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TECHNICAL NOTES

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UNDERSTANDING DC INSTRUMENTATION AMPLIFIERS

DC INSTRUMENTATION AMPLIFIERS are simple devices, used to modify signals in some specified way. However selecting amplifiers can be difficult, because specification terminology is neither widely understood nor universally standardized. Users may therefore benefit from a review of current practices.

Specifications

Amplifier specifications are either *referred to input* (RTI) or *referred to output* (RTO). With the former, phenomena observed at the output vary with gain; with the latter, values are independent of gain. The total performance observed at the output is therefore described by the sum of all RTO quantities plus the product of all RTI effects times gain.

Source Impedance

Source impedance generally gives the maximum allowable resistance of the signal source. However some manufacturers use this quantity to indicate the source resistance at which all other specifications apply.

Amplifier operation is sometimes possible with a highly reactive source, or one whose resistance is greater than that listed. However this should be checked with the manufacturer, since some designs become erratic or unstable under these conditions. If extremely high source resistance is expected, FET input, charge amplifying, electrometer, or other special classes of device may be needed.

Source Current

Amplifier input transistors act as constant current generators, in series with amplifier input terminals. The circuit is closed through the source resistance, back to the amplifier. The current flow through this path may be referred to as *pump-out current*, *bias current*, *input current*, or *differential bias current*. The only important distinction is whether the specification gives the maximum current at either terminal, or the maximum difference between terminals. As an example, an amplifier may be specified to have less than 100 nA bias current from either terminal, but less than 20 nA differential current.

If the path resistance between the terminals is not negligible and neither side is grounded, a difference current could produce an offset voltage while an absolute current would charge both input lines with respect to ground. Such a charge constitutes a self-generated common-mode voltage, which can cause error or saturation. With low capacity to ground and high bias current, saturation will occur rapidly. Amplifiers commonly provide high-resistance return paths, but common-mode voltage can still build up during floating operation.

Temperature Coefficients

The zero or voltage offset temperature coefficient of an amplifier is expressed as a change in output per degree, with a given source resistance. The temperature coefficient of the source current should also be determined. This can be multiplied by the source resistance and added to the nominal RTI voltage temperature coefficient to obtain an overall effective value.

Temperature coefficients are usually mean values over a stated range, rather than the maximum shift which can occur with a one-degree change. The offset voltage is rarely a linear function of temperature, so an average based on two measurements may not be indicative of values which occur between the points. When two-point testing is employed, it may be desirable to use the ambient and upper or lower temperatures of interest rather than 0°C and the appropriate limit.

Specifications for temperature coefficients normally apply after an amplifier has reached thermal equilibrium. In most cases a warm-up period is specified which applies after a temperature change. However if the ambient temperature and energization change simultaneously, the unit may not be able to stabilize within the specified interval. If an amplifier is used in a rapidly changing environment, the user should therefore be extremely cautious. Some units will exceed the normal temperature coefficient under transient thermal conditions, while others will make the transition smoothly. Few manufacturers offer a dynamic temperature coefficient specification on standard products.

Linearity

Linearity is usually specified as a percent of full scale. It is often assumed that if an amplifier is calibrated at some output level, the actual gain will be within the stated percent of the established value at every point in the operating range. This is usually wrong. Most linearity specifications refer to an ideal straight line, rather than a desired gain curve passing through the calibration points.

An amplifier calibrated at +10 volts may therefore have an accuracy of 0.04% FS at mid-scale, even though variation from an ideal straight line through the origin is only ±0.02% (Figure 1a). If the ideal straight line does not pass through zero, the same linearity specification could be met even though the worst case error due to non-linearity could be 0.08% (Figure 1b).

To achieve the specified linearity, it would be necessary to plot gain, introduce a zero offset, and calibrate at an output level where the linearity curve crosses the desired gain line. This is usually less economical than specifying a unit with higher nominal linearity.

Another factor to be checked in linearity specification is the definition of full scale. If the amplifier has an output capability of ±10 V, full scale might be defined as either 10 V or 20 V. Since linearity is usually expressed as a percent of full scale, this can make a sizeable difference in the permissible voltage error.

A related consideration is the full-scale range over which the amplifier is to be used. If the stated linearity is ±0.01% of a nominal 10 V full scale output, the linearity in a 5 V system could be 0.01% or 0.02% of 5 V. Clarification must be obtained from the manufacturer, and the best assurance is the applicable test and acceptance procedures.

In evaluating linearity, it is usually sufficient to test at the highest and lowest gains, since linearity will tend to be worst at these settings. If an amplifier has separate gain modes due to changes in circuit configuration, the upper and lower ends of the high gain mode should be tested, along with the lowest system gain.

If a user generates procurement specifications, it is advisable to determine an acceptable calibration procedure before establishing the desired linearity. Best straight line and percent of reading interpretations should be avoided. The former often leads to confusion in acceptance testing, while the latter creates problems in measuring low signal-level gain. The intended full-scale level over which linearity is to apply should be specified, and unipolar operation should be noted if intended since this may reduce the price.

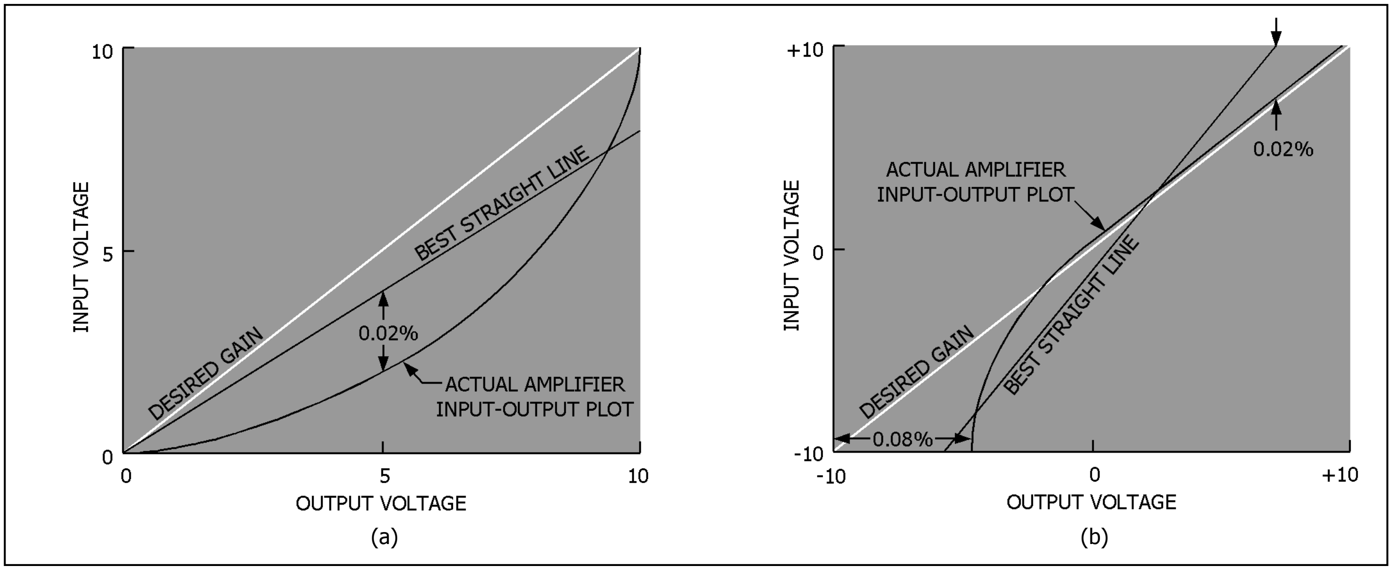
Accuracy

Gain accuracy is normally determined with full-scale output, low signal source impedance, and no output load. The specification is generally expressed as a percent of full scale, which applies on all gain ranges. Amplifiers may also have a gain accuracy which is the sum of a percent and a fixed voltage deviation. The latter can be a significant fraction of the input voltage when the gain is high.

Stability

It is difficult for a user to evaluate the stability of an amplifier with respect to time. Different specifications do not necessarily imply any real difference between two amplifiers. Further, tests made on representative amplifiers do not guarantee the performance of other products from the same or other production runs.

The user must therefore rely on the integrity of the manufacturer and inferences drawn from related factors. For example, testing can show whether a manufacturer is pushing the published specification or has a comfortable margin. Manufacturers should also be able to reference test data compiled by the



(a)

(b)

FIG. 1. AMPLIFIER LINEARITY based on a best straight line is ±0.02% (a) accuracy based on the desired gain is only 0.04% FS at mid-scale; (b) accuracy is only 0.08% FS at an input level of −10 V.

semiconductor suppliers, and provide their own test results on zero stability.

When evaluating long-term gain stability a user should consider the amplifier loop gain and the quality of the feedback resistors. Low loop gain or high temperature coefficients increase the probability of poor stability with time. The absence of temperature coefficient values should be even more highly suspect.

Common-Mode Rejection

Common-mode rejection (CMR) and common-mode-rejection ratio (CMRR) describe ability to disregard a voltage applied simultaneously to both input terminals. Both terms are referred to the input. CMR is normally given in decibels (dB) while CMRR is stated as a direct ratio, such that a CMR of 60 dB implies a CMRR of 1000/1. In such a case, a 10 V common-mode voltage produces an error signal at the input of 10 mV. If the amplifier gain is 1000, the error signal at the output is 10 V.

A CMR specification should include the applicable gain. The amount of input unbalance may also be important, and a value of 1 kΩ is often used as a standard for evaluating relative performance. The frequency of the common-mode voltage (CMV) should also be known. If the CMV is expected to undergo step changes, because the input is switched or scanned, the amplifier may settle normally, overload momentarily, or even undergo catastrophic failure. This should be checked with the manufacturer.

Coupling

Several techniques are used to couple amplifier inputs and outputs. It is useful to understand the characteristics and advantages of the various methods in selecting amplifiers for certain applications.

Transformer- or *flux-coupled* amplifiers typically operate with high CMV and have high CMR. *Post-isolators* are the most common transformer coupled devices. These consist of preamplifiers, followed by high-frequency modulators, transformers, demodulators, filters, and output stages. Such components provide high isolation, but typically result in poor gain stability. Also, intermodulation effects are introduced, and the complexity results in high cost and low reliability.

If high-frequency CMV is encountered with a post-isolator, the CMR can be approximated by reducing the 60 Hz specification by 6 dB/octave. This extrapolation should not be carried too far without checking with the manufacturer. A disadvantage of the post-isolator in some applications is the high capacity from guard to ground. For example in two-wire input scanning, the guard is normally connected to one of the signal leads. Common-mode currents which would normally pass through the guard to ground must then flow through a portion of the signal lines. A low guard-to-ground capacity should be used in such a case.

The *direct input modulator* is a second type of transformer coupled amplifier. After direct modulation at the input, the signal is transformer-coupled to an ac amplifier followed by a demodulator and output stage. If only modest bandwidth and input resistance are required, this concept offers simplicity, reliability, and low cost while providing high CMR, high CMV capability, low temperature coefficients, and low 1/f noise.

Direct-coupled differential amplifiers are inherently capable of high loop gain, and therefore have high stability. These units have traditionally operated with only low common-mode voltage. However new designs are able to draw moderate power from the common-mode source through the guard shield. This can drive floating power supplies in the input circuit to the CMV level. An alternative is to use a high-voltage amplifier, and sense the common-mode voltage from a high-impedance divider across the input terminals. This design can provide high resistance and low capacity between guard and ground.

Most direct coupled amplifiers have maximum CMR at maximum gain, where signal levels are lowest, and minimum CMR at minimum gain where the signal to CMV ratio is more favorable. A typical CMR spec might be 66 dB plus the gain in dB.

Above 60 Hz, CMR will usually be reduced by 6 dB/octave, as in flux-coupled units. However some designs quickly encounter a second order effect, which reduces the CMR more rapidly.

Slewing

Slewing rate is a measure of the speed at which an amplifier can change output voltages. No universal criteria have been accepted for measurement of this speed. Some manufacturers use the maximum rate of change observed with a square wave input, while others use a sinusoid and complete slewing rate at the frequency and output level where distortion and/or dc offset is detected.

Rise time is normally expressed as the interval between the 10% and 90% point of a full-scale step. In physical evaluations, it is useful to test steps in both directions.

Settling time is the interval required for the output to reach and remain within some small percentage of its final value, after a full-scale input step. The error allowed at the point of the measurement varies between manufacturers and models. Special oscilloscopes must be used to measure the settling time of fast amplifiers.

Overload Recovery

Overload recovery is usually defined in terms of the magnitude of the overloads, the recovery period, and the allowable residual error at the point of measurement. There are no standards for expressing this parameter. Typical specifications might be 50 µsec to within 0.1% of FS and 150 µsec to ±0.05% of FS. Extrapolations in these cases can be completely invalid.

Overload recovery is often given insufficient attention. For example a designer might base the speed of an input commutator on amplifier settling time, and then lose data on a channel following one which exceeds the amplifier full-scale input level.

Bandwidth

Small signal bandwidth typically defines the frequency range over which the amplifier gain is within ±3 dB of the dc level. Bandwidth may also be defined in terms of the range over which the gain is less than 3 dB down from the dc value. The latter would allow unlimited peaking to occur without violating the specification.

The slewing rate specification can be checked to determine the maximum frequency at which full-scale output can be obtained. Another factor which might be important is the difference in bandwidth between gain positions. The specification is normally a minimum bandwidth, and in low cost units might increase considerably at lower gains. More sophisticated amplifiers provide circuits to compensate bandwidth for gain changes.

If an amplifier has a variable bandwidth control, the cutoff frequencies are usually still defined simply as the −3 dB point. If this criterion holds, the dynamic characteristics of all classical filters should be identical except for final break-points.

In writing filter specifications, it is common for a user to insist on some minimum response characteristic. However, it is not uncommon to specify the number of poles, the filter type, and the cutoff frequency, and then to add a response specification that contradicts the first three. For example a 3-pole Bessel filter with a −3 dB ±1 dB attenuation at 1 kHz can be specified, but not with a ±0.02% response dc through 800 Hz.

The soak effect produced by dielectric absorption in capacitors should also be considered. A filter with inexpensive capacitors might be unable to meet settling time specifications after soaking at full scale for a few minutes. The effect is small, but in cases such as in-motion load cell weighing, it can degrade accuracy considerably.

Output Characteristics

Output voltage, current, and resistive load ratings are fairly straightforward. Problems in this area are generally of an applications nature, or caused by phenomena not covered by the specifications.

Capacitive loading indicates the amount of capacitance which can be connected across the output without causing instability. The user is expected to consider the output current in considering specific capacitive loads. For example, a 0.1 μF load cannot be driven at 20 V peak to peak and 100 kHz if the maximum output current is only 10 mA. A more subtle but similar limitation occurs in a dc system which is commutated at a fast rate. The user must calculate the charge time which must be allowed with the available current.

Some amplifiers use power transformers with high-capacity couplings to the ac line. In such cases, the output common line may be grounded directly or so heavily bypassed to ground that it is essentially grounded. Under laboratory conditions, the output from such an amplifier may appear satisfactory, since the amplifier and monitoring scope are usually at equal power line ground potential. However in a system, the output recorder may be some distance from the amplifier or even on a different power system. Ac current will therefore flow between the amplifier and the output device. The resulting error voltage can be mistakenly attributed to an input-ground loop, but this can be checked by reducing the gain or shorting the input. An error introduced in the output lines would remain constant.

Some users attempt to obtain polarity inversion by reversing the output leads. Since most output devices are essentially single-ended, this amounts to grounding the normal output, and deriving a signal from the low side of the output. This is not normally a good practice and although it may work with some amplifiers, it will fail completely with others. An example of the latter is an amplifier which has heavy capacitive shunts from its common terminal to ground. When inverted, the amplifier must drive the capacitive load.

Noise

Amplifiers are inherently susceptible to radio frequency interference (RFI), since it is impossible to perfectly shield all input and output lines. RF filtering at the input requires bypass capacitors to ground while common-mode rejection requires that no such capacity exist. A certain amount of RF filtering can be accomplished without affecting common-mode rejection but this is not totally effective. The problem usually requires the cooperation of the user and the manufacturer. Some possible areas of compromise include CMR, bandwidth, input capacity, output impedance, and specific sources of interference.

From the user point of view, RFI evaluations can be useful since there can be a substantial difference between amplifiers. However testing is often inconclusive, since one amplifier may produce a 5% error in a 1 V/meter field at 120 MHz, while a second unit produces a 10% error with the same field strength at 200 MHz, and a third produces a 10% error under some completely different set of conditions. It would be difficult to decide which was superior.

The most important single thing that a user can do is simply be aware of the possibilities. RF which produces glitches on the output is easily recognized, but most users are not aware that RF is often rectified in the amplifier and produces a dc output.

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