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Leden, Bo

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B. LEDEN

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B. Leden

ABSTRACT.

In this report a general one thermistor reciprocal network is considered. It is shown, that an output function of the network is a linear function of the standard function

$R_{th}/(R_{th} + R(T))$.

The resistances R(T) and R_{th} are the thermistor resistance at temperature T and the Thevenin equivalent resistance with respect to the thermistor terminals respectively. A design criterion, which applies to the general network, is presented. The relative merits of the criterion is discussed. One circuit, suitable for the purpose of temperature measurements, is selected. The complete scheme of a constructed temperature transducer is given. The transducer is a complete solution to the problem of the nonlinear characteristic and the dataspreading of the thermistor sensors for a fairly wide range of temperature.

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1. INTRODUCTION.

Significant advantages can be obtained by using thermistors as temperature measurement elements because of their high temperature sensitivity, fast response, good stability, low cost, convenient ranges of operation resistances and wide range of shapes and sizes. Outstanding features of the sensors are the high temperature sensitivity, fast response and small size, which includes almost microscopic units. However, the design of convenient measuring circuits for use with these elements is complicated by two facts, viz. the nonlinear characteristic and the dataspreading of the thermistors.

In section 2 it is shown, that the output function of a general one thermistor reciprocal network is a linear function of a standard function

$$R_{th}/(R_{th} + R(T))$$

where R_{th} is the Thevenin equivalent resistance with respect to the thermistor terminals and R(T) the thermistor resistance at temperature T. Universal design criteria may thus be developed. A design criterion, proposed by the author, which applies to the general network, is presented in section 3. The relative merits of the criterion is discussed. In section 4 an idealized transducer and its output function is considered. Table 4.1 shows the maximum linearity error of the transducer, given by the proposed criterion and a least square criterion, at different temperature ranges. The linearity error falls below 0.5% at a temperature span of 30^{o}C. Thus the transducer solves the problem of the nonlinear characteristic of the thermistor for a rather wide range of temperature. The solution to the problem of the dataspreading also appears in this section. The construction and calibration of a temperature transducer is presented in Section 5. The complete scheme of the transducer is given. Table 5.1 represents a useful tool, when the calibration is carried out. The long term stability of the thermistor is discussed in Section 6. This section also includes the measurement results. Table 6.1 clearly shows, that the ideal temperature transducer may well be realized by the constructed one.

This paper has direct connection with the need of a temperature transducer utilizing a sensor of small size and fast response capable of recording the temperature accurately in the range of 20°C - 30°C. The constructed transducers registrate the boundary temperature and the temperature profile of a one dimensional heat diffusion process, described in |3|.

2. A STANDARD OUTPUT FUNCTION OF A ONE THERMISTOR RECIPROCAL NETWORK.

In this section we show that the current in any branch in a network comprising linear resistors, a single thermistor, and zero-impedance generators may be expressed as a linear function of a standard function $R_{th}/(R_{th} + R(T))$, where R_{th} denotes the Thevenin equivalent resistance with respect to the thermistor terminals and R(T) the thermistor resistance at temperature T. Universal design criteria for one thermistor linear networks may thus be developed.

Consider a network with nodes ℓ, m, n, o, ..., node voltages V_ℓ, V_m, V_n, V_o, ..., and branch currents $I_{\ell m}$, $I_{\ell n}$, $I_{\ell o}$, I_{mn}, ... The branch ℓm comprises the linear resistance $R_{\ell m}$ and the zero-impedance generator $E_{\ell m}$. The quantities $I_{\ell m}$ and $E_{\ell m}$ are positive if the current and the voltage respectively are directed from ℓ to m.

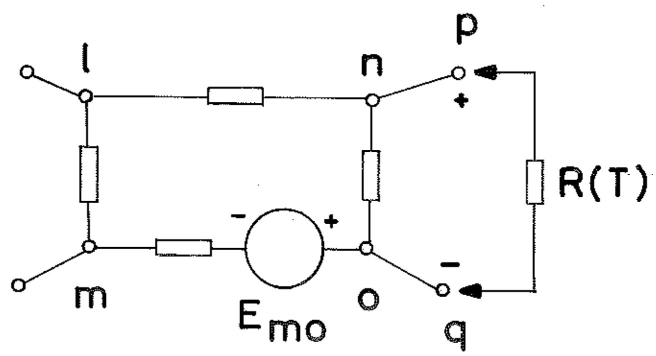

Fig. 2.1 - A general network comprising linear resistors and zero-impedance generators.

If a lead containing a resistance R(T) is connected to the nodes p and q superposed currents and voltages are generated in the network. The Thevenin theorem states, that these superposed currents and voltages are the same as the partial currents and voltages, caused by a zero-impedance generator, placed in the junction lead. The voltage of the generator should equal the original voltage E_{th}^{pq} across the nodes and be directed as this will force the current. The partial currents and voltages may be calculated from the considered network with all internal generators short-circuited and the junction lead comprising the thermistor and the generator E_{th}^{pq} connected to the terminals p and q according to the principle of superposition. The network is found in Fig. 2.2.

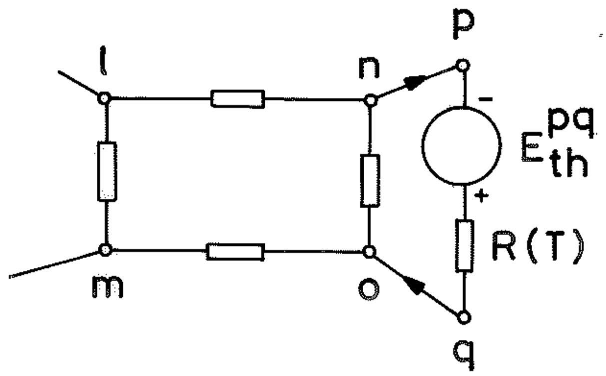

Fig. 2.2 - The network with all internal generators short-circuited and the junction lead containing the thermistor and the generator E_{th}^{pq} connected to the terminals p and q.

The current in the junction lead reaches

$$I_{pq} = \frac{E_{th}^{pq}}{R_{th}^{pq} + R(T)} \tag{2.1}$$

where R_{th}^{pq} is the Thevenin equivalent resistance with respect to the thermistor terminals. There exists a linear relationship between the current in the branch ℓm and the current I_{pq}. The relation is written

$$I'_{\ell m} = L^{pq}_{\ell m} \, I_{pq} \tag{2.2}$$

In the network of Fig. 2.1 the current in the branch ℓm with the thermistor connected across the terminals p and q is the sum of the current $I^0_{\ell m}$ existing before the connection of the lead and the current $I'_{\ell m}$. Thus we have according to eq. (2.1) and (2.2)

$$I_{\ell m} = I^0_{\ell m} + L^{pq}_{\ell m} \frac{E^{pq}_{th}}{R^{pq}_{th} + R(T)} \tag{2.3}$$

which proves the thing. For obvious reasons the voltage across two arbitrary nodes in the network will also be a linear function of the standard function F(T), where

$$F(T) = \frac{R_{th}}{R_{th} + R(T)} \tag{2.4}$$

We now conclude, that for a given thermistor resistance temperature characteristic the linearity of an output function from the network is essentially governed by a single parameter R_{th}, which is the Thevenin equivalent resistance with respect to the thermistor terminals. The simple voltage divider circuit may thus be diminished to yield as linear response as any other one thermistor reciprocal network. The disadvantage of the divider circuit is that the slope and horizontal displacement of the output function of the divider cannot simply be controlled. Another circuit should be found to realize a convenient temperature transducer.

3. A DESIGN CRITERION OF A ONE THERMISTOR RECIPROCAL NETWORK.

The basic formula, relating the zero-power resistance of a thermistor to the temperature in $^{\circ}C$, is

$$R(T) = R_o \exp B\left(\frac{1}{T + T_{abs}} - \frac{1}{T_o + T_{abs}}\right) \tag{3.1}$$

where B is the material constant of the thermistor and R_o the zero-power resistance at temperature T_o. The temperature T_{abs} is $273.15^{\circ}C$. The material constant B increases slightly with increasing temperature. The formula (3.1) is the one obeyed by semiconductors, whose temperature dependence of resistivity can be assumed to arise from the thermal excitation of carriers over a single energy gap.

From the previous section we know that the output function of a one thermistor reciprocal network may be expressed as a linear function of a standard function

$$F(T) = \frac{R_{th}}{R_{th} + R(T)} \tag{3.2}$$

By inserting eq. (3.1) into (3.2) we obtain

$$F(T) = \frac{1}{1 + \frac{R_o}{R_{th}} \exp B\left(\frac{1}{T + T_{abs}} - \frac{1}{T_o + T_{abs}}\right)} \tag{3.3}$$

For any specified resistance ratio R_o/R_{th} and thermistor resistance ratio temperature characteristic the function F(T) describes an "S" shaped curve. By permitting the ratio R_o/R_{th} to assume a serie of constant values, an entire family of "S" shaped curves are generated. Five members of the family, viz. R_o/R_{th} = 2.00, 4.00, 8.00, 13.33, 25.00, are shown in the temperature range

-20^oC - $+180^oC$. The material constant of the thermistor is $B = 3500^oK$.

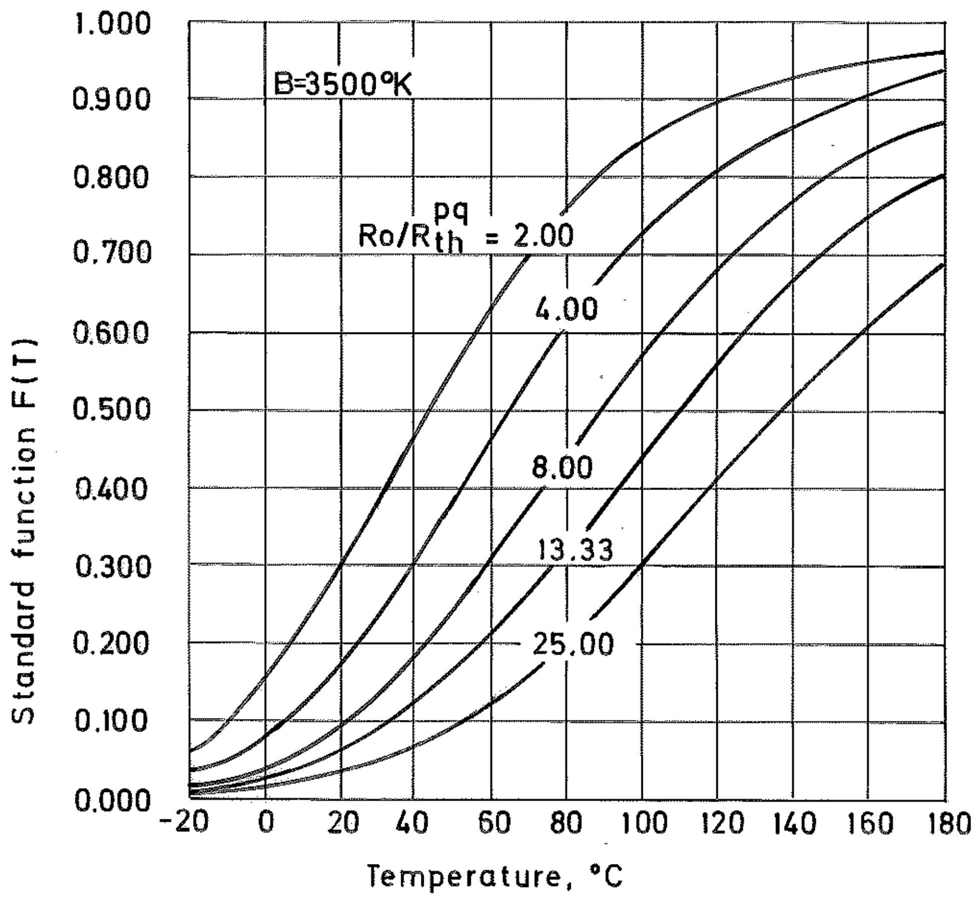

Fig. 3.1 - The standard function F(T) in the temperature range -20^oC - $+180^oC$.

Note, that the curves in Fig. 3.1 exhibit a long section of almost constant slope in the vicinity of the inflection point.

The criterion, proposed by the author, suggests that in a specified temperature range $T_1 \leq T \leq T_2$ the resistance R_{th} should be chosen so that equal output voltage increments are obtained in the ranges $T_1 \leq T \leq T_m$ and $T_m \leq T \leq T_2$. The temperature T_m denotes the mid point temperature. The criterion is referred to as the matched increment criterion and yields

$$R_{th} = \frac{R(T_1) - \frac{\Delta R_1}{\Delta R_2} R(T_2)}{\frac{\Delta R_1}{\Delta R_2} - 1} \tag{3.4}$$

where

$$\begin{cases} \Delta R_1 = R(T_1) - R(T_m) \\ \Delta R_2 = R(T_m) - R(T_2) \end{cases} \tag{3.5}$$

The criterion may be satisfied provided that

$$R(T_1) > \frac{\Delta R_1}{\Delta R_2} R(T_2) \tag{3.6}$$

For small temperature spans the proposed criterion yields an excellent linearity. The relative merits of the criterion are apparent in a situation, where any precise information about the thermistor resistance temperature characteristic is not available. The situation is the one often appearing in practice. Then a poor estimation of the optimal resistance R_{th} may be obtained whatever criterion is employed. Therefore it is of great importance, that the condition stated as optimal can be verified simply. The matched increment criterion satisfies this requirement as distinguished by the criteria mentioned in |1| and |2|. Further rules are readily found which yield the adjustment of the resistance R_{th} in a nonoptimal situation. This aspect is discussed in section 5.

4. AN IDEAL TEMPERATURE TRANSDUCER AND ITS LINEARITY ERROR.

There are a variety of networks, where a thermistor may be utilized for the purpose of temperature measurement. The network, which finds wide-spread use for precision temperature measurements, is the one thermistor Wheatstone bridge. The circuit (4.1) shows the bridge connected to a differential amplifier. The bridge voltage is E and the amplifier gain K.

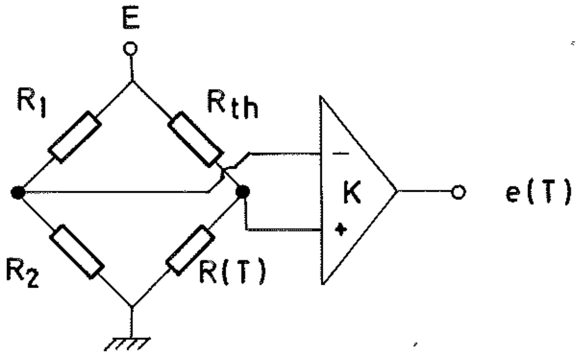

Fig. 4.1 - An idealized temperature transducer.

For the circuit of Fig. 4.1 the output function is given by

$$e(T) = \left(\frac{R_{th}}{R_{th} + R(T)} - \frac{R_1}{R_1 + R_2} \right) (-KE) \qquad (4.1)$$

and is thus a linear function of the standard function F(T). The horizontal displacement and the slope of the output function are simply given desired values by adjusting the bridge arms resistance ratio $R_1/(R_1 + R_2)$ and the product KE of the gain and the bridge voltage. The Thevenin equivalent resistance with respect to the thermistor terminals is R_{th}, i.e. the linearity of the transducer is determined by a single resistance.

In a case, where the transducer is balanced at the mid point temperature T_m and the output swing satisfies $-e_0 = e(T_1) = \leq e(T) \leq e(T_2) = e_0$, the ratio $R_1/(R_1 + R_2)$ and the product KE are

$$\begin{cases} \dfrac{R_1}{R_1 + R_2} = \dfrac{R_{th}}{R_{th} + R(T_m)} \\ KE = -\dfrac{1}{\Delta R_1} \left(1 + R(T_m)/R_{th}\right)\left(R_{th} + R(T_1)\right)e_0 = \\ \quad = -\dfrac{1}{\Delta R_2} \left(1 + R(T_m)/R_{th}\right)\left(R_{th} + R(T_2)\right)e_0 \end{cases} \tag{4.2}$$

where ΔR_1 and ΔR_2 are defined by eq. (3.5). The Thevenin resistance R_{th} is determined by eq. (3.4). The output function (4.1) may be written

$$e(T) = -\frac{R_{th} + R(T_1)}{\Delta R_1} \frac{\Delta R}{R_{th} + R(T)} e_0 = -\frac{R_{th} + R(T_2)}{\Delta R_2} \frac{\Delta R}{R_{th} + R(T)} e_0 \tag{4.3}$$

The difference ΔR is given by

$$\Delta R = R(T) - R(T_m) \tag{4.4}$$

In the formula above T_1 and T_2 denote the lower and upper end point temperatures respectively of the considered temperature range.

We now define the departure from linear response of the output function (4.3) by the expression

$$\Delta e = e(T) - \frac{T - T_m}{T_2 - T_1} e_0 \tag{4.5}$$

In table 4.1 the maximum linearity error given by the matched increment criterion appears for the temperature ranges 24°C - 26°C,

$20^oC - 30^oC$, $15^oC - 35^oC$, $0^oC - 50^oC$, and $0^oC - 100^oC$. The corresponding values of the set of parameters R_{th}, $R_1/(R_1 + R_2)$ and KE are presented. The table also shows the set, which minimizes the sum of the square of the expression (4.5) in 101 equidistantly situated points and the corresponding maximum linearity errors for the same temperature ranges. The voltage swing is 20 V. The thermistor characteristic is calculated from eq. (3.1), where

$$\begin{cases} R_0 = 2000\ \Omega \\ B = 3500^oK \end{cases} \tag{4.6}$$

Temp. range ^oC	Matched increment criterion R_{th} ohms	$\frac{R_1}{R_1+R_2}$	KE volts	max. lin. error %
24 - 26	1417.88	0.414842	-1046.41	0.003
20 - 30	1419.33	0.415090	- 209.89	0.06
15 - 35	1424.12	0.415908	- 105.90	0.3
0 - 50	1456.70	0.421413	- 45.42	2
0 -100	600.73	0.426881	- 29.95	4

Temp. range ^oC	Least square criterion R_{th} ohms	$\frac{R_1}{R_1+R_2}$	KE volts	max. lin. error %
24 - 26	1417.80	0.414829	-1046.37	0.003
20 - 30	1419.12	0.415054	- 209.64	0.06
15 - 35	1423.29	0.415764	- 105.38	0.3
0 - 50	1451.21	0.420371	- 43.70	2
0 -100	592.85	0.422861	- 27.71	4

Table 4.1 - The set of parameters R_{th}, $R_1/(R_1 + R_2)$, KE and the maximum linearity error, given by the matched increment criterion and the least square criterion at different temperature ranges.

The two criteria yield approximately the same maximum linearity errors in the considered temperature ranges. The table thus clearly demonstrates, that the linearity of the transducer is essentially governed by a single parameter, viz. the Thevenin equivalent resistance with respect to the thermistor terminals. The maximum linearity error increases as the temperature range is increased. At a temperature span of 30°C the linearity error still falls below 0.5%.

Thermistors can be supplied with the resistance of the units recorded at one or more specified points over a wide temperature range to within a very high accuracy. Thereby the set of parameters R_{th}, $R_1/(R_1 + R_2)$ and KE can be evaluated from eq. (3.4) and (4.2) for the specified voltage swing. The time consuming calibration procedure may be avoided. A complete solution to the problem of dataspreading is obtained by letting the sensor probe include the thermistor and the Wheatstone bridge. The transducer module should thus only comprise the amplifier. The thermistor and the bridge attached to it is exchanged as a new probe is inserted in the module.

5. DESIGN AND CALIBRATION OF A TEMPERATURE TRANSDUCER.

The temperature transducer discussed in section 4 is realized using a VECO 0.060" Glass Probe Thermistor, type 32A129. The unit has a nominal resistance of 2000 ohms and a temperature coefficient of -0.039/°C at 25°C. The considered temperature range is 20°C - 30°C. The output voltage swing is 10 V. The midpoint temperature corresponds to zero output voltage. The connection between the output voltage e(T) and the body temperature T of the thermistor should thus be

$$e(T) = 25 + T \qquad (5.1)$$

The complete schemes of the constructed transducer appear in Fig. 5.1 and 5.2.

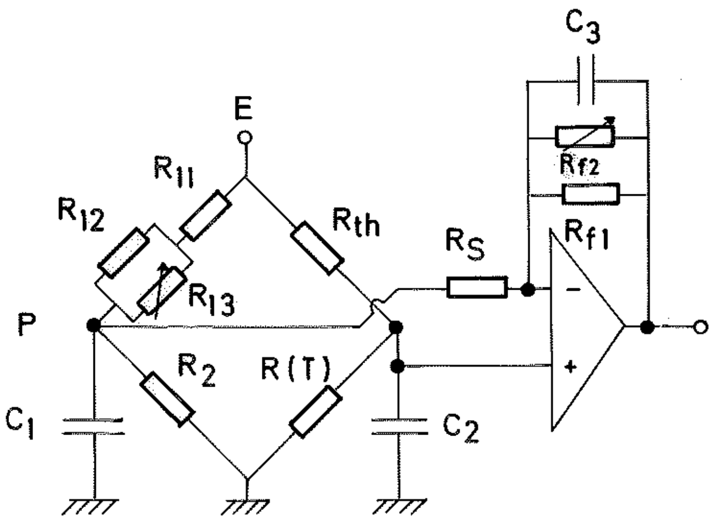

Fig. 5.1 - A realization of a temperature transducer.
Resistances; R_{11}= 150 Ω, R_{12}=500 Ω, R_2=500 Ω, R_S=500 Ω, R_{f1}=500 kΩ.
Potentiometers; R_{13}=200 Ω, R_{f2}=1MΩ.
Capacitors; C_1=500 pF, C_2=50pF, C_3=50pF.

The operational amplifier operates as a follower with gain. Thereby a neglectable loading effect is obtained on the bridge arms, comprising the resistances R_{th} and R(T). The bridge is balanced with the potentiometer R_{13}. The gain of the operational amplifier is controlled by the potentiometer R_{f2}. In order to improve the resolution the resistances R_{12} and R_{f1} are connected in parallel with the resistances R_{13} and R_{f2} respectively. The resistance R_s is merely introduced to simplify the offset adjustment of the amplifier. As the thermistor is removed the point P is automatically grounded and the offset adjustment can be performed with an internal potentiometer appearing in Fig. 5.2. The capacitors C_1, C_2, and C_3 are filter capacitors. The potentiometers are 22-turn cermet potentiometers. All resistances are metal film units. The bridge is fed by a stable zenerdiode reference voltage E. The magnitude of the voltage is limited by the self-heat of the thermistor. A current passing through the thermistor causes a self-heat ΔT, given by

$$\Delta T = P/\delta \qquad (5.1)$$

where P is the effect dissipated in the thermistor and δ the dissipation constant. The dissipation constant in still oil of the thermistor employed is

$$\delta = 2mW/^{o}C \qquad (5.2)$$

If a maximum self-heat of $0.01^{o}C$ is tolerated and the thermistor is immersed in still oil the bridge voltage should fulfil

$$E < 330\ mV$$

The bridge voltage is 306 mV.

The operational amplifier consists of an input stage and an integrated operational amplifier 809 CJ.

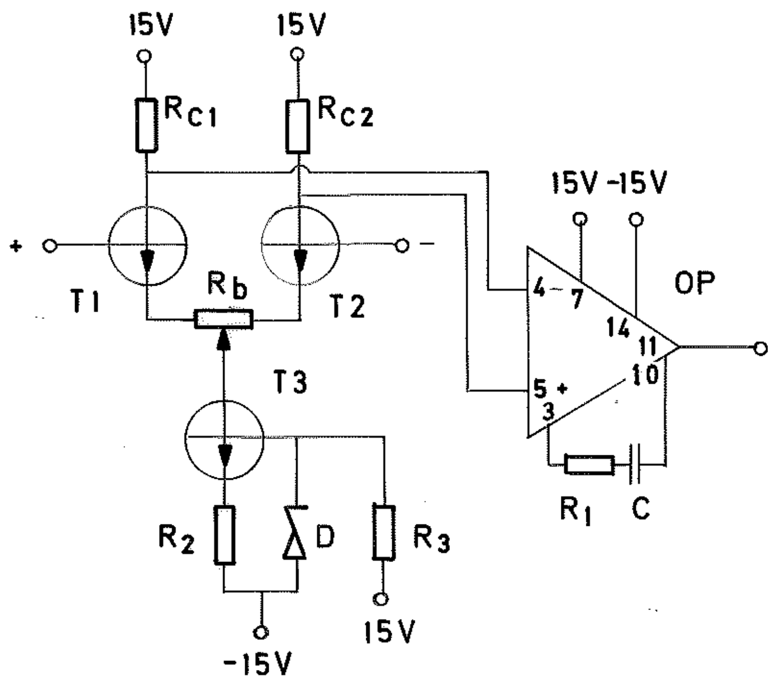

Fig. 5.2 - The operational amplifier of the transducer.
Operational amplifier; OP = Amelco 809 CJ.
Transistors; T_1, T_2 dual transistors SA 2769, T_3 = 2N1711
Diod; D = 1N747
Resistances; R_{c1}=220 kΩ, R_{c2}=220 kΩ, R_1=1.5 kΩ, R_2=68 kΩ
R_3=4.7 kΩ
Potentiometer; R_b=100 Ω.
Capacitor; C=500 pF.

The closely matched integrated dual transistors yield a low drift to the input stage. The constant current generator gives the amplifier a high input impedance and CMRR. The temperature coefficient of the base emitter voltage is partly compensated by the negative coefficient of the zenerdiode 1N747. The collector resistances of the dual transistors are 1% metal film units. The offset adjustment is performed with a 22-turn cermet trimpotentiometer R_b. The typical input offset voltage of the operational amplifier is 1 μV/°C.

The output voltage of the transducer equals

$$e(T) = \left(\frac{R_{th}}{R_{th} + R(T)} - \frac{R_1}{R_1 + R_2} - \frac{1}{K}\frac{R_2}{R_1 + R_2}\right)(- KE) \qquad (5.4)$$

where

$$\left\{\begin{aligned} R_1 &= R_{11} + \frac{R_{12}\ R_{13}}{R_{12} + R_{13}} \\ R_f &= \frac{R_{f1}\ R_{f2}}{R_{f1} + R_{f2}} \\ R_{in} &= R_s + \frac{R_1\ R_2}{R_1 + R_2} \\ K &= 1 + R_f/R_{in} \end{aligned}\right. \qquad (5.5)$$

The constant term in eq. (5.4) differs from the one of the ideal transducer by a term

$$\frac{1}{K}\frac{R_2}{R_1 + R_2}$$

The slightly different expression for the output function is caused by the feedback current in the real amplifier.

The calibration procedure has two purposes, viz. to set the potentiometers R_{13} and R_{f2} and check the value of the resistance R_{th}. In the considered case the potentiometers should be adjusted to yield the output voltages 0 V and -5 V at the temperatures 25°C and 20°C respectively. The potentiometer R_{13} must first be set. The calibration is checked by reading off the output voltage at 30°C. The voltage should be 5 V. If another value is red an appropriate adjustment ΔR_{th} of the resistance R_{th} may be found in Table 5.1.

The adjustment ΔR_{th} as a function of the output voltage e(30) may quite simply be developed from the formula given in section 4. The case which applies yields

$$\Delta R_{th} = R_{th} - \frac{5R(20) - \frac{\Delta R_1}{\Delta R_2} R(30)\, e(30)}{\frac{\Delta R_1}{\Delta R_2} e(30) - 5} \qquad (5.6)$$

e(30) volts	ΔR_{th} ohms	e(30) volts	ΔR_{th} ohms	e(30) volts	ΔR_{th} ohms
4.90	-330	4.97	- 92	5.04	115
4.91	-294	4.98	- 61	5.05	142
4.92	-258	4.99	- 30	5.06	169
4.93	-224	5.00	0	5.07	195
4.94	-190	5.01	30	5.08	221
4.95	-157	5.02	58	5.09	247
4.96	-124	5.03	87	5.10	272

Table 5.1 - The adjustment of the Thevenin resistance R_{th} at different output voltages e(30).

The resistance R_{th} should be increased, if the output voltage exceeds 5 V at 30°C and vice versa. The thermistor resistance temperature characteristic is the one earlier employed, i.e. R_0 = 2000 ohms, B = 3500°K. The calibration procedure provides, that a temperature controlled bath is available.

6. LONG TERM STABILITY OF A THERMISTOR AND MEASUREMENT RESULTS.

The basic cause for instability in a thermistor is due to changes in the electrical contact between the semiconductor and the thermistor leads. For this reason thermistors which have sintered in leads exhibit much better stability than those, which have metalized surface contacts. The used thermistor has sintered in leads. The change per year in the resistance R(25) is 0.05% or 1 ohm. The thermistor must not be exposed to any mechanical stresses and should be kept at room temperature.

Eleven temperature transducers are constructed. The output of the transducers are recorded as a function of the temperature. The thermistors are immersed in a temperature bath, whose temperature is varied from 20^{o}C to 30^{o}C with the temperature increment 0.50^{o}C. The measurement results are shown in Table 6.1. The relation between the output voltage and the body temperature of the thermistor should be the one given by eq. (5.1). If the departure from linear response is defined by eq. (4.5) we find, that the major part of the transducers have a linearity error falling below 0.01^{o}C in the considered temperature range, i.e. the linearity is better than 0.1%. The maximum error found in the table reaches 0.017^{o}C. Note, that the output function of the transducers describes the "S" shaped curve postulated in section 2. The mean drift per 12 hours of the eleven transducers are also registrated. The drift reaches 1 mV or 0.001^{o}C.

The bath temperature is measured by means of a mercury-in-glass calorimeter thermometer of accuracy 0.01^{o}C. Corrections are made for the stem exposure. The stability of the bath is 0.01^{o}C. The long term accuracy of the used digital voltmeter is ±0.01% of full scale and ±0.02% of reading.

As mentioned in the introduction the design of convenient measuring circuits for use with thermistor sensors is complicated by the nonlinear characteristic and the dataspreading of the thermistors. Tables 4.1 and 6.1 plainly show, that the first problem may be overcome for a fairly wide range of temperature by diminishing the transducer according to the matched increment criterion. The complete solution to the second problem is presented in section 4. The solution applies to the idealized amplifier, but is simply modified to include the constructed transducer.

Output function e(T)

Temp. °C	TR1 volts	TR2 volts	TR3 volts	TR4 volts	TR5 volts	TR6 volts	TR7 volts	TR8 volts	TR9 volts	TR10 volts	TR11 volts
20.00	-4.994	-4.996	-4.995	-4.992	-4.991	-4.993	-4.988	-4.993	-4.983	-4.997	-4.998
20.50	-4.505	-4.503	-4.507	-4.500	-4.502	-4.503	-4.498	-4.504	-4.491	-4.506	-4.508
21.00	-4.003	-4.002	-4.002	-4.000	-4.001	-4.002	-4.003	-4.007	-3.995	-4.005	-4.008
21.50	-3.506	-3.506	-3.506	-3.503	-3.504	-3.504	-3.501	-3.506	-3.497	-3.508	-3.507
22.00	-3.008	-3.006	-3.008	-3.005	-3.005	-3.006	-3.004	-3.011	-3.000	-3.007	-3.010
22.50	-2.509	-2.508	-2.510	-2.508	-2.509	-2.510	-2.507	-2.511	-2.502	-2.507	-2.512
23.00	-2.006	-2.006	-2.007	-2.006	-2.007	-2.008	-2.005	-2.009	-2.002	-2.006	-2.009
23.50	-1.504	-1.502	-1.503	-1.501	-1.504	-1.504	-1.503	-1.507	-1.500	-1.504	-1.506
24.00	-1.006	-1.005	-1.007	-1.005	-1.006	-1.006	-1.004	-1.008	-0.999	-1.005	-1.006
24.50	-0.508	-0.503	-0.502	-0.500	-0.505	-0.506	-0.504	-0.508	-0.498	-0.508	-0.506
25.00	-0.003	0.000	0.000	0.005	0.000	0.000	0.000	-0.003	0.005	0.003	0.001
25.50	0.497	0.504	0.503	0.505	0.508	0.507	0.506	0.508	0.509	0.503	0.509
26.00	0.993	1.000	1.000	1.000	0.996	0.993	0.992	0.991	1.002	0.999	0.994
26.50	1.492	1.495	1.495	1.500	1.493	1.492	1.490	1.490	1.502	1.499	1.492
27.00	1.993	1.998	1.998	2.001	1.995	1.994	1.990	1.990	1.998	1.996	1.990
27.50	2.490	2.498	2.498	2.499	2.495	2.497	2.493	2.496	2.507	2.499	2.501
28.00	2.997	3.003	3.003	3.008	3.003	3.001	2.996	2.999	3.006	2.999	3.000
28.50	3.502	3.508	3.510	3.514	3.510	3.508	3.500	3.506	3.512	3.504	3.508
29.00	3.993	4.000	4.002	4.009	4.003	4.000	3.997	4.000	4.008	3.989	4.001
29.50	4.497	4.497	4.498	4.501	4.500	4.497	4.493	4.494	4.504	4.492	4.500
30.00	4.999	4.996	5.000	5.000	5.002	5.000	4.990	4.998	5.004	4.995	4.994

Table 6.1 - The output function of the constructed transducers in the temperature range 20°C - 30°C.

7. REFERENCES.

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