Linear Pots and Straight Lines

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If engineers understood the terms which describe a precision potentiometer's linearity, they would save time and money and get the best part for the job.

LINEARITY is perhaps a precision potentiometer's most important characteristic—and also one of the most confusing. There are a number of basic types of linearity and this frequently causes misunderstandings between designers on a project or between designers and manufacturers. Such confusion can result in poor circuit performance, extra costs, unnecessary component rejections, and frustrating delays. A thorough knowledge of the various types of linearity—and the correct usage and terminology for each—can help engineers avoid such problems. But first, what types of linearity are we concerned with?

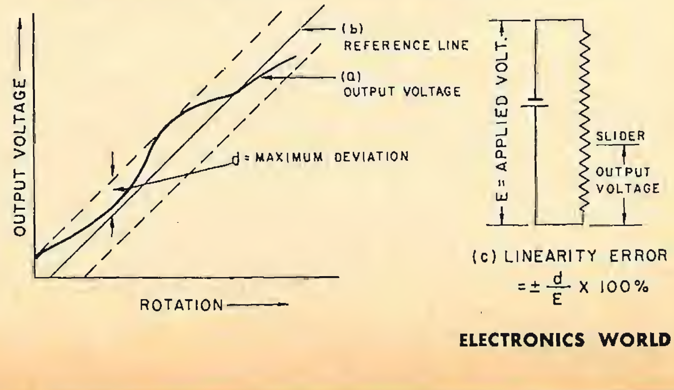
What is Linearity?

Any discussion of linearity requires an understanding of the three basic elements illustrated in Fig. 1. First, the engineer must have a picture of the potentiometer's output(s). This is obtained by connecting the potentiometer as shown and recording the output voltage while rotating the shaft. (In actual practice only the output voltage deviations from a theoretically perfect master are of interest.) Next, he must establish a straight line from which to measure deviations (*b*) and then he must have a means of expressing linear errors that does not depend on rotation, resistance, or test voltage (*c*). This is accomplished by expressing the maximum deviation of the output curve (in volts) as a percentage of the applied voltage. Errors in linearity are always understood to be plus or minus even though the maximum deviation may not occur in both directions.

In other words, no matter how linearity is defined, it is always a measure of the deviation of the potentiometer's actual output voltage from some straight reference line and is always expressed as a percentage of the applied voltage.

The only difference among the various definitions of

Fig. 1. Potentiometers are called linear when their outputs follow a straight line. Linearity errors can be plus or minus.



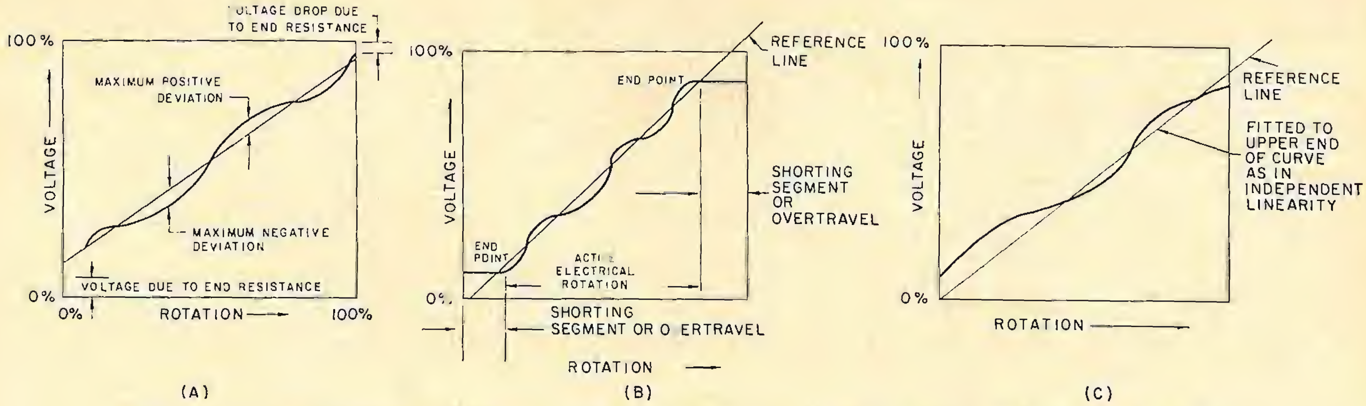


Fig. 2. (A) A potentiometer whose deviation is measured over its "active electrical length", or "end points" (B), is independently linear. The reference line of a zero-based linear pot (C) passes through 0% voltage point at 0% rotation.

linearity is in the position of the reference line. There can be just as many definitions as there are ways of drawing reference lines on an output *versus* rotation chart. However, there are only four generally accepted definitions: independent, zero-based, terminal-based, and absolute linearity.

Independent Linearity

In independent linearity, voltage deviations are measured from a reference line placed to minimize the maximum excursions. By definition, then, a potentiometer can have no lower linearity value than its independent linearity figure. In this case, the positive and negative errors are equal.

The significant feature of this measurement is that the reference line's slope and position are determined only by the output curve and thus may assume any value (Fig. 2A). In actual practice, they are held within reasonable limits by specifying the maximum end resistance. However, it is important to remember that independent linearity is a measure of the "straightness" of the potentiometer output. Other types of linearity measurements relate the potentiometer's output to some other factor, such as an index point or rotation.

Independent linearity is nearly always defined as being measured over the "active electrical rotation" or between the "end points". These are equivalent expressions and are illustrated in Fig. 2B. Only that part of the output curve between the end points was considered in determining the position of the reference line. Engineers often specify this type of linearity when trimmers are available to adjust end voltages, as for example, in XY plotters. However, independent linearity is not used when maximum accuracy is required.

In spite of this limitation, independent linearity is the most commonly used type, since it is adequate for most applications and is the least expensive.

Zero-Based Linearity

In zero-based linearity, the reference line passes through the zero voltage point at 0% potentiometer rotation (Fig. 2C) The potentiometer's upper end is adjusted to minimize deviations. In this type of linearity, the reference line's position is specified, but the slope is unrestricted except, as in independent linearity, by the actual output curve of the potentiometer. Standard practice is to consider the counterclockwise end point as the 0% rotation point.

Engineers specify zero-based linearity when the linearity at the beginning end point must be held within a certain tolerance. If the tolerance were not held, a voltage of opposite polarity would be required to compensate for the beginning-end voltage error and a trimmer to compensate for errors at the other end. This could be an expensive technique and should be avoided if possible.

Terminal-Based Linearity

In terminal-based linearity, the reference line must pass through the 0% voltage point at 0% rotation and the 100% voltage point at 100% of the active rotation.

In Fig. 3A, it is obvious that the slope of the reference line is much more restricted than when using zero-based linearity. Figs. 3B and 3C, however, show that the slope (in terms of voltage change per degree) can still vary within certain limits. The limits are determined by the tolerance on electrical rotation.

In many applications, a particular potentiometer is picked to match a circuit and if the potentiometer is replaced, the entire circuit or system must be recalibrated. Therefore, circuits that utilize this type of linear potentiometer are more expensive. For this reason, this definition is almost never used today. It has been superseded by the specification "absolute linearity".

STANDARD LINEARITY DEFINITIONS

(Revised Standard Terms and Definitions, July 1964. Precision Potentiometer Manufacturers Association—now Variable Resistive Components Institute.)

Independent Linearity: The maximum deviation of a potentiometer output from a straight reference line whose slope and position was chosen to minimize error. It is expressed as a percent of the total applied voltage.

Zero-Based Linearity: The maximum deviation of a potentiometer output from a straight reference line drawn through a specified minimum output ratio and extended over the component's actual electrical travel and rotated to minimize deviations. Unless otherwise specified, the minimum output ratio is zero.

Terminal-Based Linearity: The maximum deviation of a potentiometer output from a straight reference line drawn through specified minimum and maximum output voltage ratios which are separated by the component's actual electrical travel. Unless otherwise specified, minimum and maximum output ratios are zero and 100% of applied voltage.

Absolute Linearity: The maximum deviation of a potentiometer output from a straight reference line drawn through the specified minimum and maximum output ratios which are separated by the theoretical electrical travel. An index point on the actual output is required.

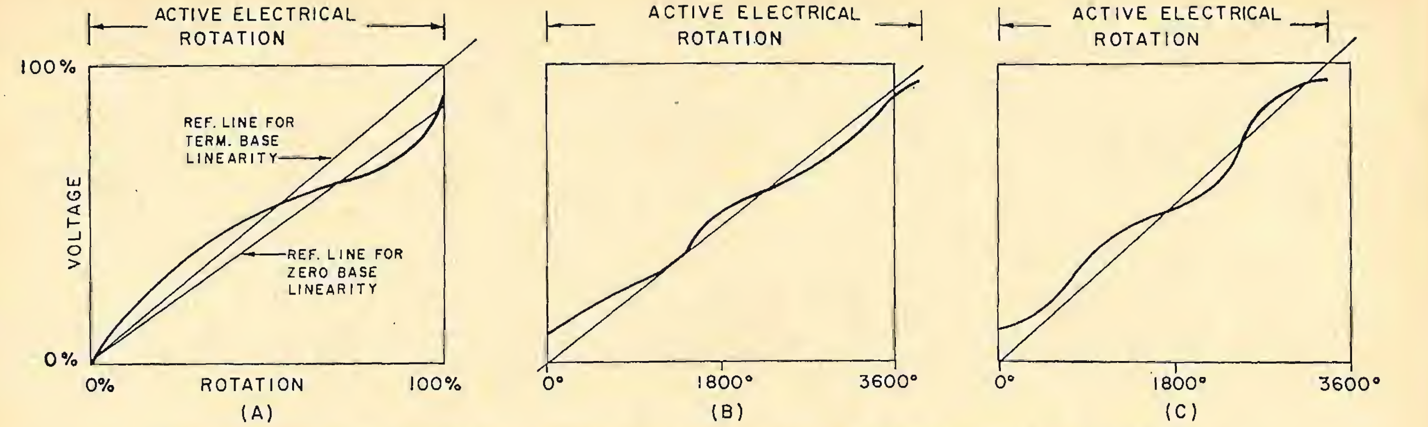


Fig. 3. Although the reference lines of terminal-based potentiometers pass through zero voltage at 0% rotation and maximum voltage at 100% rotation, slope can vary within certain limits as indicated by linearity graphs.

Absolute Linearity

In absolute linearity, the reference line is drawn from the 0% voltage point at 0% rotation to the 100% voltage point at some fixed angle. Thus, both the voltage reference and the angle which determines the slope of the reference are independent of the potentiometer being tested. This means the reference line of all potentiometers (measured over the same angle) have a constant slope in terms of voltage change per degree. The angle which determines the slope is called the "theoretical angle". While it is standard practice to do so, it is not necessary that this be the same as the angle over which the linearity is measured.

A potentiometer compared to this fixed reference line is being compared to an absolutely perfect or ideal potentiometer. Consequently, one potentiometer can be replaced by another without mechanical or electrical adjustment or trimming.

The difference between a terminal-based linearity reference line and an absolute-linearity reference line is shown in Fig. 4A. Here the actual active electrical rotation is shown greater than the nominal or theoretical rotation. This is usually the case in multi-turn potentiometers where the tolerance is positive.

Using Absolute Linearity

The designer must know what position of the potentiometer shaft represents 0% rotation before he can properly phase the component into his system. If the end point is chosen, the installation is simplified. However, one reason this is not a standard practice is because it limits the potentiometer's accuracy. This is illustrated in Fig. 4B. Here the output curve lies mostly below the reference line AA. If the reference line were moved over to BB, the output curve would not have as much deviation, but the reference line would not pass through zero at the end point.

End resistance is another reason the end point is not used. Again, the average slope of the output line is different from the reference line. It starts higher at one end and finishes lower at the other. By moving the end points slightly, the output curve can be made to follow the reference more closely. This is shown in Fig. 4C.

To avoid these restrictions, an "index point" is used and it is standard industry practice to specify the voltage at 50% of the nominal angle. Such a potentiometer carries a label which might read "1800° = 49.937% E_{in}". This enables a technician to find a point on the actual output curve and identify it as a particular angle.

Potentiometers that have absolute linearity are commonly used in precision servo systems or in any circuit where extreme accuracy is desired. Their big advantage is that no trimming is required either at initial installation or when they are replaced.

Summary

As a quick recap, the identifying characteristics of the reference line for the various linearity types are as follows: independent—slope and position determined by the output curve and can have any value; zero-based—position determined by an end point and slope determined by output curve; terminal-based—slope and position determined by end points (This definition of linearity is obsolete.); and absolute—slope is constant and determined by some given angle between the zero and one hundred percent voltage points. The position is determined by an index point. No mechanical or electrical trimming is necessary. ▲

Fig. 4. In graph (A) absolute and terminal-based linearity reference lines are compared. The other curves demonstrate how linearity is improved by (B) moving the reference line, and (C) by moving the end taps.