A Comparison of the Noise and Voltage Coefficients of Precision Metal Film and Carbon Film Resistors*

T. R. WILLIAMS† AND J. B. THOMAS†

Summary—**Measurements of the current noise and voltage coefficient are given for metal film and carbon film resistors. In general, the noise power in the metal resistors was less than that in the carbon by a factor of 10^3, although a few of the former type were very noisy. For many typical applications in and below the audio spectrum the current noise in a large fraction of the metal resistors will be smaller than thermal noise even at rated dissipation. The voltage coefficients of the metal resistors were less than those in the carbon by a factor of about 10; in most units of the former type the coefficients were less than 3×10^{-5} per cent/volt, and in a few units they were less than 1×10^{-6} per cent/volt. Voltage coefficients of both signs were found in the metal resistors, while all of them were negative in the carbon resistors.**

Introduction

During the past ten years, precision pyrolytic carbon film resistors have been used widely in numerous critical and semicritical applications. Such resistors have a number of undesirable characteristics, however, and in order to meet the more stringent requirements placed on resistors in present-day equipment, much effort has been devoted to the development of new types of precision resistors.[1-5] The performance of some of these new types is quite superior to the pyrolytic carbon type in many ways and, in fact, with respect to stability and noise, approaches that of wire-wound resistors. Since their HF behavior is comparable to that of resistors of the pyrolytic carbon type, it appears likely that they will find widespread use, not only as replacements for wire-wound and pyrolytic carbon film resistors, but also in new applications.

Carbon and metal film resistors exhibit noise known as current noise when a direct current is passed through them; in addition, they are nonlinear. In carbon resistors of the same manufacture, the current noise and the nonlinearity among similar resistors are highly correlated.[6] Even though the noise and nonlinearity of the newer types of resistors are much smaller than in carbon resistors, there are numerous situations in which these properties are of extreme importance, and it is necessary to know what their order of magnitude will be in a typical case. Little information on this subject has been reported, and, accordingly, an investigation was initiated.

This paper presents a comparison of the current noise and voltage coefficients of pyrolytic carbon film precision resistors and some of the recently introduced metal film precision resistors in which the metal film is fused to a ceramic glaze. Resistors having a rated dissipation of one watt were used throughout, and the nominal resistances were 20 K and 50K. Measurement conditions were identical for all resistors of the same nominal resistance. Because of the small magnitude of the voltage coefficient in some of the resistors, measurements were quite difficult and, therefore, the circuit used is given and discussed in some detail.

It is shown that, in general, the noise power in the new metal resistors is several orders of magnitude smaller than in the carbon resistors and, in most cases, their voltage coefficients are substantially smaller. In contrast with carbon resistors, whose voltage coefficients are all negative, voltage coefficients of both signs were found in the metal resistors. Furthermore, the metal resistors do not exhibit the high degree of correlation between current noise and voltage coefficient found in carbon resistors.

Apparatus

The equipment used for the noise measurement was described previously.[6] Briefly, a wave analyzer tuned to 40 cps was used to determine the noise power spectral density. The averaging time of the analyzer meter was increased to about one minute for the measurements by adding an external capacitor across the grid of the final dc amplifier, so that measurements consistent to within about five per cent could be made readily.

The circuit used for the voltage coefficient measurements is given in Fig. 1. With the switches as shown, the resistor under test, R, was placed in the bridge and the bridge balanced. The null was detected with a galvanometer having a sensitivity of 0.003 μamp/mm which was used with an Ayrton shunt. Switch S_1 was then turned to its lower position, thereby connecting a direct-coupled oscilloscope having a maximum sensitivity of 1 mv/cm to the bridge output. Following this, the switch S_2 was turned to its lower position, placing the 2-μf capacitor across the bridge; with S_2 in its upper position this capacitor was charged to the voltage V_2, and on the switch-

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† Dept. of Elec. Engrg., Princeton University, Princeton, N. J.

[1] S. J. Stein and J. Riseman, "Evaporated metal film resistors," *Proc. Symp. on Electronic Components*, Washington, D. C., pp. 100–106; 1954.

[2] S. J. Stein and J. Riseman, "Precision and high temperature metal film resistors," *Proc. Symp. on Electronic Components*, Washington, D. C., pp. 171–174; 1956.

[3] C. Wellard and K. Gentner, "Pyrolytic alloy high temperature resistors," *Proc. Symp. on Electronic Components*, Washington, D. C., pp. 179–183; 1956.

[4] R. C. Langford and J. G. Ruckelshaus, "A new thermally-fused metal-to-ceramic volume resistor," *Proc Symp. on Electronic Components*, Washington, D. C., pp. 192–199; 1956.

[5] S. J. Stein, "Multipurpose evaporated metal film resistors," IRE Trans. on Component Parts, vol. CP-3, pp. 119–124; December, 1956.

[6] T. R. Williams and J. B. Thomas, "Current noise and nonlinearity in carbon resistors," IRE Trans. on Component Parts, vol. CP-5, pp. 151–153; December, 1958.

ing of S_2, approximately half of this voltage was applied to the resistor under test. The nonlinearity of R caused the bridge to be slightly unbalanced and, consequently, the bridge output was a pulse of about 40-msec duration, the leading edge of which had a height proportional to the resistance change of R. This height was observed with the oscilloscope, and the resistance change computed from it and the system parameters.

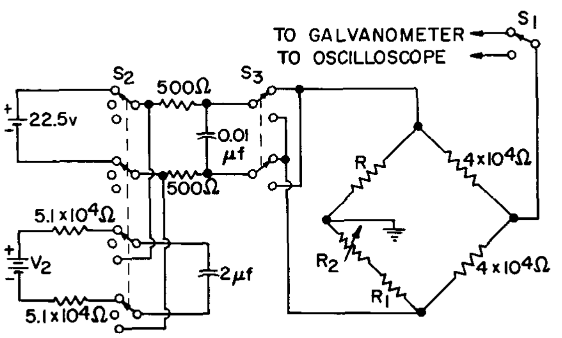

Fig. 1—Diagram of circuit used for voltage coefficient measurements.

Since some of the smallest resistance changes observed were of the order of a few tenths of an ohm, it was necessary to minimize leakage currents and other stray effects. The entire circuit was shielded, and porcelain insulators were used to isolate the batteries from the shield. Ceramic rotary switches were used. Even with these precautions, consistent measurements were frequently not possible when the humidity was high. The reversing switch S_3 was used in testing for leakage and also for checking the symmetry of the volt-ampere characteristics of the resistors.

It was necessary, of course, to carefully distinguish the resistance changes due to the applied voltage from those due to the temperature change of the resistor during the measurement. Some preliminary measurements were made in the course of which a high-voltage battery, instead of a charged capacitor, was placed directly across the bridge when S_2 was turned to its lower position. In this case the bridge output voltage exhibited a rapid initial change, proportional to the initial resistance change, followed by a relatively slow change due to the heating of the resistor under test. With manual switching it was not possible to switch rapidly enough to prevent appreciable heating. Measurements were tedious and difficult to repeat since it was necessary to wait until the temperature of the resistor under test and the other resistors in the bridge returned to equilibrium. The use of a charged capacitor in place of the battery eliminated this difficulty.

Temperature changes in the other resistors in the bridge were minimized by the use of wire-wound power resistors having 25-watt ratings. The variable resistor R_2 was a precision decade resistor having steps of 0.1 ohm.

The switching of S_2 caused a large transient voltage which overloaded the oscilloscope for about 0.5 msec and caused the leading edge of the bridge output pulse as viewed on the oscilloscope to be rounded slightly. The low-pass filter formed by the two 500-ohm resistors and the 0.01-μf capacitor was intended to minimize the effects of this transient.

The measurement conditions are summarized in Table I. The voltage V_v is the voltage across the resistor under test when switch S_2 was turned to its lower position during the measurement of the voltage coefficient, and V_n is the voltage across the resistor during the noise measurement. The bridge sensitivity given is the bridge output voltage for a change of one ohm in the resistance of R.

TABLE I

MEASUREMENT CONDITIONS

Nominal Resistance	Bridge Sensitivity	V_v	V_n
20 K	5.26 mv/ohm	217 v	135 v
50	2.53	264	193

The accuracy of the voltage coefficient measurements was greatest, of course, for the largest resistance changes, being limited only by the accuracy with which the pulse height could be determined on the oscilloscope. Measurements consistent to within 5 per cent could be made readily. For resistance changes of about one ohm the accuracy was about 10 per cent, since the initial balance was made only to the nearest tenth of an ohm. For still smaller changes the accuracy was quite poor, due both to the limited sensitivity of the oscilloscope and the inaccuracy of the initial balance. All measurements were repeated at least twice, and, in the case of the smallest changes, three or four measurements were made and averaged. The operation of the equipment was checked frequently during the measurements by following the test procedure described previously with a 50-K or 20-K wire-wound resistor.

RESULTS

The bridge output pulse height was measured as a function of the voltage V_2 for a number of the resistors which exhibited large changes. Typical results are shown in Fig. 2 where the cube root of the pulse height has been plotted vs the voltage V_2. As nearly as could be measured the points fall on a straight line, indicating that the resistance change is proportional to some power of the magnitude of the applied voltage. For the metal resistors the slopes are approximately equal to one, and such was the case in most of these; hence, since the bridge output varies approximately as the cube of V_2 and since it is also proportional to the product of V_2 and the resistance change, the resistance change varies approximately as the square of the applied voltage in the metal resistors. In the carbon resistors the resistance change did not increase as rapidly with applied voltage; hence the slopes were less, as shown in Fig. 2. Furthermore, the slopes showed more variation among resistors. The resistance

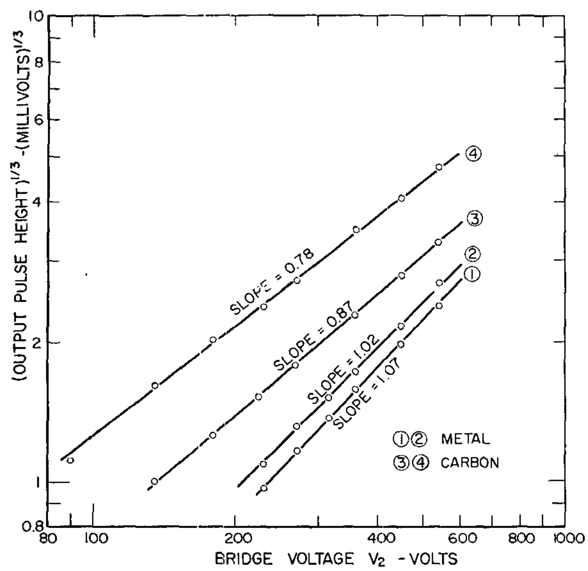

Fig. 2—Variation of bridge output pulse height with applied voltage for metal and carbon film resistors.

change varied as some power less than 2.0 of the applied voltage; values of this power ranging from 1.2 to 1.9 were measured, and values near 1.3 were found to be quite common. In most of the metal resistors it was not possible to make the measurements described above due to the extremely small magnitude of the resistance change, even at the highest voltages employed.

The voltage coefficient is defined by

$$\sigma = 100\left(\frac{1}{V_1 - V_r}\right)\left(\frac{R_1 - R_r}{R_1}\right) \text{ per cent/volt} \quad (1)$$

where R_1 is the resistance measured with one-tenth rated voltage across the resistor, R_r is the resistance measured with rated voltage, and V_1 and V_r are one-tenth and full rated voltage, respectively. Since the resistance changes are very small, R_1 in the denominator of (1) was taken to be the nominal resistance. This coefficient was computed from the observed resistance change under the assumption that the resistance change varied as the 1.3 and 2.0 power of the applied voltage for the carbon and the metal resistors, respectively.

Since the resistance change in both carbon and metal resistors increases more rapidly than the applied voltage, the voltage coefficient cannot be used directly to estimate resistance changes for voltages other than rated voltage. In such cases the following relationship holds:

$$\frac{\Delta R}{R} = \frac{0.009 \mid V \mid^{\gamma}}{[1 - (0.1)^{\gamma}]V_r^{\gamma - 1}}\,\sigma \quad (2)$$

where ΔR is the resistance change in ohms, R is the nominal resistance in ohms, V and V_r are the applied voltage and rated voltage, respectively, in volts, and γ is equal to 2.0 for the metal resistors and 1.3 for the carbon resistors. This relationship is derived in Appendix I.

The measure of current noise employed here is defined by

$$\theta = \frac{v_n}{V_n} \quad (3)$$

where v_n is the rms noise voltage in microvolts over a band extending from 10 to 10^4 cps, and V_n is the dc voltage across the resistor in volts. This definition was chosen in order to give a quantitative indication of the order of magnitude of the noise to be expected in a typical application. Calculations were based on the measured value of the power spectral density of the voltage at 40 cps and it was assumed that the spectral density varied inversely with frequency and directly with the square of the applied voltage.[7,8]

Conrad has proposed a noise index, the conversion gain, defined by

$$G_c = 10 \log \frac{P_a}{P} \quad (4)$$

where P_a is the available noise power per cycle at 1000 cps, and P is the dc power dissipated in the resistor.[9] The relationship between the two measures of noise is given here for convenience in comparing the present results with those of Conrad:

$$G_c = 20 (\log \theta) - 164.4. \quad (5)$$

This relationship is derived in Appendix II.

The noise and the magnitudes of the voltage coefficients for all resistors are plotted in Fig. 3. It is immediately apparent from this plot that there is, in general, a large difference in the noise of the two types of resistor. A great majority of the metal resistors have a noise smaller than 0.03 μv/v, while nearly all the carbon resistors have a noise greater than 0.1 μv/v. The noise power in the carbon resistors is typically greater than that in the metal by a factor of roughly 10^3, corresponding to a 30-db difference in conversion gain. There are exceptions: three of the metal resistors, which have been indicated in Fig. 3, exhibited large, erratic bursts of noise which increased the noise power by several orders of magnitude. The measurements for these given in Fig. 3 were made during periods when the resistors were relatively quiet, and during such periods the noise was comparable to that in the carbon resistors.

A dotted horizontal line is drawn in Fig. 3 below which the accuracy of the noise measurements decreased rapidly,

[7] G. T. Conrad, Jr., "Noise measurements of composition resistors, II. Characteristics and comparison of resistors," IRE Trans. on Component Parts, vol. CP-4, pp. 79–92; November, 1955.

[8] C. J. Christensen and G. L. Pearson, "Spontaneous resistance fluctuations in carbon microphones and other granular resistances," *Bell Sys. Tech. J.*, vol. 15, pp. 197–223; April, 1936.

[9] G. T. Conrad, Jr., "A proposed current-noise index for composition resistors," IRE Trans. on Component Parts, vol. CP-3, pp. 14–20; March, 1956.

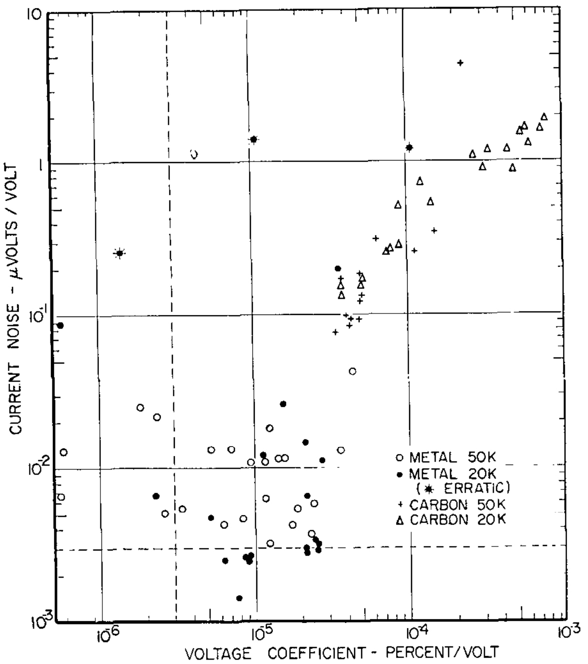

Fig. 3—Noise and voltage coefficients of resistors.

due to the fact that at the line the noise being measured was roughly the same as the internal noise of the amplifier; it was estimated that at the line the accuracy was about 10 per cent. It is noteworthy that a sizeable fraction of the metal film resistors had noise which was almost unmeasurable with the equipment used.

The conversion gains corresponding to various values of θ are readily found with the aid of (5). Thus, the conversion gain for $\theta = 1.0$ μv/v is -164.4 db, that for $\theta = 0.1$ μv/v is -184.4 db, etc. The carbon resistors have conversion gains ranging from about -190 to -155 db, which is consistent with Conrad's results.[9]

The metal resistors show a significant improvement in voltage coefficient over the carbon resistors. All of the carbon resistors have a voltage coefficient greater than 3×10^{-5} per cent/volt while the metal resistors have, in general, coefficients less than this value. Typically, the coefficient is greater in the carbon resistors by a factor of about 10. Some of the coefficients in the metal resistors were exceptionally small and, hence, extremely difficult to measure. A dotted vertical line is shown in Fig. 3 to the left of which the accuracy is poor. The voltage coefficient at the line corresponds roughly to a resistance change of 0.3 ohm during the measurement. In view of the accuracy of the initial balance mentioned earlier the coefficient corresponding to the three points on the extreme left is zero as nearly as could be measured, and the three points have been included only for completeness.

In contrast with the carbon resistors, which all had negative voltage coefficients, a majority of the 50-K metal resistors and about half of the 20-K metal resistors had positive voltage coefficients. The coefficients were of the same order of magnitude, in general, although the largest coefficient found was negative.

As noted previously, the voltage coefficients and noise among groups of similar carbon resistors are highly correlated. For example, the normalized correlation coefficient of $\log \sigma$ and $\log \theta$ was calculated for the 20-K carbon resistors and found to be 0.96, indicating a high degree of correlation. In contrast, the points corresponding to the metal resistors are quite widely scattered and show no obvious correlation. In view of the limited accuracy of many of the points corresponding to metal resistors, it was felt that a calculation of the correlation coefficients would not lead to significant results.

Conclusions

The new type of metal film resistor studied in this investigation exhibits current noise which is considerably smaller than that typical in the pyrolytic carbon film type; roughly, the noise power is smaller by a factor of 10^3, which represents a remarkable improvement in performance. In fact, in many situations the current noise in these new resistors will be negligible compared to thermal noise, even at rated voltage. For example, the thermal noise at 30°C over a band extending from 10 to 10^4 cps is 1.8 μv for a 20-K resistor and 2.9 μv for a 50-K resistor. More than one-third of the metal resistors had a noise of less than 5×10^{-3} μv/v, and at rated voltage this amounts to 0.71 and 1.1 μv in the 20-K and 50-K resistors, respectively. Thus, over the audio frequency range, many of the new resistors have a noise comparable to wire-wound resistors. It must be remembered, however, that a few of the metal resistors had a noise comparable to and sometimes exceeding that in the carbon resistors.

The voltage coefficients of the new resistors are significantly smaller than the carbon resistors, and most of them had resistance changes of less than 50 ppm up to rated voltage.

In view of the fact that the new metal resistors have excellent HF properties and small temperature coefficients, they show great promise not only as replacements for pyrolytic carbon and wire-wound resistors, but also for use in numerous new applications requiring high-stability precision resistors.

Appendix I

The observed resistance changes are given by

$$\Delta R = k \mid V \mid^{\gamma} \tag{6}$$

where k is a constant and V is the voltage applied to the resistor. Thus when rated voltage is applied

$$R_r = R_0 + k \mid V_r \mid^{\gamma} \tag{7}$$

and when one-tenth rated voltage is applied

$$R_1 = R_0 + k \mid V_1 \mid^{\gamma} \tag{8}$$

where R_0 is the resistance with no applied voltage. Since all resistors used were 1 per cent precision resistors, R_0 will be taken as the nominal resistance R. Now

$$R_1 - R_r = k(|V_1|^\gamma - |V_r|^\gamma) \tag{9}$$

and, since V_1 is one-tenth of V_r, (1) can be written

$$\sigma = \frac{100k(1-(0.1)^\gamma)V_r^{\gamma-1}}{0.9(R+k|V_1|^\gamma)}. \tag{10}$$

The quantity $k|V_1|^\gamma$ in the denominator is much smaller than R and can be neglected. Therefore k is given by

$$k = \frac{0.009R\sigma}{(1-(0.1)^\gamma)V_r^{\gamma-1}}. \tag{11}$$

Eq. (2) results when (11) is substituted into (6).

Appendix II

Let the spectral density of the noise voltage be

$$S_v(f) = K\frac{I^2}{f} \tag{12}$$

where I is the dc current through the resistor in amperes, and f is the frequency in cps. The mean-squared noise voltage in (μvolts)^2 over the band extending from 10 to 10^4 cps is

$$v_n^2 = 10^{12}\int_{10}^{10^4} S_v(f)\,df = 6.9 \times 10^{12}KI^2. \tag{13}$$

Now V_n is the dc voltage across the resistor so that

$$\frac{v_n^2}{V_n^2} = \theta^2 = \frac{v_n^2}{I^2R^2} = \frac{6.9\times 10^{12}K}{R^2} \tag{14}$$

where R is the resistance in ohms. Therefore, K is given by

$$K = \frac{\theta^2R^2}{6.9\times 10^{12}} \tag{15}$$

and the spectral density at 1000 cps is

$$S_v(1000) = \frac{\theta^2R^2I^2}{6.9\times 10^{15}}. \tag{16}$$

Since the available noise power for a bandwidth of 1 cps at 1000 cps is given by

$$P_a = \frac{S_v(1000)}{4R}\Delta f \tag{17}$$

where Δf is 1 cps, it follows that

$$P_a = \frac{\theta^2I^2R\,\Delta f}{2.76\times 10^{16}} = \frac{\theta^2P\,\Delta f}{2.76\times 10^{16}} \tag{18}$$

where P is the dc power dissipated in the resistor. The conversion gain is therefore given by

$$G_c = 10\log\theta^2 - 10\log(2.76\times 10^{16}) + 10\log\Delta f \tag{19}$$

Eq. (5) follows immediately when Δf is set equal to 1 cps.

Problems in Long-Term Component Reliability*

K. E. LATIMER†

Summary—**The motion of submerged repeaters during laying and pick-up in deep water has been investigated and the results are presented.**

An attempt has been made to gather together in a systematic way the very scattered references to long-term deterioration problems affecting the choice of materials of which components are made.

Component testing procedure is discussed and special features of individual components which affect long-term deterioration are mentioned.

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† Submarine Cables Ltd., Greenwich, London, Eng.

Introduction

In one of his new bulletins on component research, Mr. Dummer enumerated the various categories of components from the point of view of their field of application. In spite of the very small numbers of components used in submarine cable repeaters, as compared with those used in other branches of the electronics industry, he nevertheless recognized that such components formed a separate class, having special long-life requirements which were not necessarily satisfied by components developed for other purposes [1].

Since then a submarine telephone cable system has been laid across the Atlantic, and it will not be long before