

White Paper 1: Understanding Transducer Characteristics and Performance

Understanding Linearity

End point linearity

There are several ways to interpret and represent the linearity of a transducer and those most commonly used are: – end point linearity, best fit straight line (BFSL) and least squares BFSL linearity. All of these plus the implications of asymmetry in bi-polar devices are discussed in this White Paper, beginning with End Point Linearity.

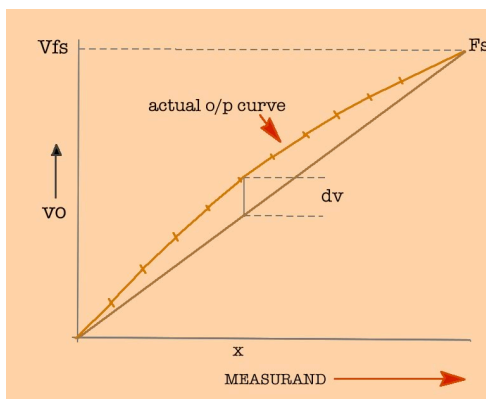


Fig1. End point linearity

The perfect straight line transducer output is represented by the general equation:

$$V_o = Mx + b$$

Where V_o = transducer output

M = the slope of the ideal output characteristic

x = the value of the measurand at a given point

b = the zero offset

It can be seen that the exaggerated output curve in Fig.1 shows a deviation from the straight line of 'dv' and so we can express this error as:

$$\%FS \text{ non-linearity} = \frac{dv \times 100 \%}{V_{fs}}$$

Usually the point that deviates most from the simple straight line will be used to specify the 'linearity' of the transducer. It should be noted that the percentage is quoted using the normal full-scale output of transducer V_{fs} .

It is obvious from the diagram that a better straight line could be drawn along the plotted points so that all of them are closer to it. This is called the 'Best Fit Straight Line' (BFSL). □

Best fit straight line method of definition

In practice the relationship between the measurand and the output of most transducers is not perfectly linear and it is therefore necessary to find a way of using these devices to achieve the most accurate overall results. This can be achieved by constructing what is known as the 'Best Fit Straight Line' (BFSL) through the calibration points in such a way that the maximum deviation of the curve from the line is minimised, as indicated in the Fig.2, below.

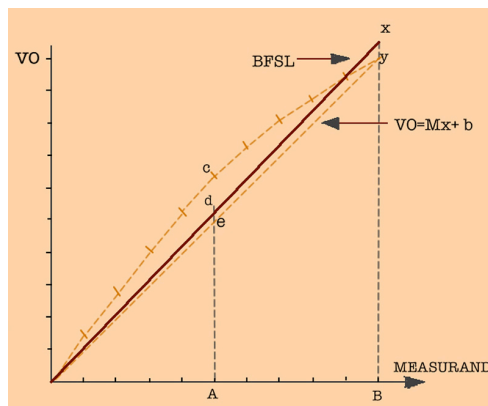



Fig. 2 Best fit straight line

The diagram simply illustrates how, instead of drawing a straight line between the origin and the end point at 'B', we can construct a line, which effectively halves the maximum deviation that would appear at point "A" and shares it with the end point at "B". Thus the deviation from the BFSL, and hence the linear error, is effectively halved.

However, it should be appreciated that this is simply a means of interpretation of the results and relies entirely on the system, including the measuring equipment, being set up to take advantage of this technique.

To take advantage of this method in the case illustrated, it is necessary to set up the system so that when the transducer is at full scale 'y' at point 'B' the indicated output would be set to the value of 'x'. This then effectively halves the error indicated at 'A' which would now deviate from the BFSL by the amount 'c' – 'd' rather than 'c' – 'e' if we simply had constructed an 'end point straight line'.

It can be clearly seen that this enables us to effectively halve the errors in the system and thus record better results over the whole measuring range. Note, however that it is quite easy to construct a BFSL on a graph of transducer output against measurand, it is not so easy to do when faced with a simple set of figures. In practice we need a better, quicker and more consistent means of determining the BFSL, which can also take into account transducers with bi-polar outputs such as LVDTs and tension/compression load cells.

The answer to this problem is the 'Least squares method' of determining the BFSL. This is a statistical method, which enables the BFSL to be determined mathematically over any chosen working range, and is the most valuable method for use in computerised calibration systems. 

Least Squares Best Fit Straight Line Method

The 'Least Squares Best Fit Straight Line' method is preferred by most transducer manufacturers because it provides the closest possible best fit to all data points on the curve, and can be most readily adapted to the computerised calibration systems in common use.

The Least Squares Best Fit Straight Line is a statistical method and as such may not be a 'purist' approach. But provided that the characteristics of the transducers are correctly optimised at the design and development stage and are represented by a continuous smooth curve, the assessment is meaningful and accurate.

In practice, up to 20 calibration points will be taken over the whole working range of the transducer and the measured input and output values at each point used to provide the data for each calculation of the slope of the 'Least Squares Best Fit Straight Line' using the following equation:

$$\text{Slope}(s) = \frac{\sum_{d=1}^n X_d Y_d}{\sum_{d=1}^n X_d^2}$$

Where: X_d = known input data points

Y_d = actual sensor output at each X_d data point

n = number of data points

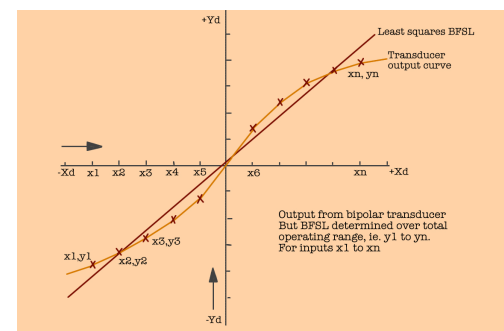


Fig.3 Least square best fit straight line method

Having mathematically determined the slope of the best fit straight line it is then possible to determine the maximum deviation of any point from this line using the equation:

$$\% d = 100 \left(\frac{Y_{d\max} - SX_d}{SX_{fr}} \right)$$

Where fr = full working range.

As with other methods the maximum deviation would be expressed as a percentage of the total linear range of the device. It should be noted that since this evaluation is done over the total range of the transducer, the best fit straight line may not pass through the zero point of a bi-polar device such as a LVDT, universal load cell, differential pressure transducer etc.

However, this does not have any great practical significance since the zero output point is usually adjustable electronically anyway.

In general it can be readily agreed that this method is by far the most efficient one, but it must be used with care and understanding. Clearly because of its statistical nature, the number of data points will have a direct bearing on the ultimate validity of the assessment. In practice, the more uneven the characteristic curve, the more data points must be used in order to take the incremental non-linearity into account. □

Understanding Accuracy

Accuracy – some of the important factors to consider

Fundamentally, 'Accuracy' simply describes how closely the indicated value represents the actual measurand being monitored, whilst taking into account all possible sources of error that are relevant to the application.

It is our experience that accuracy is very often confused with linearity, which is of course only one source of potential error, albeit quite a significant one. In fact in the practical world the quoted accuracy of a measurement should include at least some and possibly all of the following sources of error:

1. Linearity
2. Repeatability
3. Resolution
4. Hysteresis
5. Zero temperature coefficient
6. Gain temperature coefficient
7. Long term stability
8. Calibration equipment errors and the calibration standard

Clearly then, accuracy can be closely defined for a given set of operating conditions but it is vitally important to take into account all contributing factors if the very best results are required.

Furthermore, it must be remembered that not all manufacturers will define these parameters in exactly the same way, so choosing the best device for your job can become quite a challenge.

Our review of "Linearity" in this White Paper has given a flavour of how the definition of this particular parameter can vary and thus have a very considerable bearing on the realisable accuracy of the measurement.

In this section we will examine all of the above factors in the 'Accuracy' equation and demonstrate how a device having a linearity of 0.1% can very quickly be degraded to a device having an overall accuracy of maybe one or two percent under its operating conditions.

It should be appreciated that there are two main aspects to these potential sources of error. Firstly there is the inherent performance of the transducer and secondly the quality of the means of measurement of that performance i.e. the calibration equipment. It is generally accepted that the test equipment must be at least five times more accurate than the device being tested in order to be confident that the claims for the transducer are correct.

Repeatability

Repeatability is simply the ability of a transducer to consistently reproduce the same output signal for repeated application of the same value of the measurand. It is a clear factor and one that varies with different methods of sensing the measurand. For instance an inductive or capacitive method will be potentially better than a strain gauged device, typically 0.001% and 0.05% respectively.

Resolution

Resolution represents the smallest increment of the measurand that can be determined by the transducer.

The resolution of most modern transducers is good and mainly limited by the noise levels of the associated electronic circuits. In general the resolution of most analogue sensing techniques, e.g. strain gauge, inductive, capacitive would be well within 10 parts per million, but potentiometers, incremental digital and absolute digital devices have resolutions determined directly by design and mainly limited by the number of bits.

So, resolution is possibly the least worrying of these sources of error because it is either clearly defined or not very relevant.

Hysteresis

Hysteresis represents the difference in output from a transducer when any particular value of the measurand is approached from the low and the high side.

In general, hysteresis occurs when a sensing technique relies on the stressing of a particular material such as strain-gauged metals, and would have a worst case value of 0.2% for a low-cost device. Some transducers such as inductive or capacitive-based displacement transducers do not exhibit this error at all because they do not involve the stressing of any material to convert the measurand into an electrical signal.

Summary

In summary, these three error factors together – repeatability, resolution and hysteresis - could contribute up to 0.26% FS inaccuracy in the measurand of a particular parameter and these are fixed for a given type of transducer and also independent of temperature. Errors introduced by temperature coefficients, the calibration equipment and the overall effect of these various sources of error on the final accuracy of the measurand are examined next.

Temperature Coefficients

All types of transducers exhibit two sources of temperature error due to:-

(a) Zero coefficient

(b) Gain coefficient

Sometimes these two elements can be taken as a combined coefficient but this will not necessarily be equal to the simple addition of the zero and gain coefficients, but rather the sum of the two, bearing in mind that the value of these coefficients can be either positive or negative. The zero coefficient is simply the change of output of the transducer when set at its zero output condition as the temperature is changed and is expressed as a percentage of F.S. per degree centigrade (F.S./°C), or sometimes in parts per million.

It can be affected by several elements of the device. For instance expansion or contraction of any mechanical parts, changes of resistance, capacitance or inductance in the overall electrical circuit, or even changes in magnetic properties in some devices. Furthermore, if the device includes complex electronic components then it is certain that changes in these will also affect the overall output of the device as the ambient temperature changes. This error would typically be $\pm 0.001\%$ to $\pm 0.01\%$ F. S./°C for non-electronic, to 0.01% to 0.02% F. S./°C for transducers having "built-in" electronic circuits.

Gain changes with temperature are caused by many of the same basic constituent parts as zero changes, but in this case they have a direct effect on the sensitivity or the output per unit measurand. The errors from this source would be typically in the same ranges as that for the zero coefficient. We could find that a simple addition of these errors would result in a total error for an electronic device that could yield a coefficient of the order of $0.04\%/^{\circ}\text{C}$. In practice, the combined error of zero and gain coefficients would give a typical error of say 0.02 to $0.03\%/^{\circ}\text{C}$. This can be sometimes improved by using special compensation techniques.

Long-term stability

Long-term stability is a factor that is rarely quoted by manufacturers, but of considerable interest in some applications. Clearly, it can only really be determined by very long term monitoring in controlled conditions, which for small and relatively inexpensive components, is not practical. It is therefore more likely that initially, at least, a figure will be quoted based on the long experience of the manufacturer and the knowledge of the components and techniques incorporated in the design. Obviously the degree of difficulty is increased by the variation in the conditions under which the transducer is intended to operate. Depending on the complexity of the device a typical figure for this would be 0.05% per annum to 1.0% per annum for fairly benign conditions but may be significantly higher in rugged conditions, hence the importance of regular calibration checks of the device.

Calibration Errors

Calibrations are usually carried out in ambient conditions with a temperature of around 20°C. Generally, there are just two sources of error in the calibration process:

(a) Human error. Obviously it is important to ensure as far as possible that the minimum amount of human determination is involved in this process. Today much of it is computerised so that all calculations are accurate and consistent.

(b) Equipment error. The ultimate accuracy of the calibration will of course be very dependent upon the calibration standard used to input the measurand to the device under test. It is generally accepted that this should be at least 5 times more accurate than that claimed for the finished transducer and regularly checked against equipment closely traceable to National Standards. For instance, a purely mechanical device such as a linear vernier gauge will need more frequent checking than say a dead weight load or pressure tester.

applications we would see a maximum temperature range of say 50°C and we would not generally expect to achieve much better than around 1 % accuracy under these conditions. □

Summary of factors influencing accuracy

In conclusion, we can say that taking into account linearity, repeatability, hysteresis, resolution, temperature coefficients, long term drift and calibration errors, a device which offers an overall accuracy of say 1% over a temperature excursion of 100°C is excellent and one that can offer 0.5% is absolutely exceptional. In practice for most industrial

Load cell symmetry

Most Load Cell applications call for measurements to be made in either compression or tension only, but in some instances, such as through zero fatigue testing, measurements need to be made in both tension and compression on the same load cell. Usually referred to as a 'Universal' Load Cell.

In such cases the 'symmetry' of the load cell becomes an issue and needs to be taken into account in the overall accuracy equation as illustrated in the 'Accuracy' section previously in this White Paper.

Obviously, it is desirable for the output from the load cell to be the same for a given load in tension as that for compression, but this is not a feature that automatically exists in most strain gauged load cells. In practice special care has to be taken in the strain gauging of the cells to achieve a characteristic that is close to symmetrical and in general a higher linearity cell will have a better symmetry than a cell with poor linearity.

Fig.4 illustrates very simply how a non-symmetrical load cell gives a different slope in its output when loaded in tension and compression. The symmetry is defined as the difference between these two slopes expressed as a percentage of the full scale output for the load cell where full scale is the output from the load cell either in compression or tension.

Typically, the Honeywell Sensotec* Model 41 Universal load cell will have a symmetry of 0.25% F.S. and the Model 45/47 has a symmetry of

0.1%F.S. But cells having lower linearities will very often have a non-symmetry of 1 % or even greater.

*RDP Electronics Ltd has been sole distributors for Honeywell Sensotec products in the UK since 1978.

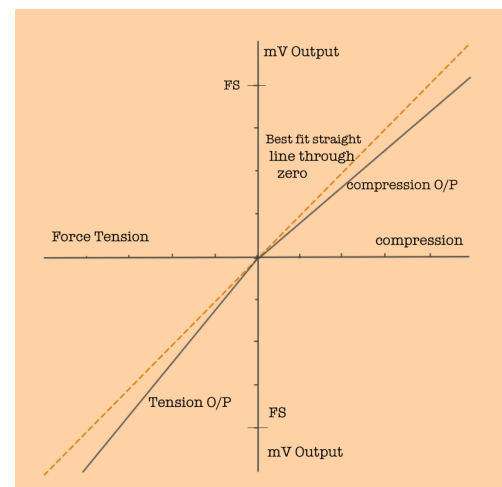


Fig. 4 – Load cell, tension/compression symmetry

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