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Methods for calculating the main static performance specifications of transducers

传感器主要静态性能指标计算方法

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Table of Contents

Methods for calculating the main static performance specifications of transducers

1 Scope

This Standard specifies the definitions and calculation methods of the main static performance specifications of general transducers.

This Standard is applicable to the calculation of the main static performance specifications of transducers during the process of development, production and use. It is also applicable to the development and revision of product standards for various transducers.

2 Definitions

For the purposes of this document, the following terms and definitions apply.

2.1 Basic terminologies

2.1.1 static characteristics

the relationship between output and input when measured under constant or slow-change conditions

NOTES:

1 The static characteristics of the transducer include a variety of performance indicators that can be determined by static calibration.

2 The static performance specifications of the transducer shall normally be marked with the applicable temperature range.

2.1.2 static calibration

the process of obtaining static characteristics under specified static test conditions

2.1.3 measuring range

the interval expressed by the maximum measured (measured upper limit) and the smallest measured (lower measured limit) under the premise of ensuring performance indicators the transducer that working characteristics are represented by curve equation

2.2 Static calibration characteristics

2.2.1 up-travel actual average characteristics

the connection curve of the arithmetic mean point of a set of measured values at each calibration point of the up-travel

2.2.2 down-travel actual average characteristics

the connection curve of the arithmetic mean point of a set of measured values at each calibration point of the reverse stroke

2.2.3 up-travel and down-travel actual average characteristics

the connecting curve of the average point of the arithmetic mean of the positive and down-travel strokes of each calibration point, also called the actual characteristics (curve)

2.3 static performance specifications

2.3.1 resolution

the minimum input change that produces observable output changes over the entire input range

2.3.2 sensitivity

the ratio of output change to corresponding input change

2.3.3 hysteresis

the difference between the positive and down-travel stroke outputs of the transducer for the same input when the input is full-span

2.3.4 repeatability

the degree of dispersion between a set of measured outputs, in a short interval of time, under the same working conditions, when the input volume changes from the same direction to full scale, multiple times approaching and reaching the same calibration point

2.3.5 linearity

the maximum deviation of the actual average characteristic curve of the positive and down-travel strokes from the reference line, expressed as a percentage of full-span output the linearity that the reference line is the front terminal-based line

NOTES:

1 The front terminal-based line passes through the front terminal point of the actual characteristics of the transducer. However, the maximum deviation of the transducer's actual characteristics shall be minimized by changing the slope.

2 The front terminal-based line is called the zero-base line in some foreign standards and literature.

2.3.5.6 Independent linearity

the linearity that the reference line is the best straight line

NOTES:

1 The best straight line is the median line of two parallel lines that are closest to each other and can accommodate the up-travel and down-travel actual average characteristics of the transducer.

2 The best straight line guarantees that the actual deviation of the transducer’s actual characteristics is minimal.

2.3.5.7 least-squares linearity

the linearity that the reference line is the least square line

NOTE: The least-squares line shall ensure that the sum of the squares of the actual characteristics of the transducer is minimal.

2.3.6 conformity

the maximum deviation of the curve of the up-travel and down-travel actual average characteristics to the reference curve, expressed as a percentage of full-span output

NOTES:

1 There are multiple compliances that vary with the reference curve.

2 Conformity shall be limited. Conformity without qualifiers means independent conformity.

2.3.6.1 absolute conformity

the conformity that the reference curve is the specified curve, also known as theoretical conformity

NOTES:

1 The reference curve for absolute conformity is pre-defined. It reflects the conformity precision and is absolutely different from the properties of several other degrees of conformity.

2.3.8 uncertainty

an evaluation result that characterizes the measured true value in a certain range; it is a parameter that reasonably gives the dispersion of the measured value, and it is also a parameter associated with the measurement result

NOTE: Uncertainty can more reasonably represent the nature of measurement results from both qualitative and quantitative aspects.

2.3.9 total uncertainty

also known as basic uncertainty, an uncertainty obtained by static calibration under specified conditions and according to the specified calculation method

NOTE: In this Standard, the total uncertainty is combined linearity, hysteresis and repeatability. It reflects their joint role. It is not simply adding.

2.3.10 zero drift

zero output only changes with time within the specified time, usually expressed as a percentage of full-span output

2.3.11 drift of output span

full-span output changes only over time within the specified time, usually expressed as a percentage of full-span output

NOTE: If the prescribed assessment time is long, such as months to years, this indicator is often referred to as long term stability.

2.3.12 thermal zero shift

zero output change caused by changes in ambient temperature, usually expressed as a percentage of the full-span output of the unit temperature

2.3.13 thermal shift of output span

full-span output change that is due to changes in ambient temperature, usually expressed as a percentage of the full-span output of the unit temperature

3 Calculation method for single static performance specification

3.1 Establishment of static calibration characteristics

3.1.1 General requirements for static calibration

value of the difference between the maximum and minimum values of a set of n measured values at the i^{th} calibration point;

d_R - range coefficient; it depends on the number of calibration cycles n, i.e. the number of measurements at a calibration point or the sample size n. The relationship between the range coefficient d_R and the number of calibration cycles is shown in Table 2.

Table 2

n	2	3	4	5	6	7	8	9	10
d_R	1.128	1.693	2.059	2.326	2.534	2.704	2.847	2.970	3.078

NOTES:

1 The range method is slightly simpler than the Bessel formula method. However, the calculated sample standard deviation S is generally slightly larger.

2 When calculating S, if not specified, it refers to Bessel formula method. In case of dispute, the Bessel formula shall prevail.

3.7.4 Selection of standard deviation of transducer sample

3.7.4.1 If the number of calibration points is m (usually m=5~11), 2m sample standard deviation S can be calculated. This Standard stipulates that the largest S (i.e. the maximum standard deviation S_{max}) is selected to participate in the calculation of Equation 10 so as to obtain the repeatability of the transducer as a single performance specification.

3.7.4.2 This Standard allows the user to perform an equal precision test on the transducer being tested as an option according to the method of Annex E. The variance at each measurement point of the equal precision transducer has the same mathematical expectation. Therefore, the average variance can be used instead of the variance at each measurement point. Therefore, if it is determined that the transducer is an equal-precision sensor, the maximum standard deviation S_{max} shall not be taken. It shall take the average standard deviation S_{av} to calculate the repeatability. S_{av} is calculated as follow:

$$S_{av} = \sqrt{\frac{1}{2m}\left(\sum_{i=1}^{m} S_{u,i}^2 + \sum_{i=1}^{m} S_{d,i}^2\right)} \quad \cdots\cdots (15)$$

If the precision of the transducer being tested is not performed, or if the test fails, the requirements of 3. 7. 4. 1 shall still be applied. That is, calculate repeatability according to the requirements of unequal precision transducer.

NOTES:

x_{max}、x_{min} - maximum and minimum input values of the transducer.

NOTES:

1 The calculation method for terminal-based line is simple and easy to implement with the bridge detection circuit.

2 Compared with other linearities, the calculation results of terminal-based linearity is generally larger.

3.8.4 Shifted terminal-based linearity ($\xi_{L,s,te}$)

See equation (16) for calculation.

As the shifted terminal-based equation of reference characteristics, see 3.8.3 for the calculation method of its terminal-based linear equation. See A.2.2.1 of Annex A for the translation method.

NOTE: The shifted terminal-based linearity can be used to replace the independent linearity in some occasions where the requirements are not too high.

3.8.5 Zero-based linearity ($\xi_{L,ze}$)

The principle of calculation method is shown in Figure 2. The calculation formula is shown in equation (16).

By definition, a zero-based linear equation can be written as reference characteristics:

$$Y_{ze} = bx \qquad \cdots\cdots (19)$$

where,

b - zero-base linear slope, i.e. the theoretical zero point of the transducer (x = 0, y = 0) and the slope of the line connecting the center of gravity of the smallest maximum positive and negative deviation points.

For the calculation of the zero-based line, see Annex A, A1.

NOTE: The working characteristics of the transducer can be represented by a zero-based line. Its equation is simple and easy to use.

3 The front terminal-based linearity is generally better than zero-based linearity. And it can make the deviation near the zero point of the transducer smaller.

3.8.7 Independent linearity ($\xi_{L,in}$)

The principle of calculation method is shown in Figure 4. The calculation formula is shown in equation (16).

The calculation method of the best straight line is shown in Annex A, A2.

NOTES:

1 Independent linearity value is the smallest among various linearities. Independent linearity is used whenever possible to accurately measure linearity.

2 If the transmitter has an adjustment means, it can adjust the translation and adjust the slope. Adjust the best straight line to the specified straight line for the highest absolute linearity.

3 Linearity shall be added with qualifier. Linearity without qualifiers means independent linearity.

3.8.8 Least-squares linearity ($\xi_{L,ls}$)

See equation (16) for the calculation formula.

As the least-squares line of the reference characteristic, the sum of the squares of the deviation of the actual characteristics of the transducer shall be minimized. The least-squares linear equation is:

$$Y_{ls} = a + bx \qquad \cdots\cdots(20)$$

where,

Y_{ls} - theoretical output of the transducer;

a, b - intercept and slope of the least-squares line, respectively;

x - actual input of the transducer.

The intercept and slope of the least-squares line can be obtained by straight line fitting of the actual characteristics of the transducer. The calculation formula is as follow:

$$a = \frac{\Sigma x_i^2 \cdot \Sigma \bar{y}_i - \Sigma x_i \cdot \Sigma x_i \bar{y}_i}{m\Sigma x_i^2 - (\Sigma x_i)^2} \qquad \cdots\cdots(21)$$

where,

$\Delta Y_{C.max}$ - the maximum deviation of the actual characteristics curve of the transducer from the reference curve;

$\overline{y}_i$ - the total average characteristics value of the transducer at the i^{th} calibration point;

Y_i - the reference characteristics value of the transducer at the i^{th} calibration point;

Y_{FS} - the full-span output of the transducer.

NOTES:

1 Example for calculation of $\Delta Y_{C.max}$:

(1) According to up-travel and down-travel actual average characteristics $(\overline{y}_i)$, use the best curve as the reference curve to calculate the independent conformity.

(2) According to up-travel and down-travel actual average characteristics $(\overline{y}_i)$, use the working characteristics curve as the reference curve to calculate the absolute conformity.

2 The results calculated by the second method described above shall contain the components of the hysteresis and repeatability to varying degrees. Strictly speaking, it is not conformity.

3 If not stated, the conformity refers to the result of $\Delta Y_{C.max}$ calculated according to the first method above, that is, independent conformity.

4 In some applications, if necessary, it can also use a set of calibration data to calculate the conformity without $\Delta Y_{C.max}$.

3.9.2 Absolute conformity $(\xi_{C.ab})$

The calculation formula is shown in equation (23).

NOTES:

1 In several conformities, the absolute conformity requirement is the strictest.

2 If non-linear transducer is required to be interchangeable, absolute conformity shall be used.

3.9.3 Terminal-based conformity $(\xi_{C.te})$

See Figure 5 for the principle of calculation method. See equation (23) for calculation formula.

If the thermal full-span output shift of the transducer is not linear with the temperature interval, then ($T_2 - T_1$) shall be divided into several small intervals. And use equation (28) to calculate the β of each interval. Take the largest absolute value of β.

4 Calculation methods for uncertainty and other comprehensive static performance specifications

In static operation, linearity (conformity), hysteresis, and repeatability are often referred to as transducer's sub-performance or individual performance specification. And the different combinations of these specifications constitute various comprehensive performance specifications. There is no mathematically defined link between comprehensive performance specifications (such as total uncertainty) and performance specifications for each sub-performance.

Take a linear transducer as an example (the algorithm of a non-linear transducer is the same as that of a linear transducer). And it is based on the principle of measuring the performance specification of the transducer by the limit deviation. This Standard specifies the calculation methods for the following comprehensive performance specifications.

4.1 Linearity plus hysteresis (ξ_{LH})

4.1.1 General form of calculation formula

Linearity plus hysteresis is the limit of transducer system error. It is calculated as follow:

$$\xi_{LH} = \pm \frac{|\Delta Y_{LH,max}|}{Y_{FS}} \times 100\% \quad \cdots\cdots (29)$$

where,

$\Delta Y_{LH,max}$ - the maximum deviation of up-travel actual average characteristics $(\bar{y}_{u,i})$ and down-travel actual average characteristics $(\bar{y}_{d,i})$ to reference line.

NOTES:

1 If not stated, the linearity plus hysteresis shall refer to the calculated results based on the up-travel actual average characteristics and down-travel actual average characteristics of the transducer to its

reference line. Otherwise it shall indicate the type of reference line.

2 If the reference line is taken as transducer’s working characteristics line, the result of ξ_{LH} shall contain repetitive components to varying degrees. It is not linearity plus hysteresis strictly speaking.

3 For non-linear transducer, refer to this section for calculation of conformity plus hysteresis based on the same calculation principle.

4.1.2 Calculation of reference line

Use a best straight line to perform straight line fitting of transducer’s up-travel actual average characteristics and down-travel actual average characteristics. For specific practices, please refer to the relevant parts of Annex A, Annex B and Annex C of this Standard.

4.2 Linearity plus hysteresis plus repeatability (ξ_{LHR})

In this Standard, it is also called the total uncertainty of the transducer (corresponding to the original total precision, or the total error). It is to make that under reference working conditions, the deviation of the actual characteristics from its working characteristics is not exceeded by a specified confidence level. When expressed as a percentage of the transducer's full-span output Y_{FS}, it is called the relative total uncertainty of the transducer, which is often referred to as total uncertainty.

4.2.1 General form of calculation formula

$$\xi_{LHR} = \pm \frac{\max|B_i + t_{0.95}S_i|}{Y_{FS}} \times 100\% \quad \cdots\cdots (30)$$

where,

B_i - limit of total system error at the ith calibration point, which can be obtained separately by conventional non-statistical methods;

$t_{0.95}S_i$ - limit of total accidental error at the ith calibration point; $t_{0.95}$ is the inclusion factor of 95% confidence in the t distribution; S_i is the standard deviation of the sample at the ith calibration point.

Equation (30) can also be expressed as:

$$\xi_{LHR} = \pm \frac{|\Delta Y_{LHR,\max}|}{Y_{FS}} \times 100\% \quad \cdots\cdots (31)$$

where,

1 ξ_{LHR} here is corresponding to U_r in Annex G;

2 If the limit-point envelope method of 4.2.3.2 is used to calculate ξ_{LHR}, it shall be greatly simplified both in terms of concept and calculation process.

3 For non-linear transducer, refer to this section and calculate the conformity plus hysteresis plus repeatability ξ_{CHR} according to the same calculation principle.

4.2.3 Calculation method for working characteristics

When calculating the linearity plus the hysteresis plus repeatability of the transducer, the reference line shall be taken as the straight line of the working characteristics of the transducer.

4.2.3.1 Selection and calculation principles

a) Consider the working characteristics of transducer.

b) It shall be beneficial to the use of transducer.

c) It shall help to reduce the value of the total uncertainty.

4.2.3.2 L(C)HR limit-point envelope method

In general, the total uncertainty of linear transducer depends on the combined effects of linearity, hysteresis and repeatability. As shown in Fig. 9, at the $x_{i\text{-th}}$ calibration point, the up-travel average point $\bar{y}_{u,i}$ and the down-travel average point $\bar{y}_{d,i}$ are respectively determined. Then, according to 3.7.3, the sub-sample standard deviation $S_{u,i}$ at the i^th calibration point of the up-travel and the sub-sample standard deviation $S_{d,i}$ of the down-travel at the i^th calibration point are obtained. Subtract $cS_{u,i}$ from the average of the up-travel. Add $cS_{d,i}$ to the average of the down-travel. Thus, two limit-points can be obtained at the $x_{i\text{-th}}$ calibration point. The calculation formulae are as follow:

$$y_{u,i,\min} = \bar{y}_{u,i} - cS_{u,i} \qquad \cdots\cdots (35)$$

$$y_{d,i,\max} = \bar{y}_{d,i} - cS_{d,i} \qquad \cdots\cdots (36)$$

uncertainty of the transducer.

4.3 Other comprehensive static performance specifications and characteristics

The following comprehensive static performance specifications are special cases of transducer’s comprehensive static performance specifications. The calculation method is simpler than the calculation method of the transducer’s comprehensive static performance specifications, so only the calculation principle is proposed.

4.3.1 Single-travel fixed-point transducer

For example, the fixed-point error of switches such as single-travel pressure switch and temperature switch is only repeatability, and the calculation method can refer to 4.2. At this time, the working characteristic of the transducer is a fixed point. The single stroke is taken as an up-travel or a down-travel. The working characteristics of the transducer shall be taken as the actual average point of the selected up-travel or the actual average point of the down-travel.

4.3.2 Dual-travel fixed-point transducer

For example, the fixed-point error of a dual-travel pressure switch, temperature switch, etc. is only hysteresis plus repeatability. Refer to 4.2 for its calculation method. At this time, its working characteristics equation is: the measured number (Y) = the measured amount (x). The working characteristics is a fixed point, which shall be taken as the actual average point of the selected up-travel and down-travel.

4.3.3 Linearity plus hysteresis plus repeatability of transmitter

The total uncertainty shall be calculated based on the straight line of its given working characteristics. Refer to 4.2 and Annex D for its calculation method.

4.3.4 Transducer or transmitter with measured digital display

Its working characteristics equation is: the measured number (Y) = the measured amount (x). Refer to 4.2 and Annex C for the calculation method of its total uncertainty.

4.3.5 Utilization characteristics

Utilization characteristics equation: the measured amount (x) = function of transducer output f (y). For linear transducer, the characteristics equation can be derived directly from the working characteristics equation. For non-linear transducer, generally only numerical solutions (such as Newton iteration) can be used to calculate the working characteristics.

Annex A

(Normative)

General principle and calculation example of linearity calculation

A1 Calculation example for zero-based linearity

Try to calculate the zero-based line and zero-based linearity of a set of static calibration test data (average of multiple measurements) listed in the table below.

Table A1

Input x	0.00	1.00	2.00	3.00	4.00	5.00
Output y	0.03	10.05	20.20	29.60	39.90	50.00

A1.1 General calculation principle

The connection line between the desired theoretical zero point and the minimum center of gravity of the smallest positive and negative deviation points is not calculated at one time. It can only approach gradually. The so-called minimum largest positive and negative deviation points mean that each approximation shall produce a pair of largest positive and negative deviation points. What it needs is only a pair of the minimum positive and negative deviation points of a set of the largest positive and negative deviation points obtained by each approximation (the characteristic is that the absolute values of the largest positive and negative deviation of this pair of largest positive and negative deviation points are equal and minimum).

A.1.2 Calculation of the first approximation line

The theoretical zero point and the rear terminal point line are used as the first approximation line of the zero-based line. The equation is:

$$Y_{ze,(1)} = 10.00x$$

The deviation of each calibration point calculated by it is:

Table A2

x	0.00	1.00	2.00	3.00	4.00	5.00
$\Delta Y_{ze,(1)}$	+0.030	+0.050	+0.200	−0.400	−0.100	0.000

A2.1.4 Lead a plumb-line from a vertex of a convex polygon to its opposite side (a line parallel to the ordinate axis). After determining which two points in a set of data points that the opposite side of the longest plumb-line in the convex polygon is formed by the terminal-based line's deviation points of the connection line, which two points' connection line makes the absolute value of the largest positive, negative deviations equal through translation, the best straight line shall be obtained. As clearly seen from Figure A1, the plumb-line from the deviation point 4 to the deviation points 1 and 5 is the longest. This corresponds to the longest plumb-line of the actual data point 4 to points 1, 5. The length of the longest plumb-line of the actual data point is twice the maximum deviation from the best straight line.

A2.1.5 The length of the plumb-line (expanded) of each vertex of the convex polygon can be measured from the graph. It is also possible to accurately calculate the length of each plumb-line without expansion. Therefore, set the length of the plumb-line (unexpanded) determined by the connection of actual data point 4 and the points 1 and 5 as $\Delta y_{(1,4,5)}$. Its value can be calculated by:

$$\Delta y_{(1,4,5)} = \left| \frac{y_1(x_4 - x_5) + y_4(x_5 - x_1) + y_5(x_1 - x_4)}{x_5 - x_1} \right|$$

After substituting the corresponding value:

$$\Delta y_{(1,4,5)} = \left| \frac{2.02 \times (4.00 - 5.00) + 7.90 \times (5.00 - 1.00) + 10.10 \times (1.00 - 4.00)}{5.00 - 1.00} \right| = 0.180$$

Similarly, the length of another plumb-line can be calculated:

$$\Delta y_{(4,5,6)} = \left| \frac{y_4(x_5 - x_6) + y_5(x_6 - x_4) + y_6(x_4 - x_5)}{x_6 - x_4} \right|$$

After substituting the corresponding value:

$$\Delta y_{(4,5,6)} = \left| \frac{7.90 \times (5.00 - 6.00) + 10.10 \times (6.00 - 4.00) + 12.05 \times (4.00 - 5.00)}{6.00 - 4.00} \right| = 0.125$$

A2.1.6 The length of the two plumb-lines accurately calculated above is consistent with the case of the scaled line segment measured from the figure. Line $\Delta y_{(1,4,5)}$ is the longest. In fact, it is twice the maximum deviation $\Delta Y_{\text{in,max}}$. Finding the best straight line by translating the data points 1 and 5 is a bit troublesome. In fact, the connection line of the center of gravity of points 1 and 4 and the center of gravity of points 4 and 5 is the best straight line. The coordinates for center of gravity of points 1, 4 are:

Annex B

(Normative)

General principle and calculation example of conformity calculation

B1 General principle for conformity calculation

The reference curve for conformity is calculated by using the Chebyshev interlaced point group principle. And use the improved Remez algorithm. The specific principle of calculating the reference curve according to this principle can be summarized into the following four parts.

B1.1 According to the shape of the curve formed by a set of test data points, the function form or the degree of the polynomial of the fitting curve is selected empirically or by other methods (for example, looking at the variation of the adjacent difference quotients).

B1.2 If the reference curve equation has n unknown coefficients, then n+1 interlaced points shall be selected. When the mandatory reference curve passes a specified point, the staggered point is reduced by one. But the total number of interlaced points cannot be less than two.

B1.3 Orderly select the required number of interlaced points on the x-axis. In the first approximation, n points can be selected substantially equidistantly, preferably including the first and last points, to find a curve passing through the n points. In the second and subsequent approximation, the interlaced point group shall be selected according to the deviation and size of the previous set of approximation curves. The deviation signal at each staggered point shall be positive and negative alternate. The more the absolute value is the deviation point, the more the priority shall be selected or swapped into the interlaced point group. Zero deviation point can be regarded as the smallest positive deviation point or negative deviation point.

B1.4 The process of finding the final correct interlaced point group is a process that is gradually approached by continuous iteration. When the candidate interlacing points sequentially and the symbols positive and negative alternately obtain the same maximum deviation in a set of data, the interlaced point group at this time is the correct interlaced point group. The maximum deviation on the staggered point is for the same set of data. The minimum value that can be achieved for the same reference curve function form and for the same constraint requirements. The fitting curve determined by the correct interlaced point group is the desired.

B2 Conformity calculation example

The deviation of each calibration point calculated according to the curve is shown in Table B5.

Table B5

x	0.00	1.00	2.00	3.00	4.00	5.00
$\Delta Y_{f.te.(i)}$	0.000	+0.029	+0.035	+0.119 *	−0.119 *	+0.119 *

The asterisk in Table B5 shows that the deviation symbols at the three staggered points alternately achieve the same maximum value, i.e. μ = 0.119. Therefore, this first approximation curve is the front terminal-based curve.

B2.3.2 Calculation of secondary front terminal-based conformity

$$C_{f.te} = \pm \frac{\Delta Y_{f.te.max}}{Y_{f.te.max} - Y_{f.te.min}} = \pm \frac{0.119}{3.681 - 0.10} = \pm 3.323\%$$

It can be seen that it is slightly better than the zero-based conformity. From the deviation distribution, the zero deviation is zero, and the deviation near the zero point (until x=2.0) is also small. This curve is preferable if the deviation near the actual zero point is required to be small.

B2.4 Finding the quadratic best curve and the second independent conformity

Since there is no constraint on the quadratic polynomial, four interlacing points shall be selected. For the quadratic polynomial curve, the curve of the first, middle and last three points can generally be selected as the first approximation curve. And gradually select the correct interlaced point group. Since the deviation of a set of data from the front terminal-based curve is obtained in this example, it is convenient to determine the interlacing point that shall be used for the first approximation curve.

B2.4.1 Finding the first approximation curve

It shall select four interlaced points: $x=0.0, y=0.1; x=3.0, y=2.6; x=4.0, y=3.0; x=5.0, y=3.8$. According to this, a quaternary simultaneous equation system can be established:

$$0.1-[a+b(0.0)+c(0.0)^2]=+\mu$$

$$2.6-[a+b(3.0)+c(3.0)^2]=-\mu$$
$$3.0-[a+b(4.0)+c(4.0)^2]=+\mu$$
$$3.8-[a+b(5.0)+c(5.0)^2]=-\mu$$

Annex C

(Normative)

Calculation examples for transducer sub-performance specifications and comprehensive performance specifications

C1 General calculation principle

First determine whether there is suspicious data or unreasonable data in the original data (such as components with temperature effects). If there is, check the calibrated transducer, improve the calibration test equipment or the qualification conditions, and then recalibrate. The data is used to calculate the performance of the transducer after obtaining the raw data with as much unquestionable data and unreasonable data as possible.

Use the limit-point envelope method to obtain the working characteristics (equations) and total uncertainty directly from a set of data obtained from calibration. And each sub-item performance specifications shall still be treated as usual.

NOTE: Use the test method in Annex F to discover suspicious data in raw data. However, statistical tests shall not be used in the formal verification of transducer to eliminate or replace suspicious data. The correct way is to not tolerate suspicious data easily, and not to easily eliminate suspicious data. It shall identify the real cause of suspicious data and troubleshoot it to get the most reliable raw data possible. In general, suspicious data shall calculate the total uncertainty of the transducer and other indicators.

C2 Calculation examples

C2.1 Calculation example 1

Table C1 lists the data obtained from calibration of a linear transducer (no suspicious data and unreasonable data tested). It is now required to calculate the performance specifications and comprehensive performance specifications of each sub-item. Compare the calculation results of the best line method, the translation terminal-based line method and the least-squares line method.

C2.1.3 Fitting the 2m = 12 limit-points with the best straight line

Use the method provided in Annex A2, and the best working characteristics equation can be obtained:

$$Y_{in} = Y_{LHR} = -2.4445 + 96.7156x$$

The deviation of the transducer's up-travel limit-point and down-travel limit-point from the straight line of the best working characteristics is shown in Table C4.

Table C4 -- Deviations of up-travel limit-point and down-travel limit-point, up-travel actual average characteristics and down-travel actual average characteristics and total average characteristics to best working characteristics line

Deviation of up-travel average characteristics

Deviation of down-travel average characteristics

Input (x)	0.0	2.0	4.0	6.0	8.0	10.0	Remark
Fitted value (Y_{LHR})	−2.445	190.99	384.42	577.85	771.28	964.71	$Y_{FS}=967.16$
Deviation of up-travel limit-point	2.957	−1.228	−3.540	−4.281 *	−3.792	−3.256	$\Delta Y_{LHR.max}=\pm 4.281$
Deviation of down-travel limit-point	4.281 *	1.574	1.119	1.293	2.358	4.281 *	
	3.157 *	−0.290	−1.780	−2.150	−1.220	−0.130	$\Delta Y_{LH.max}=4.041$
	4.041 *	0.810	0.000	−0.090	0.100	1.030	
	3.599 *	0.260	−0.890	−1.120	−0.560	0.450	$\Delta Y_{L.max}=3.599$

Deviation of total average characteristics

In the limit-point envelope method, the total uncertainty of the transducer is numerically the maximum deviation of a set of limit-points from the fitting line or curve as the working characteristics. From the table, it can be seen that the three maximum values with the same absolute value of ±4.281 (shown with an asterisk) alternately appear, which meets the criterion of the best straight line, so the total uncertainty of the transducer is:

$$U_r = \xi_{LHR} = \pm \frac{\Delta Y_{LHR.max}}{Y_{FS}} \times 100\% = \pm \frac{4.281}{96.716 \times (10.0 - 0.0)} \times 100\% = \pm 0.443\%$$

C2.1.4 Fitting the 2m=12 limit-points with a translational terminal-based line

For linear transducer, the principle of selecting translational terminal-based line:

a) The limit-point envelope line is monotonously concave, and the line connecting the first and last limit-points of the down-travel is selected as the terminal-based line.

b) The limit-point envelope line is monotonously convex, and the line connecting the first and last limit-points of the up-travel is selected as the terminal-based line.

c) The limit-point envelope is in the shape of an S or other shape, and the line connecting the average point of the first two extreme points of the upor

$$Y = (y_{(u,6;d,0)} - x_{(u,6;d,0)} \times b) + bx$$

Substituting the corresponding data, the linear equation of the translation end can be obtained as:

$$Y = (287.7203 - 3.0000 \times 96.7156) + 96.7156x = -2.4445 + 96.7156x$$

This is the same as the working characteristic equation obtained by fitting the 2m = 12 limit-points with the best straight line. The translational terminal-based line is the best straight line in some cases. The other results of this question are the same as the above example and shall not be repeated.

C2.1.5 Fitting the 2m = 12 limit-points with a least-squares line

Working characteristics equation of transducer:

$$Y_{ls} = -0.9769 + 96.4515x$$

The deviation of transducer's up-travel limit-point and down-travel limit-point from least-squares working characteristics line is listed in Table C6.

Table C6 -- Deviation of up-travel limit-point and down-travel limit-point from least-squares working characteristics line

Input (x)	0.0	2.0	4.0	6.0	8.0	10.0	Remark
Fitted value (Y_{ls})	−0.977	191.93	384.83	577.73	770.64	963.54	$Y_{FS}=964.515$
Deviation of up-travel limit-point	1.489	−2.168	−3.952	−4.165	−3.147	−2.083	$\Delta Y_{LHR,max}=5.454$
Deviation of down-travel limit-point	2.814	0.634	0.708	1.410	3.003	5.454 *	

In the limit-point envelope method, the total uncertainty of the transducer is numerically the maximum deviation of a set of limit-points from the fitting line or curve as the working characteristics line. List in Table C6 and mark with asterisk.

$$U_r = \xi_{LHR} = \frac{\Delta Y_{LHR,max}}{Y_{FS}} \times 100\% = \frac{5.454}{96.452 \times (10.0 - 0.0)} \times 100\% = 0.566\%$$

NOTES:

1 It can be clearly seen that the total uncertainty calculated by the best straight line is 28% larger than the total uncertainty calculated by the least-squares line.

2 The total uncertainty relative to the translational least-squares line calculated from Table C6 is ±0.50%. It is 13% larger than the total uncertainty calculated by the best line.

C2.1.6 Each sub-item performance specifications and comprehensive

$\xi_{CHR}=-0.414\%$ (calculated from the actual uncertainty region and the least-squares quadratic algebra polynomial working curve)

C2.4 Calculation example 4

See Example 1 for raw data. In this example, the transducer input (x) is expanded by a factor of 100 and the output (x) is unchanged. The equation for the given working characteristics of the transducer is: Y=x. This example shall treat the transducer as a transducer with a measured digital display. The calculation process of this example is omitted. Only the calculation results are listed below for comparison. Since Y_{FS} =1000 calculated according to the working line given in this example is different from that in Example 1, the values of the resulting hysteresis and repeatability are also different from those obtained in Example 1.

Linearity:

$\xi_L=\pm 0.167\%$ (calculated relative to the best reference line)

$\xi_L=-3.484\%$ (calculated relative to a given working line)

Hysteresis: $\xi_H=0.103\%$

Repeatability: $\xi_R=0.325\%$(take $c=t_{0.95}=2.776$)

Linearity plus hysteresis:

$\xi_{LH}=\pm 0.239\%$(calculated relative to the best reference line)

$\xi_{LH}=-3.542\%$(calculated relative to a given working line)

Linearity plus hysteresis plus repeatability (total uncertainty of the transducer):

$\xi_{LHR}=\pm 0.443\%$ (calculated with the LHR limit-point relative to the best reference line)

$\xi_{LHR}=-3.855\%$ (calculated with the LHR limit-point relative to a given working line)

D3 Calculation results

The principle of calculation is in principle the same as the transducer, and the calculation process is omitted. According to the calculation of E3.2 in Annex E, determine this transmitter as equal-precision transmitter. The following are two calculation results for the equal-precision transmitter.

Linearity:

$\xi_L = \pm 0.0320\%$ (calculated relative to the best reference line)

$\xi_L = -0.0692\%$ (calculated relative to a given working line)

Hysteresis: $\xi_H = 0.0072\%$

Repeatability: $\xi_R = 0.0061\%$ (take $c=t_{0.95}=2.776$)

Linearity plus hysteresis:

$\xi_{LH} = \pm 0.0334\%$ (calculated relative to the best reference line)

$\xi_{LH} = -0.0705\%$ (calculated relative to a given working line)

Total uncertainty of the transmitter (linearity plus hysteresis plus repeatability):

$\xi_{LHR} = \pm 0.0395\%$ (calculated by LHR limit-point relative to the best reference line)

$\xi_{LHR} = -0.0766\%$ (calculated by LHR limit-point relative to the given working line)

The best reference line equation: $Y = 1.9970 + 0.8000x$

Below, the two calculation results of the transmitter according to the unequal precision transmitter are listed for comparison.

Linearity:

$\xi_L = \pm 0.0320\%$ (calculated relative to the best reference line)

$\xi_L = -0.0692\%$ (calculated relative to a given working line)

Hysteresis: $\xi_H = 0.0072\%$

Repeatability: $\xi_R = 0.0080\%$ (take $c=t_{0.95}=2.776$)

Linearity plus hysteresis: $\xi_{LH} = \pm 0.0334\%$ (calculated relative to the best reference line)

$\xi_{LH} = -0.0705\%$ (calculated relative to a given working line)

The total uncertainty of the transmitter (linearity plus hysteresis plus repeatability):

$\xi_{LHR} = \pm 0.0401\%$ (calculated by LHR limit-point relative to the best reference line)

$\xi_{LHR} = -0.0777\%$ (calculated by LHR limit-point relative to the given working line)

Best reference line equation: $Y = 1.9969 + 0.8000x$

The error curves for this example are shown in Figures D1 and D2 (all processed by unequal accuracy transmitters to reflect their unrecognized nature).

NOTES:

1 It can be clearly seen that the total uncertainty calculated from the best reference line is much smaller than the total uncertainty calculated from the given working line. Therefore, if the transmitter has a characteristic adjustment device, it is preferable to adjust the given working line to the best reference line.

2 It can also be seen that the specifications of the precision transmitters are calculated according to the equal precision and calculated according to the unequal precision, and the obtained results are similar. This shows that equal precision is just a special case of unequal precision. The calculation of unequal precision naturally includes the calculation of equal precision.

Annex E

(Normative)

Inspection of transducer precision

E1 Basic concept

The so-called transducer has the same precision, that is, although the variance at each measurement point is different, it has the same mathematical expectation. The unequal precision of a transducer, as judged by its set of calibration data, may be inherent or may result from inaccurate or erroneous measurements. For a transducer that may be of equal precision, if the maximum variance is taken to calculate the repeatability, the calculation result is conservative, but it is more insurance.

E2 Test method

There are m populations (m≥3) which follow the normal distribution N (μ, σ^2). m samples with a capacity of n are extracted independently from m populations. The variances of m samples are S_1^2, S_2^2.. S_m^2, respectively. Now check the null hypothesis $IIII_0$:

$$\sigma_1^2 = \sigma_2^2 = \cdots = \sigma_m^2 .$$

In the specific case of the transducer covered by this Standard, the variance of 2m samples shall actually be tested. The test method is the simplest to adopt the method proposed by Hartley. The statistics used by the Hartley test are:

$$HH_{max} = \frac{S_{max}^2}{S_{min}^2} \qquad \text{(E1)}$$

where,

S_{max}^2 - the largest of the 2m sample variances;

S_{min}^2 - the smallest of the 2m sample variances.

At a given significance level α, the probability that HH_{max} is greater than the critical value $HH_{\alpha(2m,t)}$ at the corresponding degree of freedom in the Hartley test threshold table (see Table E1) is:

$$P\{HH_{max} \geqslant HH_{\alpha(2m,t)}\} = \alpha \qquad \text{(E2)}$$

Annex F

(Informative)

Pre-processing of raw data

F1 Discovery of suspicious data

F1.1 Suspicious data

Any measurement may generate suspicious data. The reason for generating suspicious data is complicated. It may be a temporary or accidental failure of the calibration device or the transducer to be calculated. It may because it is difficult to predict the change of their characteristics. Raw data with suspicious data does not represent the normal performance of the transducer being used, so it shall not be used to calculate the performance of the transducer. Be careful when keeping or removing suspicious data. The correct way to do this is to: find suspicious data, eliminate the real cause of suspicious data, re-calibrate, and then calculate the raw data with as much suspicious data as possible.

F1.2 General principles of statistical test

In order to verify whether the jth data of a sample at the ith calibration point of the forward stroke is suspicious, first calculate $y_{u,i}$ and $S_{u,i}$. If the following discriminant is satisfied,

$$\max|y_u(i,j)-\bar{y}_u(i)|>kS_{u,i} \qquad \text{(F1)}$$

then this $y_{u(i,j)}$ shall be suspicious data. The k in equation F1 is the confidence factor for the test and is usually determined by 95% confidence and the number of sample elements. In order to determine if the sample has another suspicious data, use one of the following two methods:

a) Remove $y_{u(i,j)}$ from the sample, then recalculate $\bar{y}_u(i)$ and $S_{u,i}$. Then test the rest of the sample with the formula F1;

b) Make $y_u(i,j)=\bar{y}_u(i)$. Then re-calculate $\bar{y}_u(i)$ and $S_{u,i.}$ Then use formula F1 to inspect this sample data. If the transducer has only a small sample, it is not conducive to accurate inspection. This method does not reduce the sample elements, so it is superior to the previous method and is easy to implement on a computer.

F1.2.1 Grubbs test

carelessness, or calibration of working conditions. It may also be a problem of the transducer itself. Calibration shall be performed after environmental or other factors are excluded.

d) Repeatability values vary dramatically, even with zero repeatability. This may be caused by careless operation, uncertainty of the measuring instrument (accuracy) or improper selection of the range, and insufficient selection of the effective number of digits of the reading of the measuring instrument.

F2.2 Example of unreasonable data discovery

Table F4 -- Results of using computer to check the unreasonable data of the raw data of Table C1, Table D1 and Table F3

Check item	Relative number of increasing adjacent data pairs	Relative number of decreasing adjacent data pairs	Relative number of equal adjacent data pairs	H=0	H is negative
Table C1	50.00%	50.00%	0.00%	0.0%	0.0%
Table D1	56.25%	41.67%	2.08%	0.0%	0.0%
Table F3	87.50%	10.42%	2.08%	100%	3.3%

a) As seen from Table F4, it can be considered that the raw data of Table C1 and Table D1 clearly contain no unreasonable data. The determination result of the original data of Table C1 also indicates that it is a typical case without unreasonable data.

b) Look at the Table F3 data, it can be found that with the increase of the measurement cycle, the measured data has obvious increasing. It can also be known from Table F4 that the relative number of increasing adjacent data pairs is significantly different from the relative number of decreasing adjacent data pairs. Such raw data may have obvious temperature affecting component. It shall not accurately calculate the transducer's performance specifications so do not use it for calibration calculation.

c) Figure F2 shows the error curve of a transducer (m=6, n =3, raw data is omitted). Since the calibration only has 3 cycles, the previous statistical test method cannot accurately detect suspicious data. Except that the zero hysteresis at the upper limit of the measurement of the transducer is an unreasonable situation, it is determined that there is no other unreasonable data. However, as can be seen from Figure F2, the CHR curve changes drastically and is irregular, which is very unreasonable. Therefore, it can be determined that the measured data of the transducer is problematic and shall not be used for calibration calculation.

In the transducer, systematic errors and accidental errors are calculated from the same set of measured data, so that b and S are related and thus it can take $\rho_{i,(bS)}=1$. Therefore, in this case, the expression of the synthetic uncertainty of the transducer at the i^th calibration point can be simplified to:

$$U_i = b_i + S_i \quad \cdots\cdots (G3)$$

G4 Overall uncertainty

The overall uncertainty of the transducer is also called as expanded uncertainty. In the case of t distribution, when the sample has only 3~5 elements, the confidence of the synthetic uncertainty is between 60%~70%, which is not enough for most applications. Therefore, the synthetic uncertainty is usually multiplied by an inclusion factor to obtain the overall uncertainty:

$$U_i = cU_i = cb_i + cS_i \quad \cdots\cdots (G4)$$

where,

c - coverage factor; for the t distribution, $c=t_{0.95}$ has been taken in 3.7.2 to obtain 95% confidence;

cb_i - make $cb_i=B_i$, the limit value of the total system error known as the transducer at the i^th calibration point can be determined by conventional non-statistical methods;

cS_i - limit of the total accidental error of the transducer at the i^th calibration point; this Standard takes t distribution:

$$cS_i = t_{0.95}S_i$$

Thus, the expression of the total uncertainty of the transducer at the i^th calibration point can take the following form:

$$U_i = \pm(B_i + t_{0.95}S_i) \quad \cdots\cdots (G5)$$

G5 Relative overall uncertainty

The total uncertainty of the transducer over its full-span operating span, expressed as a percentage of the transducer's full-span output Y_{FS}, is the relative overall uncertainty (referred to as the overall uncertainty of the transducer; because of its basic error nature, also known as the basic uncertainty of the transducer). This is the total form of uncertainty used in this Standard. The total uncertainty formula that reflects the concept of the actual

Annex H

(Informative)

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