LVDT Signal Conditioning Techniques

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I Introduction

The earliest versions of differential transformer type devices were designed for power control of AC motors and generators, and date back to the early part of this century. These devices, while they represent the distant relative of today's LVDTs, were not practical for use in instrumentation systems.

In the early 1930s, the need for physical measurements in the chemical process industry prompted process control manufacturers to find an electrical telemetry system for remote indication of process variables. This resulted in various differential transformer designs, with indicators usually consisting of slide wire potentiometers and AC galvanometers used as a null indicator. It was not until the mid to late 1930's that transformer type devices with essentially linear output were developed.

At the outset of World War II, the LVDT had gained general acceptance as a transducer element in the process industry instrumentation and control field. Its use in the war included aircraft, torpedoes, and weapons systems, usually as a null-position indicator. By wars end, while there were a wide variety of applications of LVDTs, only a small number of instrumentation specialist had a working knowledge of the devices. This was remedied with the publication of The Linear Variable Differential Transformer by Herman Schaevitz in 1946 (Proceedings of the SASE, Volume IV, No. 2), which made a wider user community aware of the applications and features of the LVDT.

The signal conditioning associated with LVDTs was typically bulky, and therefore limited its application. It was not until the invention and commercial availability of the transistor that it was possible to consider signal conditioning internal to the LVDT to create a DC-LVDT. Early devices employed a switching inverter with special primary windings and a passive demodulator/filter connected to the LVDT secondary output. While these devices had several limitations, they have been used up to recent times in various instrumentation systems.

Advances in electronic hybrid microcircuits in the early 1970s allowed the design of DC-LVDTs with high sensitivity, low output impedance, high reliability and ruggedness. Since the introduction of the hybrid based DC-LVDT by Schaevitz, the designs have been essentially evolutionary until fully integrated LVDT signal conditioning chips became available in the late 1980s.

Today, there are many options in configuring LVDT signal conditioning, both as external devices, and internal to the LVDT. A typical selection of both types is shown in Fig. 1. As with most engineering endeavors, which topologies to use are trade-off between cost, size and performance. We will endeavor to clarify this maze to allow the user to make some decisions, either in constructing their own signal conditioning, or in deciding which approach will be best for their application.

II LVDT Basics

The LVDT (Linear Variable Differential Transformer) is an electromechanical device that produces an electrical output proportional to the displacement of a separate, moveable magnetic core. It consists of three coils, one of which is the primary of the transformer. The other two coils are usually symmetrical about the primary and in normal operation are connected in series opposing to form the transformer secondary. When the moveable transformer core is centered with respect to the two secondary windings, they will have the same magnitude of induced output voltage, but the polarity or phasing will be opposite. The net output voltage of the secondary will therefore be zero. This position is classically referred to as the electrical null position. When the magnetic core is displaced from the null position, the output of one secondary coil increase, while the output of the other coil decreases, producing a non-zero differential output voltage as a function of core displacement. The phase of this output voltage changes by 180° as the core is moved from one side of null to the other.

To use an LVDT, one needs to have available some form of AC source to drive the primary, and some form of measuring the secondary output voltage and, if directional sense is desired, the output phase. As we explain later, the excitation source is usually a sine wave with an amplitude of a few volts rms and a frequency between 1 kHz and 10 kHz. One can measure the output with an AC voltmeter, or even an oscilloscope, but the usual method is to rectify the signal and measure the resulting DC voltage. More typically, the required functions to provide excitation and a DC output voltage are provided by some from a specialized LVDT signal conditioner as shown in Fig. 2.

Today, DC-LVDTs are becoming increasingly popular, since they enable the customer to avoid issues of signal conditioning and system calibration. The internal electronics for these DC - DC devices follow the same form as shown in Fig. 2, with the possible addition of some form of voltage regulation and EMI protection circuitry.

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III Excitation Sources

Since the LVDT is electrically a transformer device, it requires some type of AC excitation. Many novice LVDT users want to use square wave, since it is easy to generate and therefore inexpensive. Unfortunately, square wave excitation has several disadvantages. Since LVDTs are inductive devices, square wave excitation will result in substantial ringing and overshoot in the output signal. In addition, since basic LVDT performance parameters such as linearity, sensitivity, and temperature effects are very frequency dependent, square wave operation usually results in a level of performance well below the users expectations. While it is possible to design LVDTs to perform reasonably well with this type of excitation, it will never yield optimum performance. Almost all LVDTs commercially available were designed for operation over a narrow range of frequencies and will perform poorly with square wave excitation.

A second option is to generate an approximate triangular waveform. While this will provide an improvement over square wave excitation for some LVDTs, the performance will be far from optimum. In addition, since triangular waveforms require additional circuitry, there is not a distinct cost savings to justify this approach.

Most standard commercial LVDTs are designed to operate with sine wave excitation. The sine wave does not have to be exceptionally “pure”. Total harmonic distortion (THD) of 2 or 3% is generally acceptable. It is important that the DC component of the excitation be kept low, since DC currents in the primary can have severe effects on the LVDT performance. The LVDT is essentially a ratiometric AC device, with the output of the secondaries directly proportional to the excitation amplitude. This implies that the amplitude stability of the primary excitation is critical. Conversely, the LVDT secondary output is only slightly dependent on the frequency of the excitation. For typical LVDTs, if the excitation frequency varies by 10%, the secondary output will only change by 1%. This means that we want to chose methods of generating sine wave excitation which will allow us to optimize amplitude stability with a THD of 2 to 3%, and a frequency stability in the order of several percent. There are many methods available in the literature for generating sine waves. We will discuss some of the simpler and less expensive approaches.

A typical RC oscillator is shown in Fig. 3.a. This is a relatively simple way to generate a good quality sine wave. This type of circuit typically provides good THD and frequency stability. Although adequate for moderate performance as shown, an automatic gain control (AGC) loop must be added to improve amplitude stability to achieve the best results. Although the RC oscillator is an acceptable circuit, the requirement of an AGC loop adds to the circuit complexity therefore increasing costs. In addition, the circuit with AGC typically exhibits slow startup and is very component value critical.

Another approach which has been used successfully is shown in Fig. 3.b. This circuit is usually called a quadrature oscillator, since both the sine and cosine outputs are

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available. The first amplifier is connected as a two pole low pass active filter, while the second amplifier is connected as an integrator. Since this implies an ultimate phase shift of 270°, the circuit will oscillate at the frequency where the lag is 180° if the loop gain is high enough. Amplitude stabilization is accomplished by a pair of zener diodes which clamp the feedback. While this does introduce some distortion, the circuit can usually be designed to have a THD of less than 2%. The temperature stability of the output depends on the temperature coefficients of the zener diodes.

Since it is easy to achieve amplitude stable square wave oscillators, an attractive and inexpensive approach of achieving a sine wave is to filter the square wave with a two pole filter, as shown in Fig. 3.c. The amplitude stability depends primarily on the amplitude of the square wave. By using the CMOS devices available today, with their superior output characteristics, one can design an oscillator with output voltage swings approaching the supply rails and with very little change over temperature.

Using the approaches shown in Fig. 3.b and c, sine waves with better than 2% THD and amplitude temperature coefficients of less than ±100 ppm/°C have been achieved.

There are also a variety of digital techniques to generate sine waves. Advantages of a digital means of sine wave generation include, ease of changing frequency, greater flexibility and smaller passive components used in filtering.

One method is to use a square wave oscillator as a clock into a shift register. The outputs of the shift register are summed through resistance values selected to get a sine wave staircase voltage output. A simple filter then converts the output into a sine wave. If all the parts are based on CMOS technology, the supply current can be kept very low. This technique is useful in low power applications such as 4 - 20 mA transmitters like the Lucas Schaevitz CTS-420.

Another methods which is used in the Model ATA2001 shown in Fig. 1 uses a microprocessor to generate a pulse width modulated waveform, with the pulse width varying in a sinusoidal fashion. Passing the waveform through an integrator will provide a sine wave output. This approach allows the excitation frequency to be easily changed to optimize with a variety of LVDTs.

IV Demodulators

The output of the LVDT is an AC signal, which must be converted to DC before it can be used in most instrumentation systems. There are numerous means of accomplishing this. The simplest forms involve some form of diode rectification, while the more complex forms involve synchronous demodulation. We will discuss some of the more common approaches.

The simplest form is shown in Fig. 4.a. Here the signal from each individual secondary is rectified with a single diode half-wave rectifier and a filter capacitor. The resulting two voltages are added with opposing polarity. When the LVDT is at its electrical null, the two voltages will be equal, and we will obtain a zero output. As the core is moved toward Sec 1, the output will go positive. The output will go negative as the core moves toward Sec 2.

The primary advantage of this approach is in its simplicity. Only six passive components are required to obtain an output signal which maintains the directional sense of the core position. In addition, the output is not effected by changes in LVDT phase shift. However, there are also a number of disadvantages with this technique. In order to maintain best output linearity, the voltage of each LVDT secondary must always exceed the threshold level of the diodes over the entire stroke of the LVDT. This can be a problem with some miniature and specialty LVDTs. Manufacturers do not generally provide individual secondary voltage information in the catalogs. In order to minimize the effects of temperature, the diodes should be well matched. Other problems which are encountered with this circuit are the effects of LVDT secondary impedance, which may be different between the secondaries and vary with both position and temperature.

An improvement on the simple diode demodulator involves the use of high gain operational amplifiers with diodes in the feedback loop, as shown in Fig. 4.b. This circuit is commonly referred to as a precision rectifier. While this greatly increases the demodulator complexity, it also eliminates two of the major disadvantages of the simple half-wave rectifier. There are no threshold levels of the diodes to worry about due to the feedback action of the amplifiers and the diodes do not need to be matched. In addition, the amplifiers buffer the LVDT from the diodes, and therefore the impedance of the LVDT secondary does not effect the output.

As we have seen, the rectifier type of demodulators have some basic problems. There are other intricacies which must be considered. Both circuits may require a substantial DC gain to obtain the desired final output. The LVDT wiring must be a minimum of five wires, and should be well balanced and of low distributed capacitance, which implies either expensive cabling, or short distances between the LVDT and the electronics. In addition, these simple rectifier circuits provide very little noise rejection.

To be published in Measurements & Control, June 1997

Many of these limitations can be eliminated by using one of the major characteristics of the LVDT. Since the LVDT is essentially a differential transformer, it has an output characteristic which can be described by a magnitude and phase function. In Fig. 4.c. we show an LVDT with the secondaries connected in a series opposing mode. This results in a variable AC signal which changes magnitude as a function of core position, and changes phase by 180° as the core passes through null. The signal can be demodulated with a phase sensitive detector, which will provide a plus and minus DC signal as a function of core position. Of the many ways of accomplishing synchronous demodulation, one of the simplest approaches is shown. The circuit shown consists of an operational amplifier, with the gain switched from an inverting to a non-inverting gain of the same magnitude. This is normally accomplished with a FET switch. The switching signal must be synchronized with the LVDT signal. This synchronized signal is usually obtained from the primary drive of the LVDT. Since the LVDT will usually have some phase shift in its transfer function, a phase shift network is usually employed to switch the signal as close to the zero crossing as practical.

This circuit is obviously more complicated than the rectifier schemes presented above, especially when the phase control requirement is added. It should be noted that phase control is not always required, since most LVDTs are designed to have very low phase shifts at a particular frequency. However, the phase shift can also compensate for large cable capacitance effects, making the circuit very useful for long cable runs to remote locations. The primary advantages of this approach are a very high degree of noise immunity, a minimum of wiring, since the signal only requires 4 wires, and in some cases can be reduced to 3 wires. In addition, it is relatively easy to add AC gain before the demodulator, making the electronics more stable. This particular approach has been a standard for high-end LVDT signal conditioners for many years, since it will work with almost any LVDT and cable combination.

To be published in Measurements & Control, June 1997

V Amplification, Filters, Calibration

The sensitivity of LVDTs is usually given as millivolts of differential secondary signal per volt of primary excitation voltage per thousandth of an inch displacement, or mV/V/0.001”. The LVDT is assumed to be wired in series opposing. The sensitivity of LVDTs ranges from 0.05 mV/V/0.001” for long stroke LVDTs to about 10 mV/V/0.001” for the shorter strokes. With typical primary excitations of 1 to 3 volts rms, the full scale secondary voltages range from less than 0.1 volts rms to over 3 volts rms. To get full scale output of ±10 Vdc, gains from 3.3 to 100 would be needed. While gains of 100 are not difficult with today’s high performance operational amplifiers, it is desirable to limit the DC gain to a range of 2 to 10 to obtain best overall zero stability. The zero stability of an LVDT is usually quite good. Since we do not want the electronics to degrade it, it usually desirable to have some AC gain in the system.

As we have already mentioned, it is difficult to add AC gain to the simple diode demodulator and precision rectifier circuits. Therefore, in situations where large gains are required, it is best to use the synchronous demodulator approach. The typical gain configuration of this approach is to have the maximum output of the demodulator be in the 1 to 2 volt range, which means that the dc gain can be kept below 10.

The dc gain stage usually incorporates several other functions required in an LVDT signal conditioner. The first is filtration of the rectified AC signal to minimize output ripple or noise. The design of a filter is a compromise between low output noise, best frequency response (both phase and amplitude) and lowest cost and complexity. Usually a good compromise for the filter is a two or three pole Butterworth filter with a signal 3 dB bandwidth of 1/10 of the LVDT excitation frequency. Assuming full wave rectification, as obtained with the synchronous demodulator, the ripple for a two pole filter would be less than 0.2% of full scale, and less than 0.01% for the three pole filter. These are ideal numbers. Actual filter circuits usually result in slightly higher figures due to noise pickup, capacitive coupling and actual component tolerances.

The DC gain stage is also where the final calibration of LVDT (or system) span and zero are accomplished. In order to minimize the calibration problems, it is important to design the calibration adjustments to be totally independent. In other words, the span and zero adjust should not interact in any way. In systems which use AC gain, the gain is usually set for a particular LVDT model or type, or adjusted in a pre-calibration mode as a coarse gain adjust, final gain adjust being done in the dc gain stage.

To be published in Measurements & Control, June 1997

VI Putting it all together

As we have already indicated, every LVDT conditioner must have a minimum of three sections. A source of excitation, some form of demodulator, and some form of filtering which usually also includes dc gain. The building blocks which we have described above can be configured to optimize the “LVDT system”.

The simplest signal conditioning scheme consists of an excitation source driving the LVDT primary. The secondaries are connected series opposing and feeding a demodulator/output stage with a gain *A*. This basic configuration is shown in Fig. 5.a. As we have already indicated, the excitation voltage will not be constant with temperature, so that we can represent it by $V_{Pri}(T)$. In addition, the transfer function of the LVDT is also a function of temperature, which we will represent by $K(T)$. The voltages of each secondary is given by e_1 and e_2, which are functions of the displacement we desire to measure. The output equation is then:

$$V_o = AK(T)(e_1 - e_2)V_{\mathrm{Pr}i}(T)$$

The output is expected to be proportional to the difference of the secondary voltages, the primary excitation voltage and the coupling term of the transformer. This is the traditional method of conditioning LVDTs because the arrangement is very easily implemented, requires only four wires, and with proper circuit design, can provide very good system performance. Most LVDT signal conditioners available on the market follow this arrangement. The only reason for employing other, more complex, techniques is when the absolute best temperature performance is required from the LVDT - Signal Conditioner system.

In order to reduce temperature errors, a second demodulator can be added to demodulate the primary excitation voltage as shown in Fig 5.b. The secondary differential voltage is divided by this voltage. This makes the output independent of the primary voltage, with the resulting output equation:

$$V_O = \frac{AK(T)(e_1 - e_2)V_{\mathrm{Pr}i}(T)}{V_{\mathrm{Pr}i}(T)} = AK(T)(e_1 - e_2)$$

Now the output is no longer dependent on the stability of the oscillator. This method is more difficult to implement since a divider is required, and the stability of the divider will effect the overall system performance. This method has not seen much use, but is the basis of the Analog Devices AD698.

Another technique, which has been employed in instrumentation grade signal conditioners is what is usually termed “Sum of secondary feedback”. Again two demodulators are used. One generates a signal proportional to the difference of the secondaries, while the other generates a signal proportional to the sum. As shown in

Fig. 5.c, this sum signal is fed back to the excitation source to control the excitation voltage according to the equation:

$$V_{\mathrm{Pr}\,i}(T) \propto \frac{1}{K(T)(e_1 + e_2)}$$

The output is then given by:

$$V_O = AK(T)(e_1 - e_2)V_{\mathrm{Pr}\,i}(T) \propto AK(T)(e_1 - e_2)\frac{1}{K(T)(e_1 + e_2)}$$

$$V_O \propto A\frac{(e_1 - e_2)}{(e_1 + e_2)}$$

As we can see, the output is no longer dependent on the oscillator and transformer temperature terms. This can be very advantageous when the LVDT is expected to see large temperature excursions. We should note that the simplified mathematics presented above is only a first order approximation. In reality, there are higher order effects which limit the improvement to about an order of magnitude in real applications. This approach is relatively easy to implement using the square wave oscillator with filter approach for generating the excitation, since the amplitude of the square wave is easily modulated.

One final approach is to use two demodulators as in 5.c, but employ a divider to accomplish the same mathematical function. This technique is shown in Fig 5.d and results in the same output function as shown above. The technique is the one used by Analog Devices in their AD598 IC.

VII Integrated Circuit LVDT Signal Conditioners

There are currently several IC signal conditioners available on the market. These devices incorporate all of the building blocks described above, to provide a complete signal conditioners. We will attempt to describe their basic operation and give some of their advantages and disadvantages. It should be noted that the primary advantage of IC signal conditioners is in the reduced number of components required for full functionality. From the descriptions given above, it will be obvious that a complete LVDT signal conditioner will probably consist of a minimum of a quad amplifier package, and about 20 passive components (for a diode rectifier configuration with square wave and filter excitation and a simple gain with single pole filter output stage).

The first generally available IC for LVDTs was the Signetics NE5521. It consists of a sine wave oscillator, synchronous demodulator, and an uncommitted op-amp. The device will operate from a single supply between 5 and 20 volts or a dual supply from ±2.5 to ±10 volts.

The oscillator has a differential output, with each output having an amplitude of Vref/8.8. The outputs are 180° out-of-phase. The oscillator voltage and thus the LVDT secondary output is ratiometric to Vref. The oscillator can be programmed for any frequency between 1 and 20 kHz by changing a single external capacitor. The synchronous demodulator normally requires that an external RC network be placed between the demodulators sync input and the oscillator's output. The auxiliary amplifier is usually used with external resistors and capacitors for gain adjust and filtering.

The advantages of the NE5521 are its single chip configuration, operation from a wide range of supplies, small size (it is available in an SOL-16 package), and it's ability to work with 4 wire LVDTs. The primary disadvantages are; a limited oscillator drive capability; no provisions for AC gain, which may cause stability problems with some LVDTs; and the need for many external components (The device requires a minimum of 4 external components, with 8 being more realistic for real applications. A universal configuration will require 12 external components.) The Schaevitz LVM-110 signal conditioner shown in Fig. 6.a uses the NE5521 as the core signal conditioner.

The next device to become available was the Analog Devices AD598. It consists of a sine wave oscillator, precision rectifier demodulators, a ratiometric decoding scheme, and an output amplifier. The device will operate from a single supply between 13 and 36 volts or the equivalent dual supply.

The oscillator again has a differential output with the amplitude programmable from 2.1 to 14 volts rms with a single resistor. The oscillator frequency can be programmed for any frequency between 20 Hz and 20 kHz by changing a single external capacitor. Unlike most LVDT conditioners which have an output proportional to the difference of the secondaries, the AD598 provides an output which is proportional to the ratio of the

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difference divided by the sum of the secondary voltages. This puts some limitations on the LVDT characteristics, but also provides a more temperature independent output. The circuit is conceptually equivalent to Fig. 5.d.

The advantages of the AD598 are it's single chip configuration, availability in an SOL-20 package, wide supply operating range (although it is not specified for operation at voltages below 13 volts), its insensitivity to phase shift, and the fact that the output is not sensitive to oscillator amplitude variations. The circuit implementation requires a minimum of 5 external components. The primary disadvantages of the device are the need for a 5 wire LVDT configuration and the requirement that the sum of the secondaries must be constant over the stroke of the LVDT. Non-constant sums will result in high LVDT non-linearities. Most LVDT manufacturers do not specify the sum of secondaries figures for LVDTs. The AD598 is used in the DC-EC and HCD series of DC LVDTs, Fig. 6.b. Here Schaevitz has optimized the actual LVDT design to take advantage of the positive aspects of the AD598.

A close relative to the AD598 is the AD698. It has the same oscillator and supply conditions with the same programming features. The principle difference is that the demodulation is accomplished with a synchronous design. The AD698 has a divider implemented with a duty cycle multiplier, but unlike the AD598, it calculates the secondary difference divided by the LVDT primary amplitude. This means that the device output is invariant with oscillator amplitude, but it does not have the enhanced temperature stability capability of the AD598. Conversely, it does not suffer from problems with LVDTs which have non-constant sum of secondary conditions. In surface mount form, it is only available in a somewhat larger (28-pin PLCC) package than the NE5521 and AD598, and is limited to operation with supply voltages above 13 volts.

VII Conclusions

For the average user, the first choice in selecting an LVDT for a measuring application should be to consider purchasing a DC-LVDT. This eliminates all consideration of external signal conditioning, and perhaps most importantly, since manufacturers usually calibrate their DC-LVDTs to better than 5% for span, the device may be used without any additional calibration by simply providing a DC power supply and some form of readout device. DC-LVDTs will usually cost more than an AC unit, they may have a somewhat more limited operating temperature range, and they will certainly be longer than the equivalent stroke AC LVDT. They are however much easier to use, are pre-calibrated, and are insensitive to cable length.

Typically, a customer will have to use an AC LVDT when there are size constraints in the application which would force the use of smaller devices. In addition, if the application requires temperatures above 85 °C an AC unit is usually the better choice. The customer will then need to determine the signal conditioning requirements and decide which approach (make or buy) is best. For most applications it is probably best to purchase a commercially available signal conditioner from the LVDT supplier, since they will be able to match the signal conditioner and LVDT to best accomplish the required measurement.

For laboratory use, where the measurements required may vary greatly, it would be wise to purchase one of the more flexible, commercially available signal conditioners, with or without display depending on the applications. With proper calibration, these units will work with a wide variety of LVDTs and provide additional features which will make the use of various measurements easier. For low volume OEM applications, there are a variety of PC board signal conditioners available on the market. These come in both line supply and DC supply variants and are usually easily incorporated into your system.

If you elect to build your own electronics, due to volume and cost considerations, we would recommended that you first contact the manufacturer of the LVDT you expect to use. They can usually provide help in making some of the trade-off decisions which might effect your application. Your first choices will usually be to use one of the commercially available IC signal conditioners to reduce cost. Which one you choose, or if you decide to go to the discrete component route, will depend on the performance you require and the characteristic of the LVDT you choose to use.

We want to point out to those who may wish to try out some of the more complex forms of signal conditioning described in this article that it is very important to contact your LVDT manufacturer. Many applications have been made extremely difficult, or even failed, because customers did not understand the interaction between a chosen LVDT and signal conditioning approach. When in doubt, talk to an LVDT expert before you commit company moneys to a particular approach.

Picture of the ATA2001, MP2000, DC-SE and HCT

Fig.1 Typical Integrated LVDT Signal Conditioners and DC LVDTs. The ATA2001 is a high end signal conditioner capable of operating with a wide variety of LVDTs, while the MP2000 incorporates functions such as limits and peak hold. The DC LVDTs are the recently introduced DC-SE single ended supply LVDT and the HCT, a true two wire 4-20 mA LVDT.

a) Picture of LVM-110
b) Picture of DC-EC electronics

Fig. 6 The Schaevitz LVM-110 uses the Signetics NE5521 to implement a complete signal conditioner module, while the DC-EC uses the AD598 to achieve small module size.

To be published in Measurements & Control, June 1997

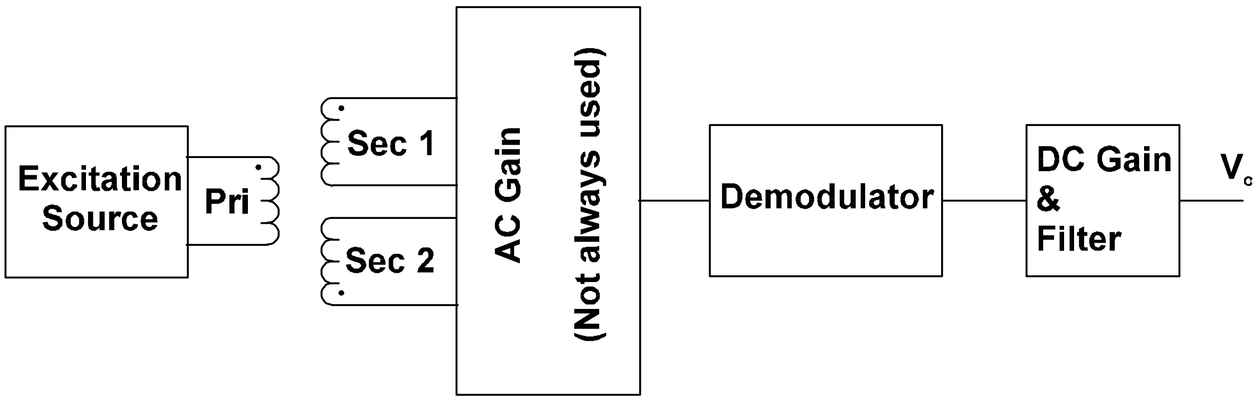
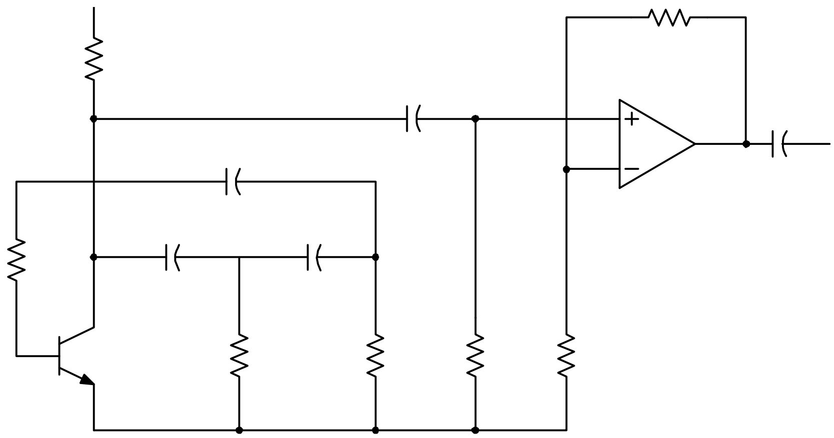
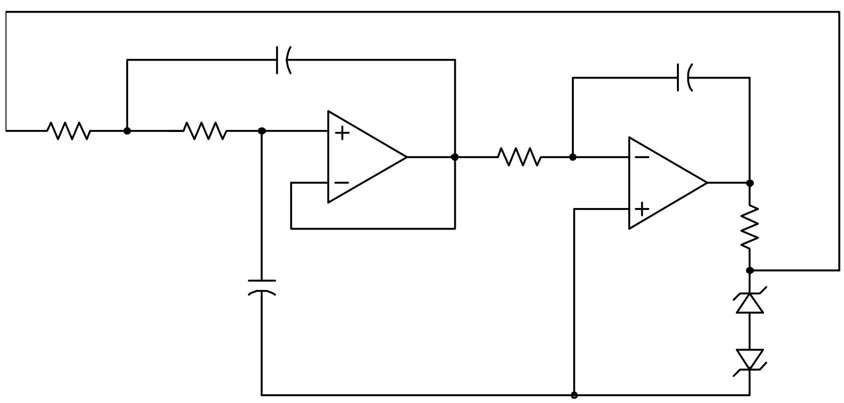


Figure 2

Typical Block Diagram of an LVDT & Signal Conditioner System



(a)



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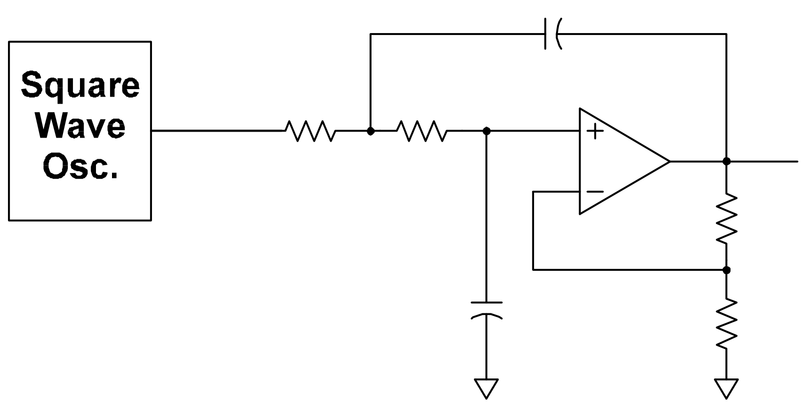


(c)

Figure 3

Three possible means of generating sine wave excitation

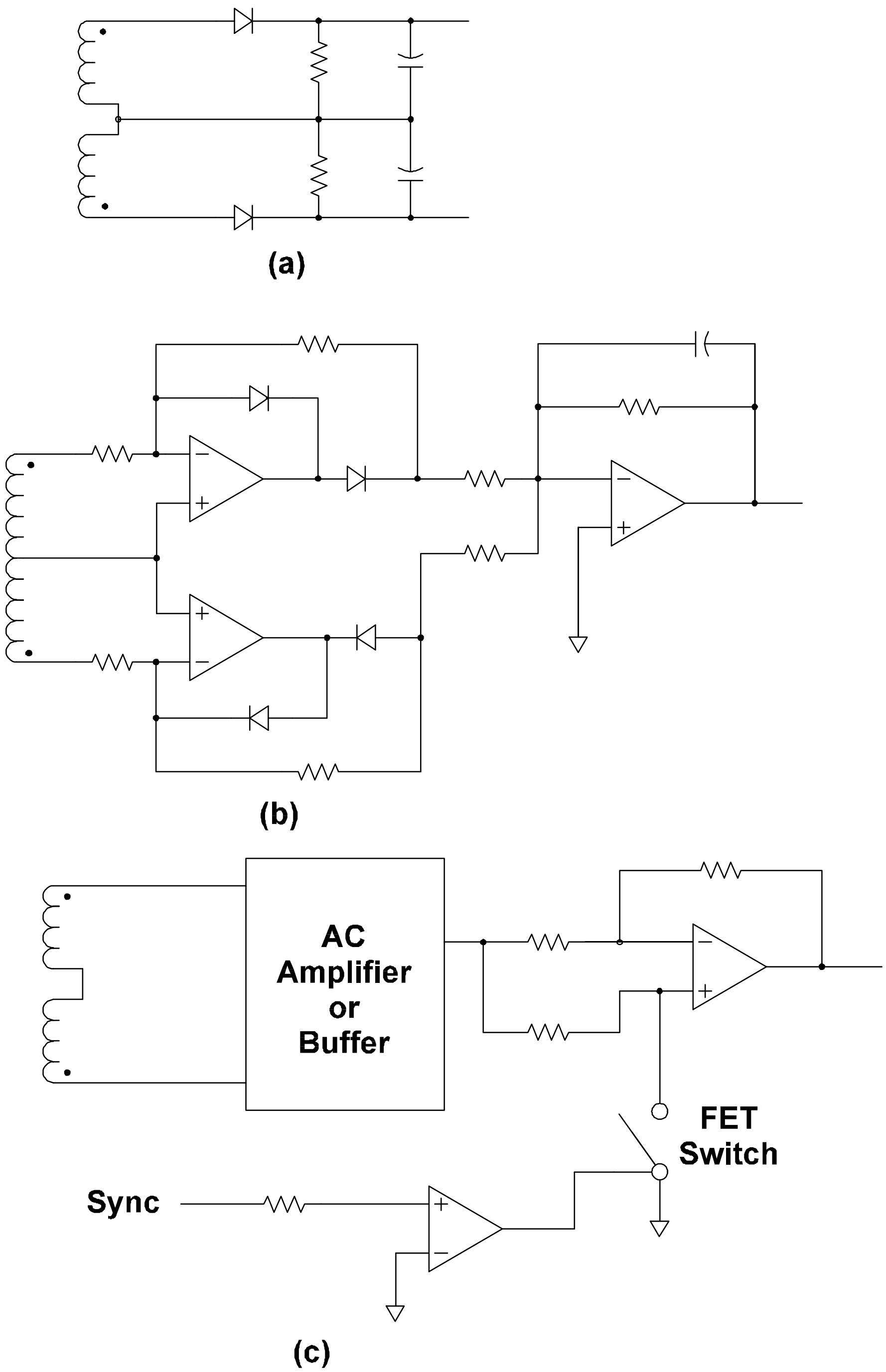
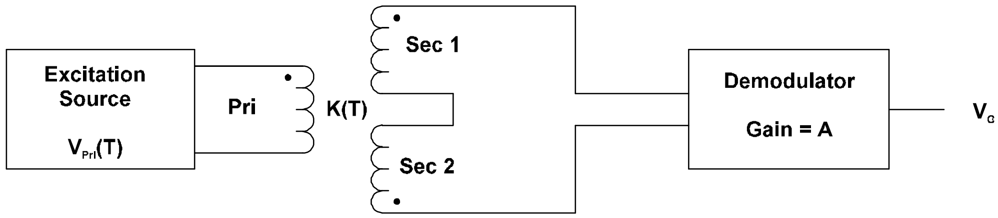
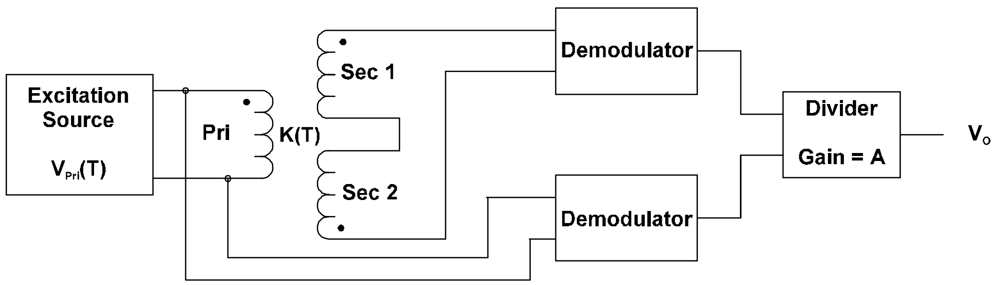


Figure 4

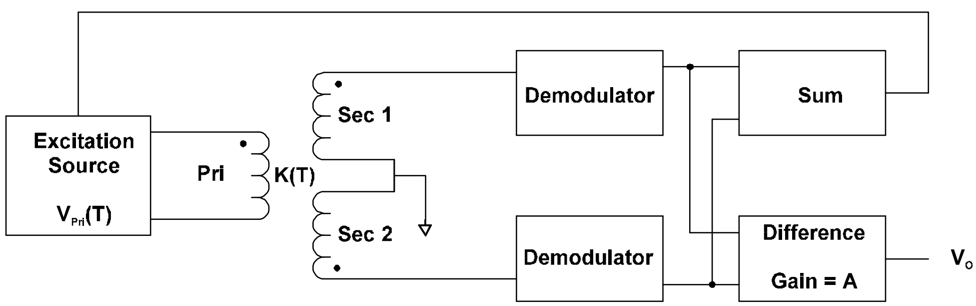
Three means of rectifying the LVDT output



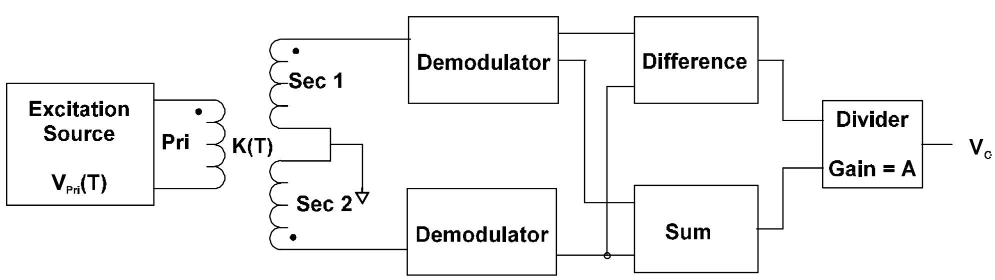
(a) $V_o = A\,K(T)\,(e_1 - e_2)\,V_{Pri}(T)$



(b) $V_o = A\,K(T)\,(e_1 - e_2)\,V_{Pri}(T)$



(c) $V_o = A\dfrac{(e_1 - e_2)}{(e_1 + e_2)}$



(d) $V_o = A\dfrac{(e_1 - e_2)}{(e_1 + e_2)}$

Figure 5
Four possible configurations of complete LVDT signal conditioners

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