Non-Linearity of Resistance/Temperature Characteristic: Its Influence on Performance of Precision Resistors

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Abstract

The relative resistance change vs. temperature function, $\Delta R/R = f(T)$, of precision resistors is commonly represented in the industry by the value of the temperature coefficient of resistance (TCR). The TCR is the slope of a chord joining two points of temperature on the $\Delta R/R = f(T)$ curve. Two such temperature points indicate the temperature range, and the slope of a chord joining the two points is the TCR. Three points form two chords and the difference in their slopes indicates the rate of change of the TCR with changing temperature.

Recordings were performed in the temperature range –55°C to 125°C of the $\Delta R/R = f(T)$ curves of precision resistors which are produced with nickel-chromium tertiary alloys. They show that the curve's shape matches closely a graph of a quadratic polynomial equation. This paper presents a method, based on such equations, permitting the calculation, for any value of temperature, of the slope—which is the TCR at this temperature—of a tangent to the $\Delta R/R = f(T)$ curve or the slope of a chord representing a given temperature range.

The actual temperature range for a given application of precision resistors can be evaluated from the expected changes of the ambient temperature and the self heating due to the levels of the dissipated power. Using a value of TCR specified by a vendor, which may refer to a different temperature range, to calculate the resistance change for a given application may lead to wrong results—especially when resistor's $\Delta R/R = f(T)$ curve has a large curvature. To properly evaluate precision resistor's behavior in a given temperature range, two nominal chord slopes and the statistical spread of their values must be known. The $\Delta R/R = f(T)$ of samples of precision resistor chips featuring Vishay Foil Resistors (VFR) Z-Foil and from six leading manufacturers of thin film resistors was recorded, and the graphs of their $\Delta R/R = f(T)$ curves and TCR are shown. The TCR specifications for thin film resistors are, in units of ppm/°C, 5 for two vendors, 10 for three vendors, and 25 for one vendor. They also differ greatly in the non-linearity of their $\Delta R/R = f(T)$ curves: in some of them the TCR is increasing with temperature; in others it is decreasing. This difference in behavior should be taken into account especially when TCR tracking between two or more resistors is required in order to maintain a stable ratio of their values. The best tracking can be achieved by forming the resistive patterns of the two resistors on the same substrate in order to impart to them the same resistance vs. temperature characteristic, but even in this case the ratio of resistance values is influenced by the magnitude of their TCR.

The Bulk Metal® Z-Foil resistors exhibit the lowest TCR over a wide range of temperatures and the smallest non-linearity of the $\Delta R/R = f(T)$ curve, providing the best solution for applications requiring high stability of the ohmic value and/or of a ratio of values. Low TCR over a wide temperature range leads also to a reduction of resistance change due to the Joule effect reducing the thermal stabilization time regardless of ambient temperature and load.

Introduction

Ohm's law, $V = I \times R$, states the proportionality between voltage V and current I, assuming a constant value R of an ideal resistor.

Real life ohmic resistors exhibit small reversible changes of their room temperature value when they are cooled or heated by a changing ambient temperature and/or by the power they dissipate (Joule effect). The ambient temperature can be controlled; but, for instance, the temperature of a current sensing resistor will still fluctuate with the change of current it is measuring and the power it has to dissipate—from zero load to its full rated power.

These changes are quantified by TCR—temperature coefficient of resistance and by a related to it PCR—power coefficient of resistance. Resistor's TCR is defined as the relative change from the reference resistance ($\Delta R/R_{Ref.}$), as measured using an insignificant level of power at a reference temperature and at a second point of resistor's steady state temperature, divided by temperature difference, ΔT). The resulting value of TCR has a unit of ppm/°C (or an equivalent unit of ppm/K).

On a resistance/temperature characteristic [$\Delta R/R = f(T)$] chart showing the curve of $\Delta R/R$ as function of T, the TCR is expressed as the slope of a chord joining two points of the curve corresponding to two temperatures. On Fig. 1 a nominal curve is shown with the cold and hot chords

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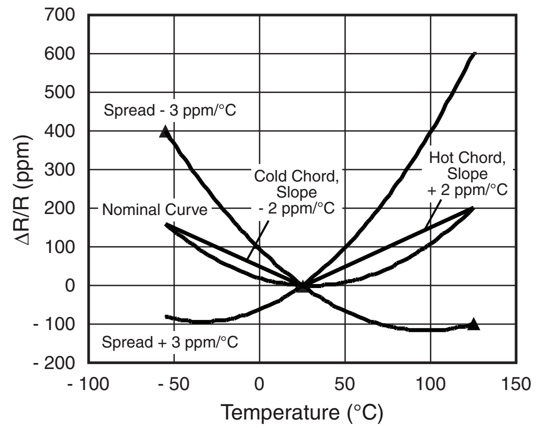

Fig. 1 – ($\Delta R/R = f(T)$) Chart of resistors of ±5 ppm/°C TCR

corresponding to a TCR of—and +2 ppm/°C and two curves corresponding to a spread of—and +3 ppm/°C from the nominal.

These two curves show the limit for resistors specified as ±5 ppm/°C TCR (2 ppm/°C nominal plus 3 ppm/°C spread of chord slopes).

The TCR (or the chord slope) is calculated:

$$TCR = (1/R_{Ref.})(\Delta R/\Delta T)$$

When these two points approach, the chord becomes a tangent to the curve at a given temperature and then

$$TCR = (1/ R_{Ref.})(dR/dT)$$

Manufacturers of precision resistors control the $\Delta R/R = f(T)$ by matching the physical properties and design of the resistive alloy and pattern (alloy's temperature coefficient of resistivity and of expansion, gage factor, and other properties—see Ref. 1, page 292) with substrate's coefficient of thermal expansion (see Ref. 2).

When chip resistors are soldered to a PCB, the difference in coefficients of thermal expansion and temperature gradients cause additional thermal strains which influence resistor's $\Delta R/R = f(T)$. Mounting a chip resistor on a ceramic and on an FR4 PCB will result in a different $\Delta R/R = f(T)$ relationship.

TCR in Resistor Standards

In international and national specifications and standards, precision resistors are assigned a stability class with its maximum positive and negative TCR value.

Fig. 2 (on page 3) shows two lines with slopes of TCR of +10 ppm/°C and—10 ppm/°C which delimit the allowed positive and negative chord slopes of resistors of this class. In this figure, the zero point on the x axis is set at 25°C and the x values are the deviations from the reference temperature of 25°C:

- Negative deviation, of 25 – (–55) = 80°C (cold temperature range) and
- Positive deviation, of 125 – 25 = 100°C (hot temperature range.

Testing Conformance with Specifications

To control conformance with specification, resistance values are measured at three temperature levels:

- $R_{Ref.}$ at reference temperature $T_{Ref.}$ representing the common room temperature, 20°C or 25°C,
- R_{LCT} at lower category temperature, T_{LCT}, and
- R_{UCT} at upper category temperature, T_{UCT}.

The lower and upper temperatures are defined in most US and European standards as –55°C and +125°C, respectively.

Two values of chord slopes—TCR_{Cold} and TCR_{Hot}—are calculated (see Fig. 1):

- $TCR_{Cold} = (R_{Ref.} - R_{LCT})(1/R_{Ref.})/(T_{Ref.} - T_{LCT})$ (cold chord slope)
- $TCR_{Hot} = (R_{UCT} - R_{Ref.})(1/R_{Ref.})/(T_{UCT} - T_{Ref.})$ (hot chord slope)

The calculated TCR values are represented on the $\Delta R/R = f(T)$ graph as the slopes of two lines crossing at the point of $T_{Ref.}$ on the x axis (see Fig. 4 on page 4).

In the USA, a specification for chip resistors MIL-PRF-55342H refers to TCR values as "Resistance Temperature Coefficient". The lowest TCR class is set at a maximum of 25 ppm/°C and the $T_{Ref.}$ at (25±3)°C.

The European specification for precision chip resistors EN140401-801:2002 is slightly different—the lowest specified TCR class is 10 ppm/°C, $T_{Ref.}$ is set at 20°C, and for the best stability class (0.1) the temperatures T_{LCT} and T_{UCT} are –10°C and +85°C, respectively. The designation "Class 0.1" indicates a stability level established by environmental testing, for instance 0.1% maximum resistance change after a load life test.

Shapes of the $\Delta R/R = f(T)$ Curves of Resistive Alloys

In applications requiring precision resistors the non-linearity of the resistance vs. temperature relationship, $\Delta R/R = f(T)$, should be taken into account. Different resistive materials have different shapes of their curves. As an example, Fig. 3 (on page 3) shows three typical curves—of resistors made with Z-Foil, nickel-chromium alloy, thin film and a nickel-copper alloy.

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The most popular are nickel-chromium based tertiary alloys. This is due to their high stability, low TCR and the possibility of shaping the slope and the non-linearity of their resistance temperature characteristic $\Delta R/R = f(T)$ by a proper choice of additives and by thermal treatment.

A nickel-copper based alloy, Constantan, is widely used for production of wirewound resistors but, in precision resistors, has a disadvantage of a high thermal EMF and limited high temperature stability.

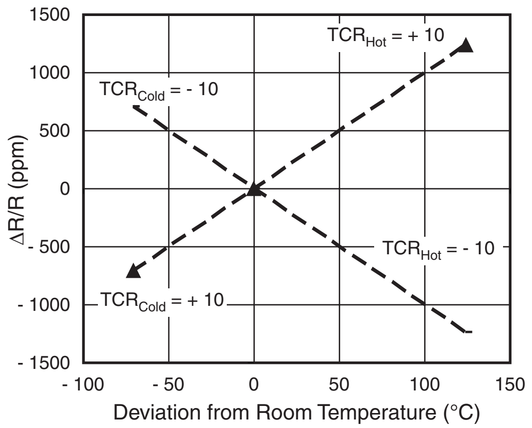

Fig. 2 – Limiting chord slopes for resistors of stability class 0.1 defining a TCR of 10 ppm/°C

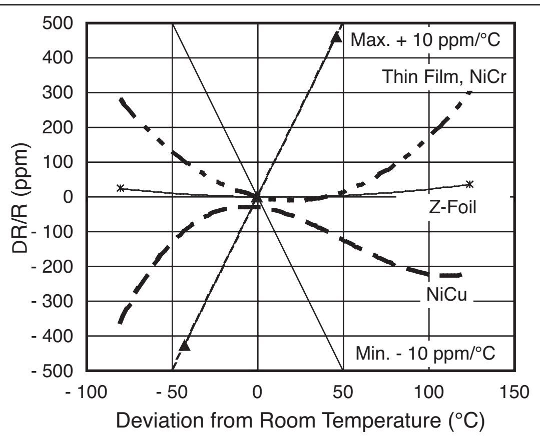

Fig. 3 – Typical $\Delta R/R = f(T)$ curves of Z-Foil, NiCu and NiCr (thin film) resistors within the maximum chord slopes of +10 ppm/°C and –10 ppm/°C

Development of VFR's Resistive Alloys and "Vishay Foil Resistor Nomenclature"

Precision foil resistors were introduced in 1962, using the C type foil (VFR nomenclature). Their nominal chord slopes are about +2 ppm/°C on the cold and –2 ppm/°C on the hot side.

Next the K type foil was developed with half the chord slopes and opposite curvature, –1 ppm/°C and +1 ppm/°C, respectivly.

Lately, the Z-Foil was introduced whose nominal chord slopes are –0.2 ppm/°C on the cold and +0.2 ppm/°C on the hot side, an order of magnitude improvement (Fig.4).

Resistor's Temperature Range and the Resulting Resistance Change: TCR vs. PCR

As the resistor's TCR changes with temperature, the limits of the working temperature range for a given application should be determined in order to evaluate resistor's stability within this temperature range.

Two factors determine the temperature of the resistive material:

- Change of ambient temperature, including the influence of neighboring heat producing components, from the reference temperature, $T_{Ref.}$, $\Delta T_{amb} = T_{amb} - T_{Ref.}$
- Self heating of the resistor due to the dissipated power (Joule effect), ΔT_{SH}

The first factor, ΔT_{amb}, has to be determined by the circuit's designer.

The second, ΔT_{SH}, can be derived from maximum expected load P to be applied to the resistor and from resistor's thermal resistance (resistive material to ambient air) R_{th}, which, for through-hole resistors can be obtained from vendors. In surface mounted resistors, R_{th} depends on the material of the printed circuit board and on the size of mounting pads and traces. These details should be communicated to vendors with the request of information about R_{th}. With a given thermal resistance R_{th}, increasing of the power P increases also the resistive element's temperature rise.

The equation of temperature rise ΔT_{SH} due to the dissipated power P is:

$$\Delta T_{SH} = P \times R_{th} \text{ and } P = \Delta T_{SH}/R_{th} \quad (1)$$

For applications requiring a TCR below 5 ppm/°C, a difference in influence of above two factors should be taken into account: The change of ambient temperature usually occurs slowly and, therefore, it can be assumed that the resistive alloy and the substrate are at the same temperature. This is not the case of self heating by dissipating a power P, especially for surface mounted devices. At the thermal steady state, most of the heat energy

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flows through the substrate to a printed circuit board (PCB), creating temperature gradients and substrate's temperature becomes lower than the resistive alloy's, causing additional thermal strains which may create a ΔR/R and may even break the substrate. To take into account the difference (of order of magnitude of a few ppm/°C, depending on the design of the resistor) between the influence of changing ambient temperature vs. self heating, the effect of the latter is calculated using the power coefficient of temperature:

$$\Delta R/R = P_{CR} \text{ x } P$$

Replacing P by its value from Equation 1:

$$\Delta R/R = P_{CR} \text{ x } \Delta T_{SH}/R_{th} \qquad (2)$$

Estimate of Resistor's TCR at a Given Temperature or in a Restricted Temperature Range When Two Chord Slopes sre Known

Recording of the ΔR/R = f(T) between –55°C and 125°C of different types of NiCr resistors indicates that the function's shape can be approximated by a quadratic polynomial equation:

$$y = ax^2 + bx \qquad (3)$$

Where:

- x is the deviation of temperature T from $T_{Ref.}$ in degrees centigrade
- y is the relative resistance change $(R_T - R_{Ref.})/R_{Ref.}$, in ppm, where R_T and $R_{Ref.}$ are the resistance values at temperatures T and $T_{Ref.}$.
- a and b are constants which determine the curvature and rotation of the parabolic curve.

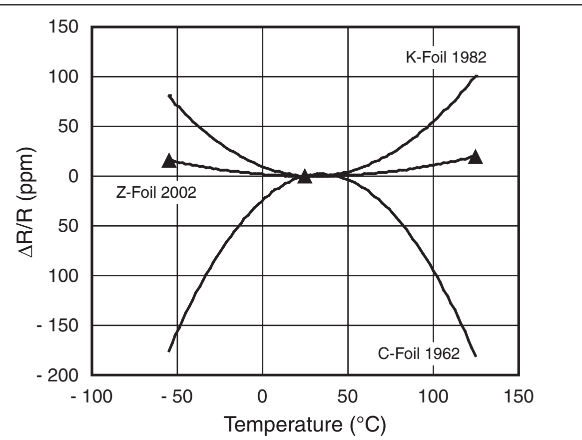

Fig. 4 – Three resistance vs. temperature characteristics of foil resistors and year of their introduction.

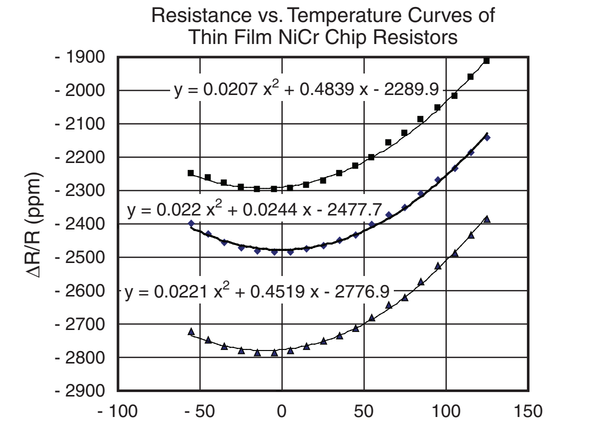

Fig. 5 – Recording of ΔR/R every 10°, quadratic trendlines and equations of three NiCr thin film chips.

The accuracy of such approximation was checked by measuring in different styles of NiCr resistors—SMD, "through hole", thin film, and foil—the deviation of resistance from its value at 25°C at temperatures every 10°, between –55°C and +125°C.

For this temperature span of 180° (–55°C to +125°C), 19 resistance deviation readings were recorded.

Fig. 5 shows an example of such recordings. Here the y axis shows the deviations from a nominal value. The Excel chart plotting the recordings and the three quadratic polynomial trendlines with their equations illustrates how closely the measurements fit the trendline.

The equation's derivative:

$$dy/dx = 2ax + b \qquad (4)$$

represents the slope of a tangent to the ΔR/R = f(T) curve —or the TCR—at any temperature T.

As this slope's equation is linear, it can also serve for easy calculation of the slope of a chord for a segment of temperatures corresponding to any specific application of a resistor by averaging the TCR of the segment's extreme temperature points.

Resistance values at three temperature points are sufficient to establish the curve and equation. It can also be derived from the cold and the hot slopes formed by measuring at –55°C, at 25°C, and at 125°C. These slopes represent also the slopes of the tangents, each at its mid-range:

- Cold mid-range T_{CMR} = (–55 + 25)/2 = –15°C and
- Hot mid-range T_{HMR} = (25 + 125)/2 = 75°C.

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As the TCR's change is linear, the TCR at any value of temperature can be calculated from the TCR at one of the mid-ranges and from the rate of change of TCR per degree:

- For one degree:

$$\Delta TCR_{1°C} = (TCR_{Hot} - TCR_{Cold})/90 \quad (5)$$

- For a temperature span, starting from one of the two mid-ranges—for instance from TCMR—to any other temperature T_2, the TCR will change by $\Delta TCR_{CMR}/T_2$:

$$\Delta TCR_{CMR/T2} = \Delta TCR_{1°C} (T_2 - T_{CMR}) = (T_2 - T_{CMR}) (TCR_{Hot} - TCR_{Cold})/90 \quad (6)$$

The TCR at any temperature T_2 is:

$$TCR_{T2} = TCR_{Cold} + \Delta TCR_{1°C} (T_2 - T_{CMR}) = T_2 - T_{CMR}) (TCR_{Hot} - TCR_{Cold})/90 \quad (7)$$

And the TCR at the reference temperature of 25°C, $TCR_{25°C}$, is:

$$TCR_{25°C} = TCR_{Cold} + (25 + 15) (TCR_{Hot} - TCR_{Cold})/90$$

or

$$TCR_{25°C} = TCR_{Cold} + (TCR_{Hot} - TCR_{Cold}) 40/90 \quad (8)$$

Importance of Considering the Non-Linearity of the ΔR/R =f(T) Curve

Let us consider two lots of resistors—one a thin film NiCr alloy type, which has a TCR difference between the hot and the cold slopes ($TCR_{Hot} - TCR_{Cold}$) of 4 ppm/°C (see TF6 in Table 1 on page 7) and a second produced with Z-Foil which has a TCR difference of 0.4 ppm/°C only.

Given large lots with a normal distribution of their TCR it is possible to select from each lot a resistor with a close to zero value of its hot slope.

Fig. 6 shows their respective ΔR/R = f(T) curves and equations for a deviation of ±100° from $T_{Ref.}$—the room temperature.

The TCR vs. temperature relationship is shown in Fig. 7. As this relation is linear, both resistors will have a zero TCR at a point at 75°C, the hot chord's mid-range.

The Z-Foil resistor maintains over the full temperature range (–75°C to +125°C) its low TCR of less then 1 ppm/°C, while the NiCr resistor changes its TCR by 0.04 per degree or 8 ppm/°C over 200 degrees (twice the difference between the hot and the cold slopes). Within the temperature range of the zero hot chord the TCR of such thin film resistor actually changes from –2 ppm/°C to +2 ppm/°C—ten times more then the Z-Foil resistor's change—an order of magnitude difference in behavior. In the cold range, the thin film resistor's TCR changes between –2 ppm/°C and –8 ppm/°C, while the Z-Foil's from –0.2 ppm/°C to –0.8 ppm/°C only.

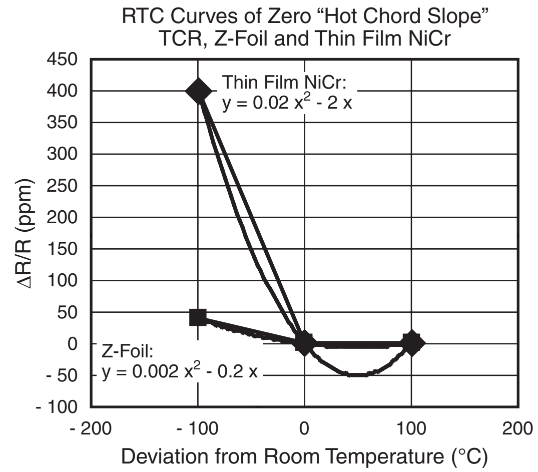

Fig. 6 – Thin film NiCr and Z-Foil resistors, both with zero hot chord slope but different ΔR/R = f(T) curve's non-linearity

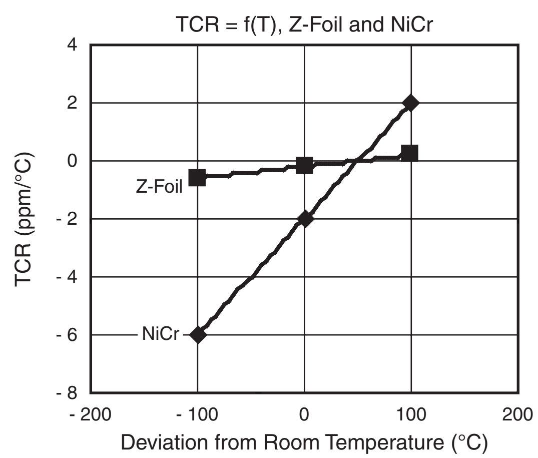

Fig. 7 – Temperature coefficient of resistance vs. temperature plot of thin film and Z-Foil resistors shown in Fig. 6

Thermal Stability of a Ratio of Two Resistance Values

In applications like voltage dividers and operational amplifiers, the stability of the device depends on the stability of the ratio r of values of the two resistors rather then on the stability of their individual values. The relative change of the ratio with temperature, Δr/r, is also expressed in ppm, like the ΔR/R.

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Given two resistors with values R_1 and R_2 at temperature T1, and their temperature coefficients of resistance TCR1 and TCR_2, their initial ratio $r_{T1} = R_1/R_2$ at T_1 will become r_{T2} at temperature T_2. The TCR_1 and TCR_2 can be calculated from known chard slopes of the two resistors using Equation (7). The relative change of ratio Δr/r will be a function of average and differential sensitivities (TCR) and constrains—deviations of temperatures T_1 and T_2 from $T_{Ref.}$ (see Ref. 1, pages 127 and 128).

The Equation is:

$$\Delta r/r = (TCR_{T1} + TCR_{T2}) \times (1/2) \times (T_2 - T_1) + (TCR_{T1} - TCR_{T2}) \times (1/2) \times (T_2 + T_1 - 2 \times T_{Ref.}) \qquad (9)$$

High ratio stability requires both low absolute TCR values of both resistors and low change of their TCR with temperature. Equation 8 assumes constant values of TCR, and the non-linearity of the ΔR/R = f(T) curve will cause an additional change of the ratio. Temperature differences between the two resistors may occur, even if they share the same substrate, due to difference in power density, in heat dissipation properties or in influence of adjacent heat producing devices.

Fast Approach to a Steady State Value by Use of Precision Resistors with Low TCR and PCR

When a step function of current is applied to a resistor, it can take, for planar resistors, a few nanoseconds to achieve an electrical steady state value of the step function, depending on very small reactance inherent to every resistor. However, the voltage measured across such resistor will continue to change, due to resistance change caused by the Joule effect, until thermal stabilization is reached (see Equation 2).

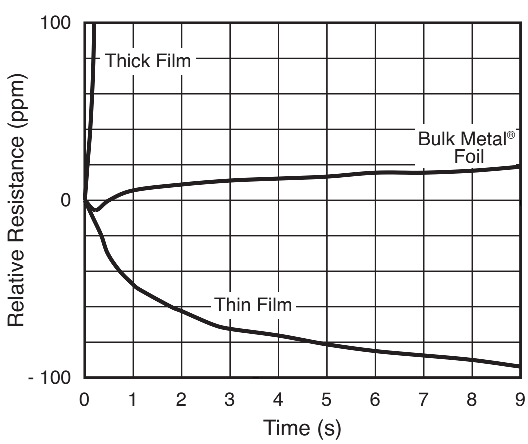

Fig. 8 – Stabilization time of Z-Foil, typical thin film, and thick film resistors

The key to high speed of the thermal step function are a low thermal time constant and a low resistance change, ΔR/R, due to the Joule effect. This can be achieved by using resistors of low TCR (see Fig. 8).

Some applications of precision resistors, like control of scanning x/y tables, require an approach to within a ppm or less to the steady state value in less than a second in order to speed up the performance of expensive equipment. In such cases, both very low TCR and PCR are required.

Review of Performance of Precision Foil and Thin Film Chips on the Market

The TCR of samples of VFR Z-Foil resistors and from six major vendors of precision thin film chip resistors was tested—the cold chord slopes (between –55°C to 25°C) and the hot chord slopes (25°C to 125°C). On purpose, we have selected from batches of thin film the best available TCR from each manufacturer.

Table 1 shows the VFR's Z-Foil's datasheet specification and test results of tested seven samples = one of Z-Foil and six from different vendors of thin film chip resistors.

The change of TCR between cold and hot ranges indicates the degree of non-linearity of the ΔR/R = f(T) curve—or the rate of change of TCR with temperature. As the distance between cold and hot mid-ranges is 90°C, the value of change divided by 90 represents the change of TCR per degree centigrade (see Equation 4).

The last row states the largest TCR for 95.4% of a lot with Gaussian distribution: adding 2 St. Dev. to the average gives the limits of spread of values of 95.4% of the population. Row 3 indicates the curvature of the ΔR/R = f(T) function. According to these two parameters, the Z-Foil sample shows the best results, followed by TF2 with good TCR but relatively high curvature, and TF4 with low curvature but higher TCR. Both TF2 and TF4 exhibit also a much larger spread of slope's values than the Z-Foil samples.

Based on two chord slopes like those in Rows 1 and 4 of Table 1, and on the known parabolic shape of the resistance vs. temperature characteristic, it is possible to calculate the TCR at any point of temperature.

Table 2 states these TCR values for resistors of Table 1, for temperatures between –55°C to 125°C, in intervals of 10°C.

The Rows 2 and 5 of Table 1 indicate that the standard deviation (St. Dev.) of values of the cold and the hot slopes are similar. Therefore, it is possible to use the values of standard deviations to predict the spread of slopes at any other point of temperature within the full temperature range.

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TABLE 1 - COLD AND HOT CHORD SLOPES PER Z-FOIL DATASHEETS AND PER AVERAGE TCR VALUES OF TESTED SAMPLES OF Z-FOIL AND THIN FILM (TF) NiCr CHIPS FROM 6 VENDORS

	DATASHEET Z-FOIL	TESTED TCR DATA - AVERAGE OF SAMPLES (ppm/°C)						
		Z-FOIL	TF1	TF2	TF3	TF4	TF5	TF6
SPECIFIED MAX. TCR	2 ppm/°C	2	5	5	10	10	25	10
1. Average Cold Slope	- 0.2	- 1.15	- 5.34	- 0.46	5.56	4.2	0.56	0.48
2. Cold Slope's St. Dev.	0.9	0.22	1	0.75	1.1	0.67	2.01	0.3
3. Change, Cold to Hot Slope	0.4	0.3	5.78	1.72	- 6.68	0.14	6.64	3.98
4. Average Hot Slope	0.2	- 0.85	0.44	1.26	- 1.12	4.34	7.2	3.5
5. Hot Slope's St. Dev.	0.9	0.25	1	0.63	1.01	0.55	1.6	0.3
6. Largest Slope and 2 St. Dev.	2	- 1.6	8.9	3.2	4.4	5.0	11.5	4.1

TABLE 2 - TCR AT TEMPERATURE POINTS BETWEEN - 55 °C AND 125 °C, BASED ON Z-FOIL DATASHEET AND ON AVERAGE TCR VALUES OF TESTED SAMPLES OF Z-FOIL AND THIN FILM CHIPS FROM 6 VENDORS

TEMP. (°C)	Z-FOIL DATA (ppm/°C)			TEST DATA OF SAMPLES (ppm/°C)						
	MAX.	NOM.	MIN.	Z-FOIL	TF1	TF2	TF3	TF4	TF5	TF6
125	2.22	0.42	- 1.38	- 0.68	3.6	2.2	- 4.8	4.1	10.9	5.2
115	2.17	0.37	- 1.43	- 0.71	3.0	2.0	- 4.1	4.1	10.2	4.8
105	2.13	0.33	- 1.47	- 0.75	2.4	1.8	- 3.3	4.2	9.4	4.5
95	2.08	0.28	- 1.52	- 0.78	1.7	1.7	- 2.6	4.2	8.7	4.2
85	2.04	0.24	- 1.56	- 0.81	1.1	1.5	- 1.9	4.2	7.9	3.8
75	2.00	0.20	- 1.60	- 0.85	0.4	1.3	- 1.1	4.2	7.2	3.5
65	1.95	0.15	- 1.65	- 0.88	- 0.2	1.1	- 0.4	4.2	6.5	3.2
55	1.91	0.11	- 1.69	- 0.92	- 0.8	0.9	0.4	4.2	5.7	2.8
45	1.86	0.06	- 1.74	- 0.95	- 1.5	0.7	1.1	4.2	5.0	2.5
35	1.82	0.02	- 1.78	- 0.98	- 2.1	0.5	1.9	4.3	4.3	2.2
25	1.78	- 0.02	- 1.82	- 1.02	- 2.7	0.3	2.6	4.3	3.5	1.8
15	1.73	- 0.07	- 1.87	- 1.05	- 3.4	0.1	3.3	4.3	2.8	1.5
5	1.69	- 0.11	- 1.91	- 1.09	- 4.0	- 0.1	4.1	4.3	2.0	1.2
- 5	1.64	- 0.16	- 1.96	- 1.12	- 4.7	- 0.3	4.8	4.3	1.3	0.8
- 15	1.60	- 0.20	- 2.00	- 1.15	- 5.3	- 0.5	5.6	4.3	0.6	0.5
- 25	1.56	- 0.24	- 2.04	- 1.19	- 5.9	- 0.7	6.3	4.4	- 0.2	0.1
- 35	1.51	- 0.29	- 2.09	- 1.22	- 6.6	- 0.8	7.0	4.4	- 0.9	- 0.2
- 45	1.47	- 0.33	- 2.13	- 1.26	- 7.2	- 1.0	7.8	4.4	- 1.7	- 0.5
- 55	1.42	- 0.38	- 2.18	- 1.29	- 7.8	- 1.2	8.5	4.4	- 2.4	- 0.9

The 14 charts on pages 8 and 9 show for each of the 7 samples of the tables above (one of Z-Foil and 6 of thin film) their $\Delta R/R = f(T)$ and TCR graphs. The x axis shows the temperatures from –55°C to 125°C and the y axis shows in the $\Delta R/R = f(T)$ graphs the relative resistance change $\Delta R/R$ (in units of ppm) and in the TCR graphs the changing TCR (in units of ppm/°C).

The vertical line located at x = –60 provides a yardstick corresponding to a TCR of minus and plus 5 ppm/°C cold and hot chord slopes on the TCR graphs and, therefore, to a $\Delta R/R$ of 5 x (–80) = –400 ppm and 5 x 125 = 500 ppm on the $\Delta R/R = f(T)$ graphs.

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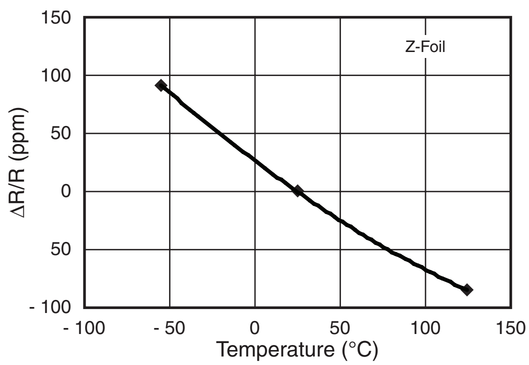
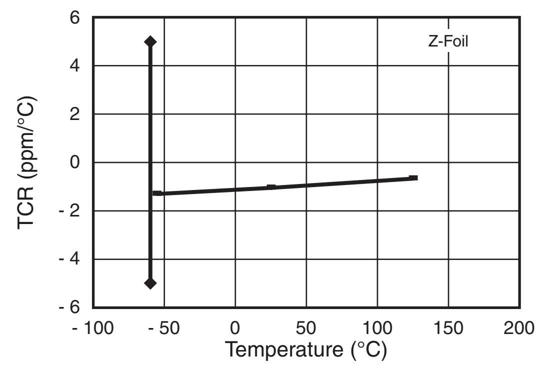
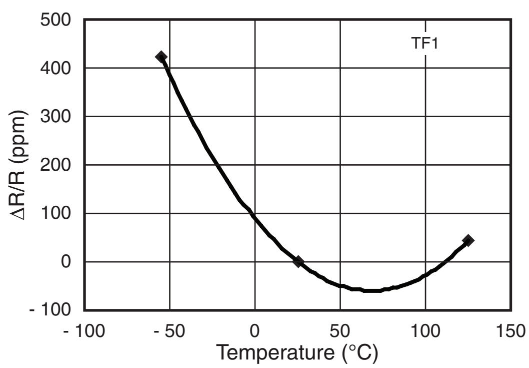
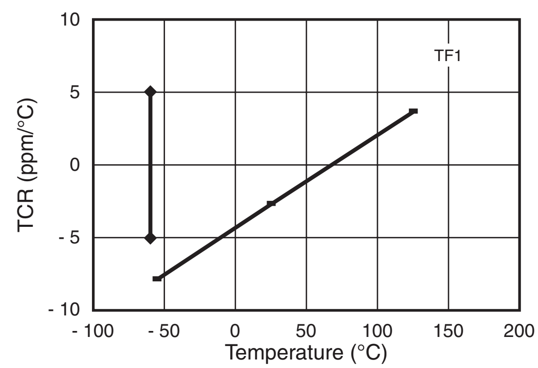
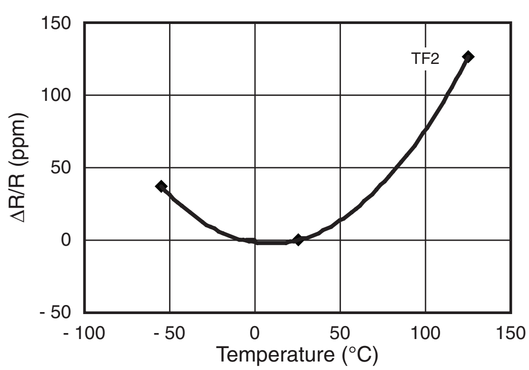
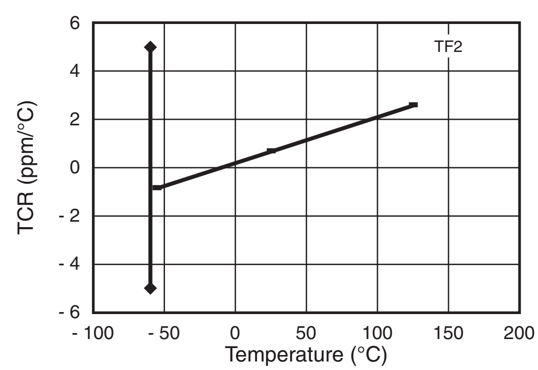
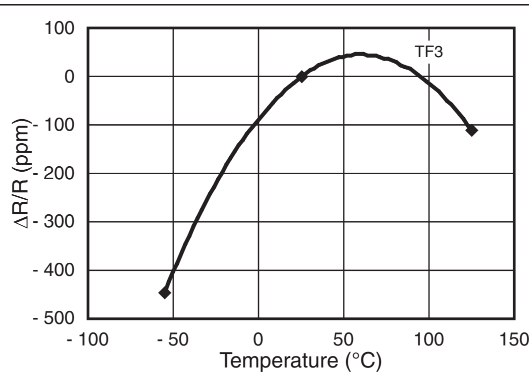
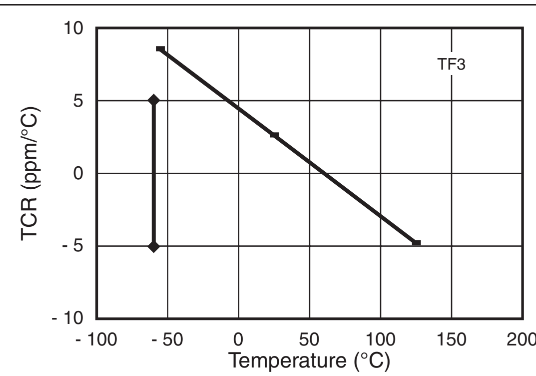
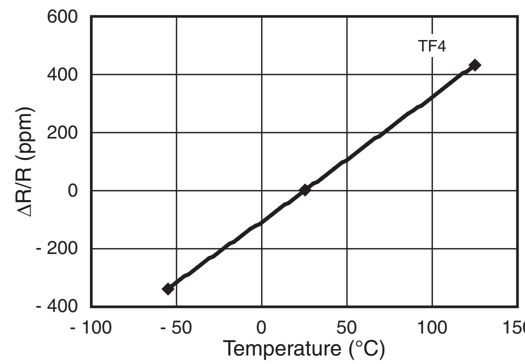
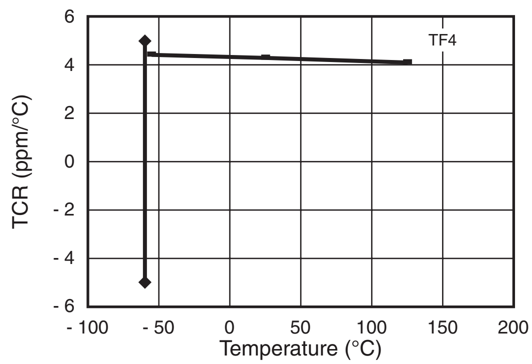
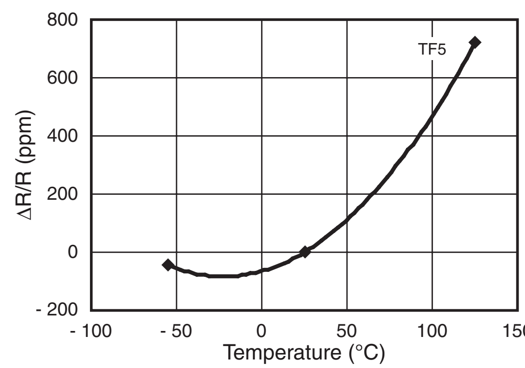
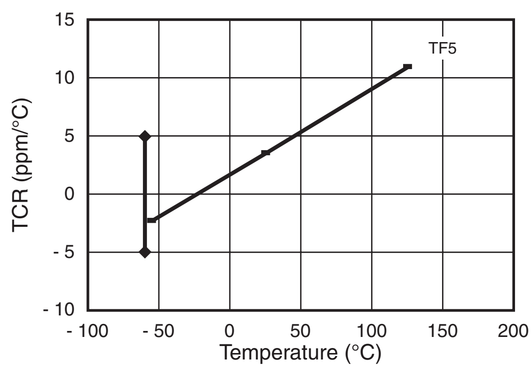
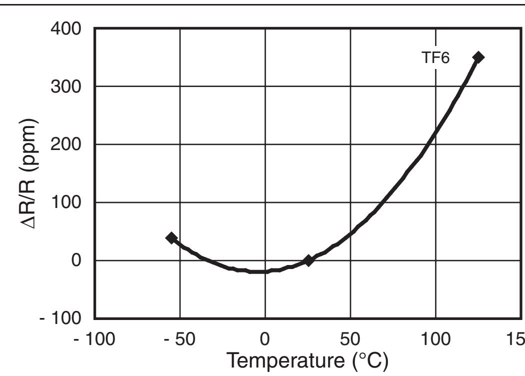
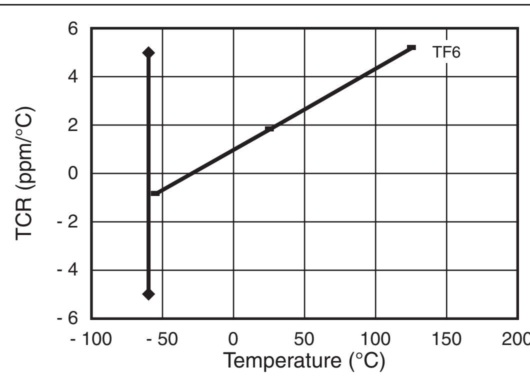
SAMPLES OF	RELATIVE RESISTANCE CHANGE VS. TEMPERATURE, ∆R/R = f(T)	TEMPERATURE COEFFICIENT OF RESISTANCE VS. TEMPERATURE, TCR = f(T)
Z-Foil		
TF1		
TF2		
TF3		

TECHNICAL NOTE

Non-Linearity of Resistance/Temperature Characteristic: Its Influence on Performance of Precision Resistors

SAMPLES OF	RELATIVE RESISTANCE CHANGE VS. TEMPERATURE, ΔR/R = f(T)	TEMPERATURE COEFFICIENT OF RESISTANCE VS. TEMPERATURE, TCR = f(T)
TF4		
TF5		
TF6		

Example of Calculation of a Chord Slope and the Maximum Value of TCR for a Given Temperature Range

Let us calculate for instance the average chord slope for a resistor from thin film vendor # 2 for an application's temperature range TR_A corresponding to an ambient temperature of 75°C and loads up to the rated power causing a temperature rise of up to 50°C.

The chord's slope for TR_A will be the same as the slope of a tangent at application's mid-range temperature T_{MRA} on the ΔR/R = f(T) curve:

$$T_{MRA} = (75 + 125)/2 = 100°C$$

The average hot chord slope per table is 1.26 ppm/°C and corresponds to a tangent at a temperature of hot chord's mid-range T_{HMR} = (25 + 125)/2 = 75°C.

Change of average chord slope, cold to hot, is 1.72 ppm/°C per the table above and occurs between a cold mid-range of (–55 + 25)/2 = –15°C and hot mid-range of 75°C, or over 75 – (–15) = 90°C.

The rate of change of the TCR with temperature is ΔTCR/ΔT:

$$\Delta TCR/\Delta T = 1.72/90 = 0.019\ ppm/(°C)^2$$

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From 75°C to 100°C, the mid-range temperature of hot chord slope to the T_{MRA}, the average chord slope will change to:

25 x 0.019 + 1.26 = 1.74 ppm/°C

To take into account the spread of TCR values in a resistor's lot, two standard deviations are added (like in the last row of Table 1). This results in a confidence level of 95.4% that the TCR in the lot will be within the limit 1.74 + 2 x 0.63 = 3 ppm/°C.

Figures 9 and 10 represent the average resistance change vs. temperature characteristic, ΔR/R = f(T) and temperature coefficient of resistance, respectively, for Z-Foil and thin film.

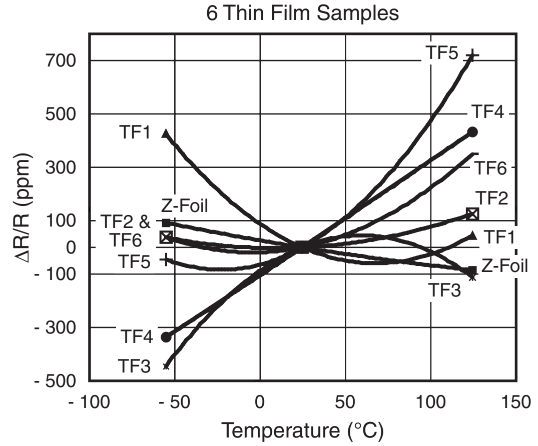

Fig. 9 – Relative resistance change vs. temperature curves of Z-Foil and thin film precision chip resistors from 6 vendors

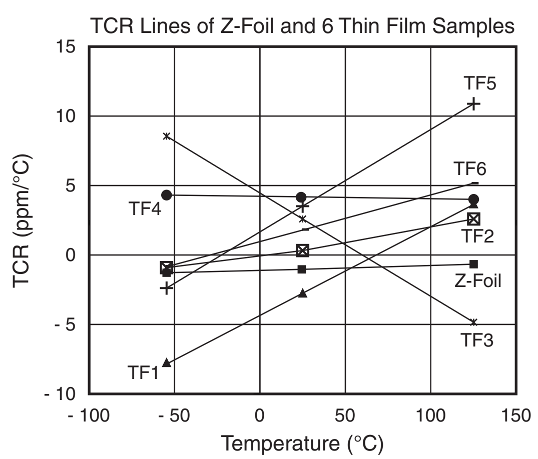

Fig. 10 – Temperature coefficient of resistance as function of temperature of resistor chips per Fig. 7

Summary and Recommendations

In high precision resistor and voltage divider applications, the absolute value and the change of the temperature coefficient of resistance (TCR) and of the power coefficient of resistance (PCR) with temperature due to the non-linearity of their resistance temperature characteristic should be minimized.

Vendor's TCR data should specify to what temperature ranges—below and above room temperature—their data refer. Based on these data, it is possible to estimate the temperature stability of a precision resistor within a specific temperature range of an application.

The application specific temperature range depends on ambient temperature, influence of neighboring heat producing components, and the power dissipated by the resistor.

The calculations sometimes reveal a higher TCR value of the TCR within application's temperature range as compared with vendor's data which refer to an average of a wide temperature range and usually do not refer to the PCR.

In case adequate information about TCR and PCR is not available, it is recommended to test a sample in order to establish the two chord slopes of the ΔR/R = f(T) curve and the change of resistance when power is applied. Based on test results, the resistance change can be calculated for the ambient temperature and the level of power fitting a specific resistor's application.

Bibliography

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2. Watson, R.B. et al. "Effects of Material Properties and Heating/Cooling Rate on Strain Gage Thermal Output Observations." ICBM12–12th International Conference on Experimental Mechanics, 2004.

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PERFORMANCE THROUGH PRECISION