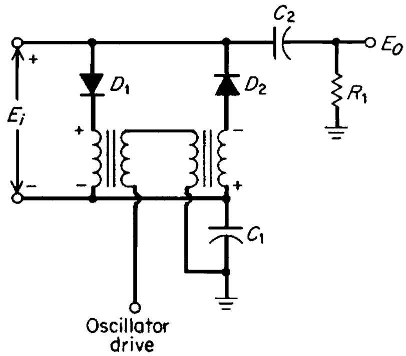

FIGURE 15.3.10 Basic varactor modulator.

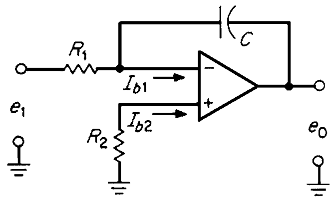

FIGURE 15.3.11 Analog integrator.

Integrators are often required in systems where the transducer signal is a derivative of the desired output, e.g., when an accelerometer is used to measure the velocity of a vibrating object. The output of the analog integrator of Fig. 15.3.11 consists of an integrated signal term plus error terms caused by the offset voltage V_{os} and the bias currents I_{b1} and I_{b2}

$$e_0 = \frac{1}{R_1 C}\int e_1\, dt + \frac{1}{R_1 C}\int (V_{os} + I_{b1}R_1 - I_{b2}R_2)\, dt$$

These error terms will cause the integrator to saturate unless the integrator is reset periodically or a feedback path exists, which tends to drive the output toward a given level within the linear range. In the accelerometer integrator, accurate integration may not be required below a given frequency, and the desired stabilizing feedback path can be introduced by incorporating a large effective resistance across the capacitor using the technique shown in Fig. 15.3.6*b*.

Digital processing of analog quantities is frequently used because of the availability of high-performance analog-to-digital (A/D) converters, digital-to-analog (D/A) converters, microprocessors, and other special digital processors. The analog input signal (Fig. 15.3.12) is converted into a sequence of digital values by the A/D converter. The digital values are processed by the microprocessor (see "The microprocessor") or other digital processor, which can be programmed to provide a wide variety of functions including linear or nonlinear gain characteristics, digital filtering, integration, differentiation, modulation, linearization of signals from nonlinear transducers, computation, and self-calibration. The Texas Instruments TMS 320 series of digital processors are specially designed for these applications.

The digital output may be used directly or converted back into an analog signal by the D/A converter. Commercial A/D converter modules are available with 15-bit resolution and 17-μs conversion times using the successive-approximation technique (Analog Devices AD 376, Burr Brown ADC 76). Monolithic integrated-circuit A/D converters are available with 12-bit resolution and 6-μs conversion times (Harris HI-774A). An 18-bit D/A converter with a full-scale current output of 100 mA and a compliance voltage range of ±12 V has been

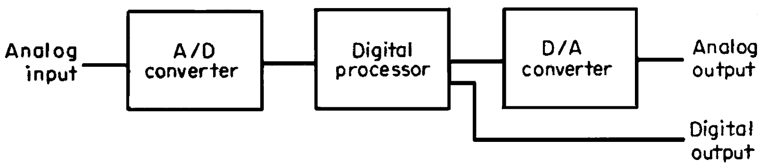

FIGURE 15.3.12 Digital processing of analog signals.

built at the National Bureau of Standards (Schoenwetter). It exhibits a settling a time to $^1/_2$ least significant bit (2 ppm) of less than 20 μs. Commercial 16- and 18-bit D/A converters are available with 2-mA full-scale outputs (Analog Devices DAC1136/1138, Burr Brown DAC 70).

The application of A/D converters, D/A converters, and sample-and-hold (S/H) circuits requires careful consideration of their static and dynamic characteristics.

The microprocessor is revolutionizing instrumentation and control. The digital processing power that previously cost many thousands of dollars has been made available on a silicon integrated-circuit chip for only a few dollars. A microcomputer system (Fig. 15.3.13) consists of a microprocessor central processing unit (CPU), memory, and input-output ports. A typical microprocessor-based system consists of the 8051 microprocessor, which provides 4 kbytes of read-only memory (ROM), 128 bytes of random-access memory (RAM), 2 timers and 32 input-output lines, and a number of additional RAM and ROM memory chips as needed for a particular application. The microprocessor can provide a number of features at little incremental cost by means of software modification. Typical features include automatic ranging, self-calibration, self-diagnosis, data conversion, data processing, linearization, regulation, process monitoring, and control. Instruments using microprocessors are described in Chaps. 15.2 and 15.4.

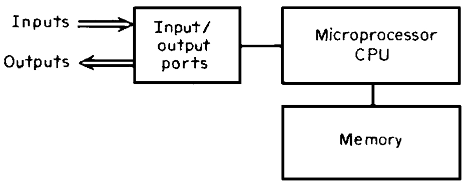

FIGURE 15.3.13 Microcomputer system.

Instrument systems can be automated by connecting the instruments to a computer using the IEEE-448 general purpose interface bus (Santoni). The bus can connect as many as 14 individually addressable instruments to a host computer port. Full control capability requires the selection of instruments that permit bus control of front panel settings as well as bus data transfers.

Voltage comparators are useful in a number of applications, including signal comparison with a reference, positive and negative signal-peak detection, zero-crossing detection, A/D successive-approximation converter systems, crystal oscillators, voltage-controlled oscillators, magnetic-transducer voltage detection, pulse generation, and square-wave generation. Comparators with input offset voltages of 2 mV and input offset currents of 5 nA are commercially available.

Analog switches using field-effect-transistor (FET) technology are used in general-purpose high-level switching (±10 V), multiplexing, A/D conversion, chopper applications, set-point adjustment, and bridge circuits. Logic and schematic diagrams of a typical bilateral switch are shown in Fig. 15.3.14. The switch provides the required isolation between the data signal and the control signal. Typical switches provide zero offset voltage, on resistance of 35 Ω, and leakage current of 0.04 nA. Multiple-channel switches are commercially available in a single package.

Output Indicators. A variety of analog and digital output indicators can be used to display and record the output from the signal-processing circuitry.

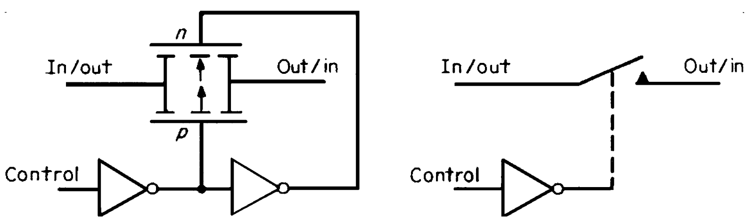

FIGURE 15.3.14 Bilateral analog switch.