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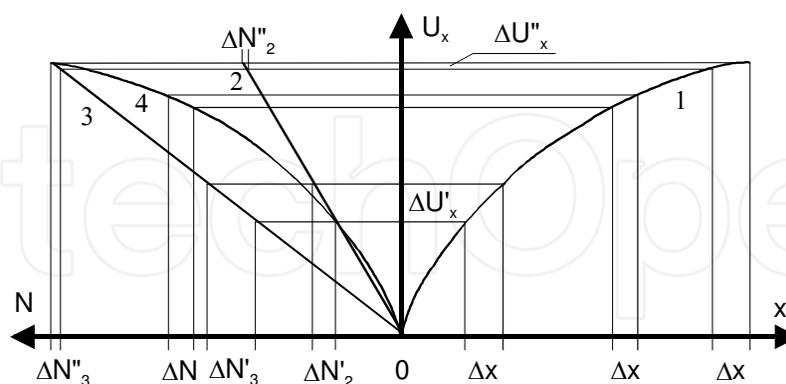
Approximation and Correction of Measuring Transducer's Characteristics

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1. Introduction

A very frequent case is that the characteristics of measuring transducers are non-linear and, apart from that, the output signal value may depend on several input values or unwanted influencing factors such as temperature, humidity etc. The need to adjust the form of information about the measured value to human perception possibilities, or to simplify the further processing of measurement information generally requires such adjusting of the slotted line element characteristics so that the resultant characteristics of the slotted line is linear, with assumed error, in the adopted coordinate system. (Bucci et al., 2000; Grzybowski @ Wagner, 1971; Iglesias @ Iglesias, 1988; Patranabis et al., 1988; Patranabis @ Ghosh, 1989)

When the measuring transducer's characteristics is very non-linear, for example in the case of certain transducers for light intensity measurement, a problem with selecting a relevant A/D transducer may occur. All methods of correcting measuring transducer's characteristics cannot eliminate the error related to insufficient A/D transducer resolution. That issue is illustrated by figure 1.



1. measuring transducer's characteristics
2. A/C transducer characteristics of small resolution
3. A/C transducer characteristics of high resolution
4. non-linear A/C transducer characteristics

Fig. 1. Impact of A/D transducer characteristics on resolution error.

At large non-linearity of the measuring transducer's characteristics (curve 1 on figure 3.5) and small inclination of A/D converter characteristics (line 2), the A/D converter resolution

is sufficient to process the voltage signal $\Delta U'_x$ to an appropriate digital code $\Delta N'_2$ in the area in which the inclination of measuring transducer's characteristics is high. On the other hand, in the area of small inclination of the measuring transducer's characteristics, the changes in output voltage $\Delta U''_x$ of the transducer are too small to be properly processed by the A/D converter to digital code $\Delta N''_2$. That problem may be partially bypassed using an A/D converter of high resolution (line 3). However, a better solution would be to adjust the processing characteristics of an A/D converter to the measuring transducer's characteristics (curve 4). The A/D converter characteristics should be described by a function reverse to the function describing the measuring transducer's characteristics and then the following linear relation would be obtained $\Delta N = c \Delta x$.

That chapter discusses issues related to the approximation of measuring transducer's characteristics and their correction in an analog to digital (A/D) converters. The thesis will consider only static characteristics of measuring transducers.

2. Transducers with successive compensation

The block diagram of a transducer with weight compensation is presented in figure 2.1.

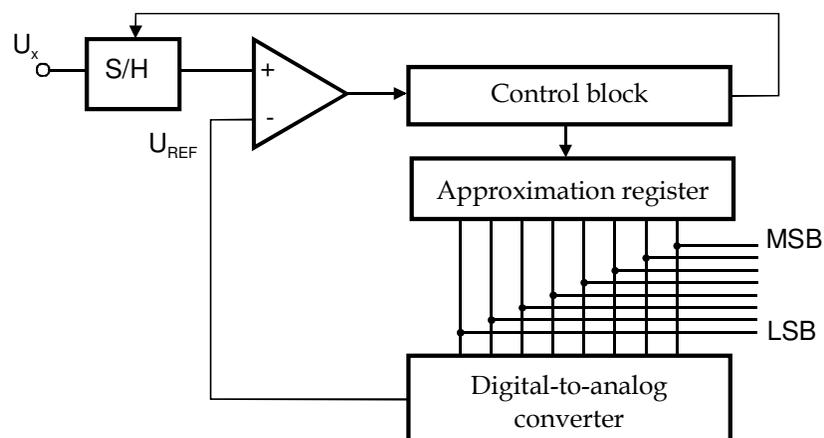


Fig. 2.1. General scheme of transducers with successive compensation.

It consists of a sample-and-hold circuit, a comparator, a digital-to-analog converter, an approximating register and a control circuit. The transducer's operating principle can be found in readily available literature.

In transducers with weight compensation, the only available element, through which the shape of a transducer processing characteristics may be influenced is the reference voltage U_{REF} . For that reason, the change of processing characteristics can be achieved by generating a non-linear reference voltage in relation to the digital output signal N :

$$U_{REF} = a \cdot g(N) \quad (1)$$

where: $g(\cdot)$ - measuring transducer's characteristics approximating function,
 a - proportionality coefficient.

The circuit of adjusting transducer processing characteristics with weight compensation by means of reference voltage generation method has been presented in figure 2.2.

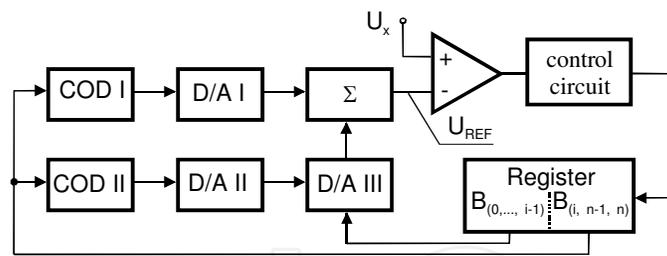


Fig. 2.2. Circuit of adjusting transducer processing characteristics.

Converter circuit consists of a comparator, a control circuit, a digital register and a reference voltage generator containing two coding circuits COD I and COD II, three digital-to-analog converters D/A I, D/A II and D/A III and an Σ adder. D/A III converter is required to have an input for external reference voltage U_{III} , thanks to which the multiplication function may be performed:

$$U_{III} = U_{0III} \cdot k_{III} N'' \tag{2}$$

where: k_{III} - processing coefficient of D/A converter III.

U_{III} - output voltage of C/A converter III

N'' - digital signal value controlling D/A converter III, dependent on bits $B_{i-1}, \div B_0$

That allows for an adequate change of the Δu value of voltage spike to one bit, and hence the change of inclination of the generated voltage characteristics. The measuring transducer's characteristics should be approximated by a range-linear function with the assumed error, figure 2.3 a), while the range points A_i, A_j, \dots should be selected so that their values meet directly, or with the proportionality coefficient, the values N_i, N_j, \dots of the A/C transducer output signal.

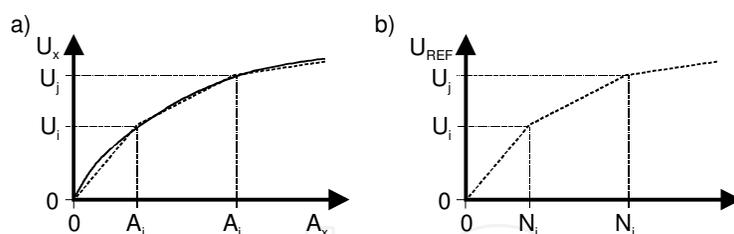


Fig. 2.3. a) Transducer characteristics and its approximation; b) waveform of reference voltage.

More significant bits ($B_{nv} \div B_i$) of the approximating register, through the coding circuit KOD I control the D/A converter I. The COD I circuit, which may be ROM memory, contains a board converting the signal value from the register to such a signal value controlling the D/A converter, as to ensure proper processing characteristics, figure 2.3 b).

The transducer converting process is conducted in the same way as for a linear transducer, figure 2.4, i.e. bits are issued one after another, starting from the most significant. When voltage from the generator exceeds the value of the voltage processed recently, the preset bit is withdrawn and another bit is incorporated. Testing all the more significant bits $B_{nv} \div B_i$ means that a specified approximation range has been selected, in which the processed input signal is located (status of bits $B_{nv} \div B_i$ provides the values N_i, N_j). Appropriate inclination of the characteristics required for a given approximation range is received by changing the reference voltage of D/A converter III. The value of that voltage is obtained from D/A

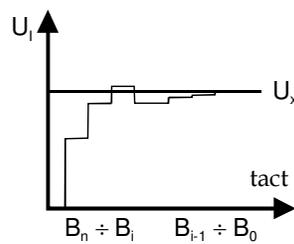


Fig. 2.4. Waveform of voltage generated in the generator circuit.

converter II controlled by bits $B_n \div B_i$, through the CODII circuit. Hence, after setting a set of bits $B_n \div B_i$ relevant to the input voltage by the approximating register, further converting process takes place, during which the less significant bits ($B_{i-1} \div B_0$) control the D/A converter III which already has properly selected inclination of the characteristics.

Beginning of the range voltage values are obtained from D/A converter I and the values of voltages in particular ranges by adding voltage value from D/A converter I with voltage from D/A converter III. Output voltages of converter s C/A I, C/A II and C/A III for i -th range are respectively:

$$U_{II} = k_I \gamma_I(N') \quad (3)$$

$$U_{III} = k_{II} \gamma_{II}(N') \quad (4)$$

$$U_{III} = k_{III} U_{II} k(N'') \quad (5)$$

where: γ_I - coefficient value received from cell of memory COD I with address N' .
 k_I - coefficient values of transducer processing.
 γ_{II} - coefficient value received from cell of memory COD II of address N' .
 N' - more significant part of number N of control circuit (bits $B_n \div B_i$).
 N'' - less significant part of number N of control circuit (bits $B_{i-1} \div B_0$).

After summing up voltages from converters D/A in the adder, U_{REF} voltage is obtained, defined by the relation:

$$U_{REF} = k_I \gamma_I(N') + k_{II} \gamma_{II}(N') k N'' \quad (6)$$

The manner of adjusting A/D converter processing characteristics with weight compensation described above requires that the linearized measuring transducer's characteristics is approximated by a range-linear function. Therefore, designing the circuit should be started by determining the approximating function with the assumed error. However, in order not to complicate the shaping circuit, the lengths of approximation ranges should be equal.

The additional errors, which may be introduced by the shaping circuit, are errors mainly from the D/A converter I, especially the linearity error, and the adder. The errors of other transducers have a smaller impact since the values of voltages generated by them are smaller than the voltage from D/A converter I.

The above-mentioned shaping circuit, in a simplified configuration, was completed in a universal temperature meter cooperating with transducers Pt-100, Pt-1000, Ni-100, PtRh-Pt, NiCr-NiAl, Fe-CuNi. The simplified scheme of the meter which allows explanation of its

operating principle is presented in figure 2.5. Input circuits containing resistance to voltage transducers and amplifiers have been omitted here.

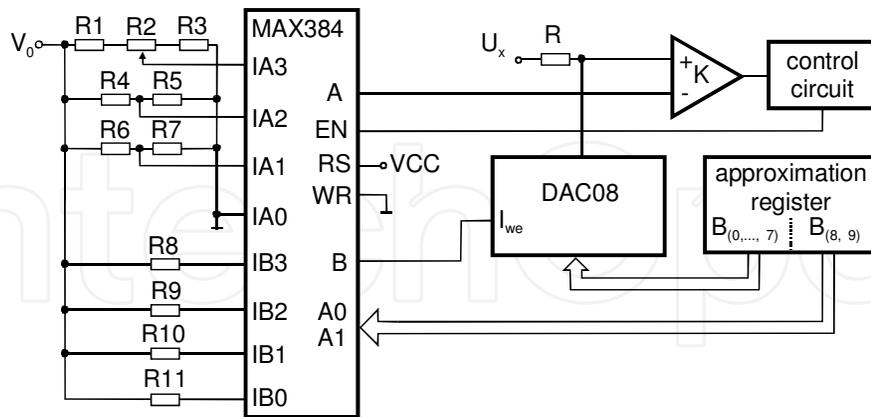


Fig. 2.5. Simplified scheme of a temperature meter.

Because the assumptions require that the absolute error of temperature measurement, submitted by the meter, to be within 1 °C for platinum transducers, 2 °C for nickel transducer and 5 °C for thermocouples, the characteristics of those transducers could be approximated by four sections. Thus, in the place of D/A converter I and the circuit COD I, a voltage generator, containing dividers R1 - R7 and half of analog selector MAX384, has been used. The DAC08 circuit has been used as a C/A III converter. That is a digital-to-analog converter with current output whose inclination of characteristics can be selected by changing the current input I_{IN} . The current can be changed through selecting, in the second part of the analog selector, one of resistors R8 - R11. For each measuring transducer, a separate module containing the selector along with dividers of voltages and current resistors was intended. Module selection was done by specifying the signal for input EN.

Converter circuit operates like an ordinary converter with successive approximation, with addition that in the first four timings (bits B_9 and B_8), the approximation range is determined, where the U_x voltage is located. The voltage from the generator, supplied to K comparator's reversing input, has the beginning of the approximation range value. The value of DAC08 transducer input current is also determined for the selected approximation range. In the other processing timings, the less significant bits are activated ($B_7 - B_0$) and, through voltage drop on resistor R caused by DAC08 transducer current output, the exact definition of U_x voltage value takes place. The status of bits $B_9 - B_0$ directly provides the value of measured temperature.

The conducted meter measurements indicated that it meets the parameters adopted in the assumptions concerning ambient temperatures 5 - 35 °C. Processing time was 2.5 ms.

Short converter processing time with successive approximation was used in the meter to measure carbon monoxide concentration. The TGS 2444 measuring transducer manufactured by Figaro USA Inc was used in the meter. In that transducer, the value of carbon monoxide concentration is processed into resistance. The measuring range is within 30 to 1000 ppm. Transducer characteristics has been presented in figure 2.6. It presents relative changes of output resistance, related to nominal resistance. Nominal resistance is given for concentration 100 ppm and ranges from 13.3 kΩ to 133 kΩ. In applied transducer the nominal resistance was 15.2 kΩ.

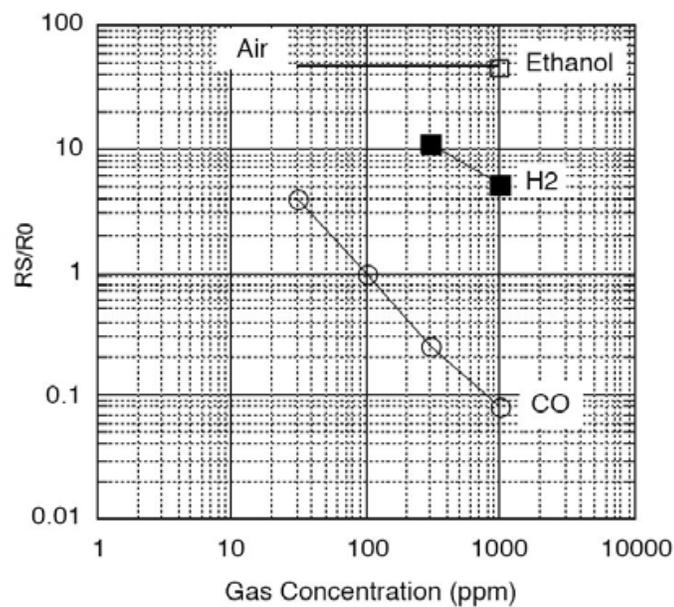


Fig. 2.6. Static characteristics of transducer TGS2442.

Transducer characteristics, presented in figure 2.6, shows a great change of inclination. For 30 ppm, the inclination is $-1,52 \text{ k}\Omega/\text{ppm}$ and for 1000 ppm $-1,26 \text{ }\Omega/\text{ppm}$ (TGS 2611). With such high non-linearity of the measuring transducer's characteristics, using an A/C transducer with influenced processing characteristics is beneficial.

Because the meter was expected to be a portable device with battery power supply, a microcontroller MSP430F435 equipped with an LCD field direct control module was used in it. There is an A/C transducer with weight compensation with resolution of 12 bits and processing frequency of up to 200 kHz within the internal structure of the micro-controller.

Calculations proved that the resolution of that transducer is too small to receive a proper resolution of measurement for high gas concentrations. Therefore, a circuit capable of adjusting transducer processing characteristics needed to be used.

The value of the digital A/D converter output signal is specified by the relation:

$$N = 4095 \frac{U_x}{U_{REF}} \quad (7)$$

The reference voltage U_{REF} is accessible from the outside, which enables manipulation of transducer processing characteristics. The simplified scheme of the meter has been presented in figure 2.7. The device consists of a microcontroller MSP430F435 manufactured by Texas Instruments, an LCD field controlled directly from the microcontroller, a double D/A converter, an RS measuring transducer, highly stable resistors R1, R2 and R3, a heating circuit (elements T2 and R4), a circuit of switching on the measurement resistor (elements T1 and R5) and elements related to power supply and keyboard not shown in the figure.

The measuring transducer requires relevant control, which entail cyclic switching on the R_h heater and in the appropriate phase, switching on the RS measurement resistor, figure 2.8.

Proper operation of a measuring transducer requires that the heating is switched on for 14 ms and, after 981 ms from turning the heating off, the measurement resistor's power supply

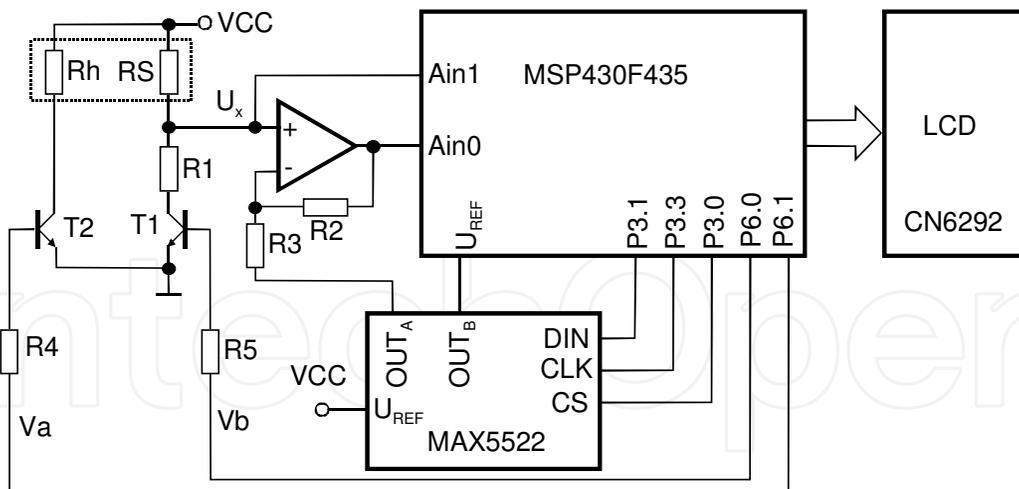


Fig. 2.7. Scheme of A/C transducer characteristics matching circuit.

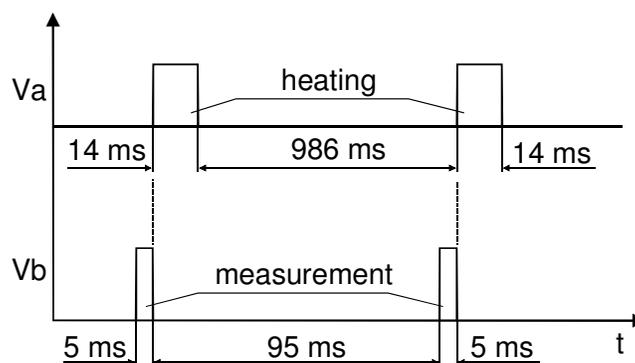


Fig. 2.8. Signals controlling measuring transducer.

is switched on. The measurement resistor activation time is to last 5 ms and the measurement should be taken during that period.

The RS measuring transducer is connected with resistor R1 in a divider circuit, which enables changing the measuring transducer's resistance to a voltage corresponding to it. Output voltage from the divider, after strengthening x6 in the amplifier, is supplied to A/D converter input. VCC voltage value was adopted as 3.3V (voltage supplying the microcontroller). The value of resistor R1 has been selected to obtain the broadest range of voltage changes U_x . Calculations, which have been omitted here, provided the value of 10 kΩ, which provides the range of voltage changes from 0.47 V to 2 V. The chart of relation between gas concentration s and U_x voltage value has been presented in figure 2.9.

The function presented in figure 2.9 is approximated by a range-linear function. With approximation error not exceeding 0.1%, 8 approximating sections were sufficient for approximation. However, the approximating function does not need to be continuous on range endpoints. The values of range points and coefficients k_i of section inclination in particular ranges have been presented in figure 2.10

Inclination coefficients k_i are determined by the relation:

$$k_i = \frac{s_{P_{i+1}} - s_{P_i}}{U_{P_{i+1}} - U_{P_i}} \quad (8)$$

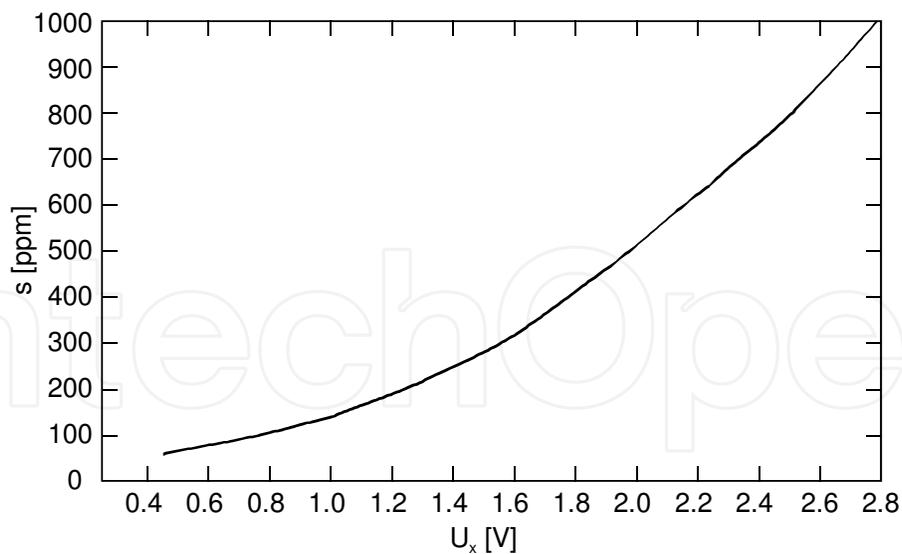


Fig. 2.9. Relation between gas concentration s and U_x voltage value.

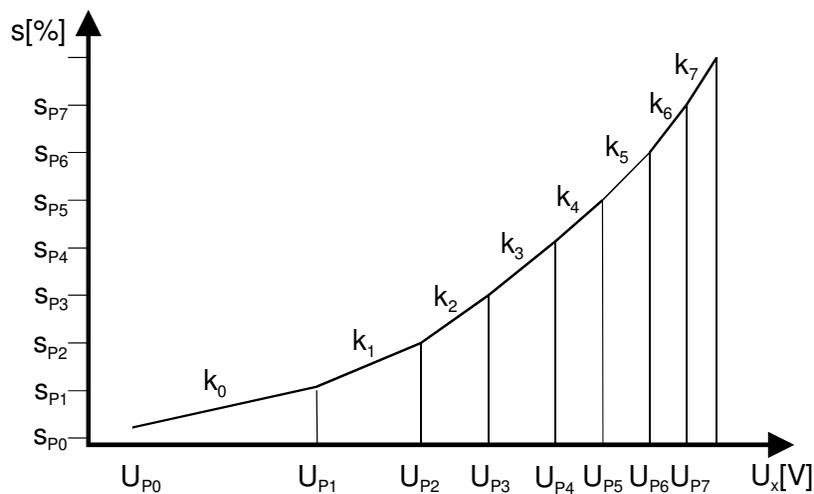


Fig. 2.10. Approximation by range-linear function.

The measurement takes place in two phases. In the first phase, input An1 is active and the initial voltage measurement U_x takes place on the divider output. In that phase, the reference voltage for an A/C transducer is the micro-controller internal voltage. That measurement provides information in which range voltage U_x is located. Then, for a given range, voltage U_{oi} is generated from D/A converter output A for the amplifier. The value of that voltage is selected so that for the value $U_x = U_{Pi}$, the voltage on amplifier output is equal to zero. At the same time, from the transducer output B, a reference voltage U_{REF} is generated for A/D converter. The value of that voltage should allow to obtain a satisfactory measurement resolution in a given range.

The voltage on output B of D/A converter is set proportionally to inclination coefficient value k_i . Such proceeding stems from the fact that the measurement value in i -th range is specified by the relation:

$$s = s_{Pi} + k_i(U_x - U_{Pi}) \quad (9)$$

The value of voltage difference $U_x = U_{Pi}$, after processing in A/D converter, can be specified using the formulation (7):

$$U_x - U_{Pi} = \frac{N_{xi} \times U_{REF}}{4095 \times k} \quad (10)$$

where: k - amplifier gain

N_{xi} - value of processing result in i -th range.

Thus:

$$s = s_{Pi} + \frac{k_i \times N_{xi} \times U_{REF}}{4095 \times k} = s_{Pi} + \Delta s_i \quad (11)$$

If we assume that a linear relation has to be met:

$$\Delta s_i = c N_{xi} \quad (12)$$

then the reference voltage should meet the condition:

$$U_{REF} = \frac{4095 \times c \times k}{k_i} \quad (13)$$

Meeting the aforementioned condition may be difficult owing to a limited range of changes in reference voltage. In that particular case, in accordance with catalogue data, the minimum value of that voltage cannot be smaller than 1.4 V, and the maximum may not be greater than $VCC - 0.2$ V. For that reason, it has been assumed that the reference voltage value should ensure the required measurement resolution:

$$U_{REF} \leq \frac{4095 \times c \times k}{k_i} \quad (14)$$

The final measurement is calculated using the formulation (11). The shaping circuit introduces two kinds of errors. The first is connected with the approximation of the measuring transducer's characteristics by a range-linear function. It stems from the possible finite values of coefficients k_i and threshold voltages U_{Pi} , what is caused by their values being generated by converter D/A. The fact that the approximating sections do not have to be continuous in range points, facilitates approximation.

The second type of errors stems from the accuracy of generating the U_{REF} voltage and errors of A/D converter. D/A converters are 10-bit converters with errors: linearity - 1 LSB, offset - 1 mV, characteristics inclination - 0.5 LSB. Those errors will have the greatest impact at endpoints of the range, where there is greatest inclination of measuring transducer's characteristics. Taking into account the above values, it has been calculated from formulation (11) that the maximum absolute error Δs should not exceed the value of 8 ppm. The conducted simulation research, in which the measuring transducer was replaced with a resistance decade, indicated that the relative measuring error d , (referred to the endpoint of the measuring range) in the whole measuring range did not exceed the value of 0.7%, figure 2.11.

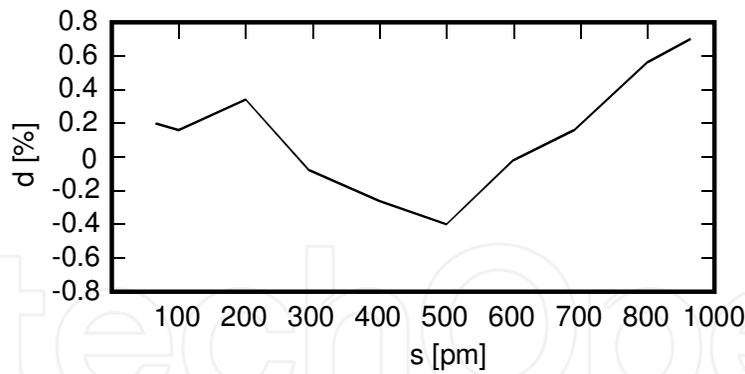


Fig. 2.11. Chart of relative error of carbon monoxide concentration meter.

3. Dual slope converters

Dual slope analog-to-digital converters are very popular owing to their simple structure, high reliability, high resolution, high processing accuracy and were one of the first to be integrated. They are mainly intended for measuring constant voltages and most often cooperate with different kinds of measuring transducers.

The block diagram of a double integral converter has been presented in figure 3.1 and the waveforms in particular points of the transducer circuit in figure 3.2.

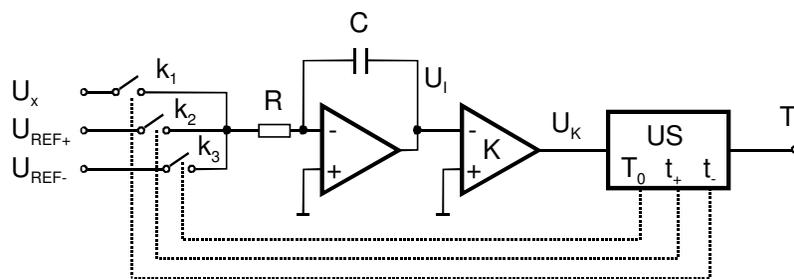


Fig. 3.1. Block diagram of double integral converter.

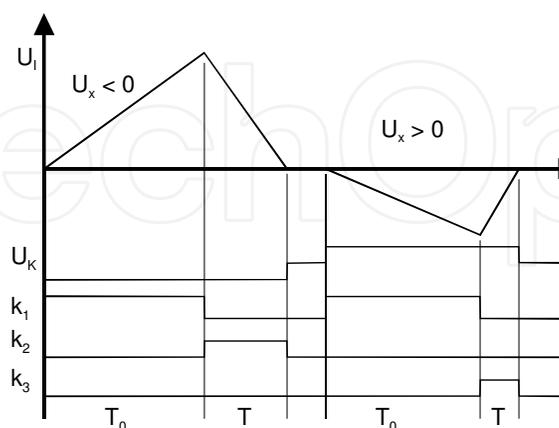


Fig. 3.2. Waveforms in particular points of double integral converter.

The converting process takes place in two phases. In the first phase, which lasts a given time T_0 , the processed voltage U_x is connected to the integrator's input through key k_1 . Then, after time T_0 , voltage U_x is disconnected and reference voltage with polarization opposite to the

polarization of voltage U_x is connected to the integrator's input. The level of voltage U_K at the comparator output indicates the polarity of the processed voltage U_x . Reference voltage integration lasts until the moment when voltage U_I at the integrator's output returns to the initial state which will result in activation of comparator K. Time T of reference voltage integration determines the result of processing.

Assuming the ideal integrator and comparator operation, voltage U_I at the integrator's output is defined by the relation:

$$U_I = \frac{1}{\tau} \int_0^{T_0} U_x dt - \frac{1}{\tau} \int_{T_0}^{T_0+T} U_{REF}(t) dt = 0 \tag{15}$$

where: $\tau = RC$ - integrator time constant

If voltage U_x is constant over processing, then relation (15) gives the following:

$$U_x = \frac{1}{T_0} \int_0^T U_{REF}(t) dt \tag{16}$$

Voltage U_{REF} also has a constant value in a transducer with linear processing and then:

$$U_x = U_{REF} \frac{T}{T_0} \tag{17}$$

Double integral converters typically have a resolution limited to about 13 - 14 bits. It stems from the fact that, with an increasing transducer resolution, the comparator must differentiate between increasingly smaller voltages at the integrator's output. The consequence is the extension of the comparator's response time and its unstable operation. In addition, the presence of noise, interference, hysteresis of the comparator and its insensibility threshold results in the fact that minimum voltage distinguished by the comparator is limited. Increasing transducer resolution, at the same time of voltage integration, would require increasing the clock generator's signal frequency. The above-mentioned factors would lead to transducer's unstable operation.

The need to increase transducer resolution to 16 - 18 bits resulted in preparing a modified double integral transducer circuit whose scheme has been presented in figure 3.3 and the waveforms of signals in selected points of the circuit - in figure 3.4.

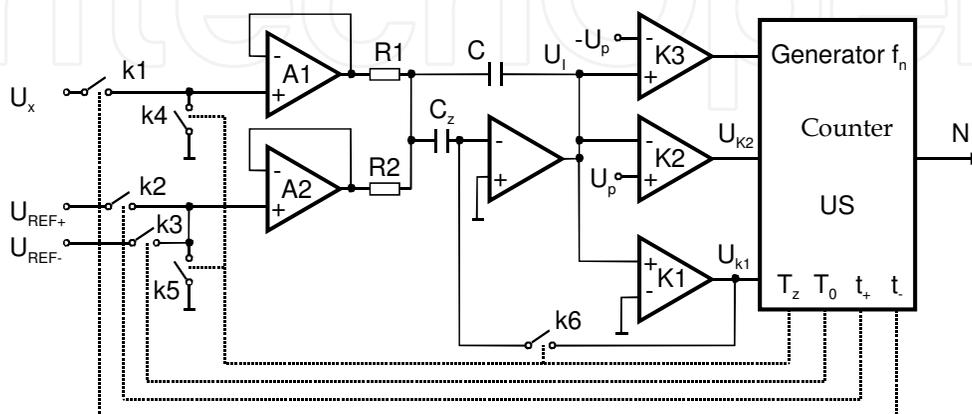


Fig. 3.3. Modified integrating transducer circuit.

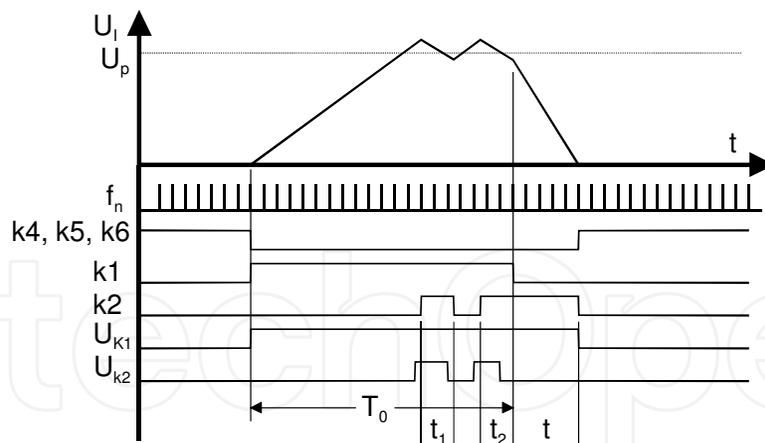


Fig. 3.4. Waveforms of signals in selected points of transducer circuit.

In comparison to the basic circuit of double integral converter, the circuit presented in figure 3.3 has been expanded with two input buffers, two additional comparators and elements allowing cyclical zeroing of the transducer circuit. The control circuit has also been changed.

The modified transducer circuit operates in the following manner: first, zeroing of the set integrator – comparator K1 takes place. That takes place when keys k4, k5 and k6 are closed. Other keys are open. Over that period, the integrator and the comparator K1 are enclosed by the feedback loop and the voltage on the integrator's reversing input reaches the value of that amplifier's offset voltage. Because the inputs of buffering amplifiers are also dense to the mass, the difference of offset voltages of input amplifier and the integrator amplifier is depositing on capacitor C_z . That voltage is remembered on the capacitor at all times throughout the process of converting. As a result, the impact of all amplifiers' offset voltage is disposed.

During integration of the processed input voltage U_x which lasts for T_0 , when voltage U_I at integrator's output exceeds the value of voltage U_p , which is the reference voltage for the comparator. Then the comparator activates, which, in turn, causes such action of the control circuit US that, synchronically with impulse f_n of the clock generator switching on takes place - respectively to polarization of the processed voltage - of key k2 or k3 supplying the reference voltage with polarization opposite to the polarization of the processed voltage to the integrator's input. It is summed up together with the processed voltage. Under the influence of the reference voltage, the voltage at the integrator's output reduces its value. If the value of that voltage falls below voltage U_p of the comparator, a change of the comparator's condition takes place and, as a consequence, the control circuit will turn off the reference voltage key again synchronically with the clocking impulse. If the value of the processed voltage is high, that process may be repeated several times. For that converter to operate properly, the absolute value of reference voltage should be greater or at least equal to the absolute value of processed voltage. After the period T_0 , the reference voltage is switched on, as in a regular double integral converter.

Because the voltage at the integrator's output returns to the initial state after the period of processing, that proves that the charge supplied from the processed U_x voltage source and the reference U_{REF} voltage source are of equal value. Therefore, an appropriate equality can be written:

$$\frac{1}{R1C} \int_0^{T_0} U_x(t) dt = \frac{1}{R2C} \left(\sum_{i=1}^k \int_0^{t_i} U_{REF}(t) dt + \int_0^t U_{REF}(t) dt \right) \quad (18)$$

If we assume that $R1=R2$ and the processed voltage value is constant during integration, the following is obtained:

$$U_x T_0 = \int_0^T U_{REF}(t) dt \quad (19)$$

where: T - total time of reference U_{REF} voltage integration.

The processing method has changed in the aforementioned transducer, but function (19) describing the relations occurring in it, is the same as function (16) for dual slope converter.

From the point of view of adjusting processing characteristics of A/D double integral converter, the relation (16) is important, which indicates the process of reference U_{REF} voltage integration. That means that using a generator generating an appropriate waveform of reference voltage will enable obtaining a desired A/D converter characteristics, (Janiczek, 1993).

In the transducer circuit presented in figure 3.5, the set of integrator, comparator, time constant and RC keys remains unchanged. On the other hand, the reference voltage generator - correction voltage, consists of an adder containing an operational amplifier, a D/A converter and EPROM memory. The meter block along with the control block US and the generator block f_n , form a circuit generating signals controlling keys k_1 and k_2 . In addition, more significant bits of the meter block are at the same time control signals for address inputs of the EPROM memory. When the second phase of double integral converter operation starts - the phase of reference voltage integration U_o , through closed key k_2 , reference voltage U_o is applied to the integrator's input. The voltage is the sum of (with appropriate coefficients specified by resistors $R2$, $R3$ and $R4$), constant voltage U_{REF} and voltage generated by C/A transducer, controlled by signals from the EPROM memory. Signals from the meter, controlling the EPROM memory, in selected time moments t_0, t_1, \dots, t_n result in sending relevant codes controlling the C/A transducer from the memory, which

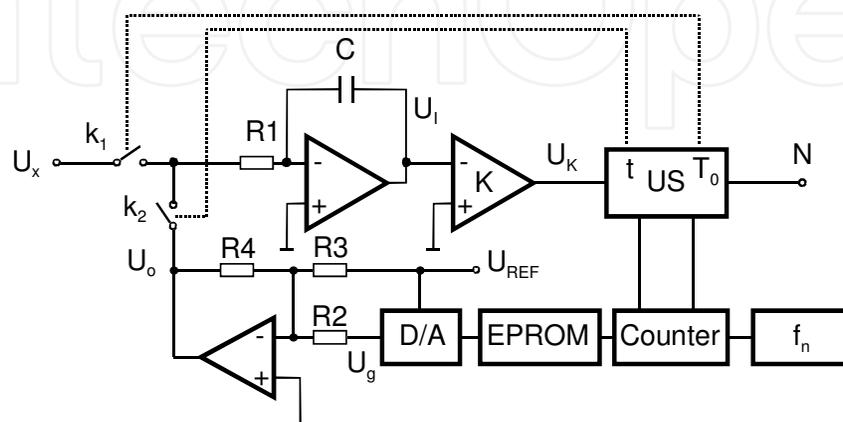


Fig. 3.5. Block diagram of transducer with adjusted characteristics.

results in generating the assumed reference voltage. A sample waveform of reference voltage U_o has been presented in figure 3.6.

Stepped reference voltage, integrated in the second phase of double integral converter operation, gives, as a result, the voltage at the integrator's output described by a range-linear function. The voltage waveform at the integrator's output during processing has been presented in figure 3.7. Time T_0 is the time of the processed voltage integration.

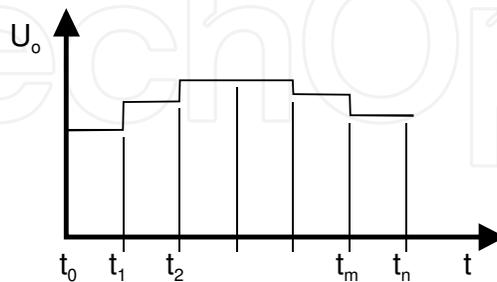


Fig. 3.6. Sample waveform of reference voltage.

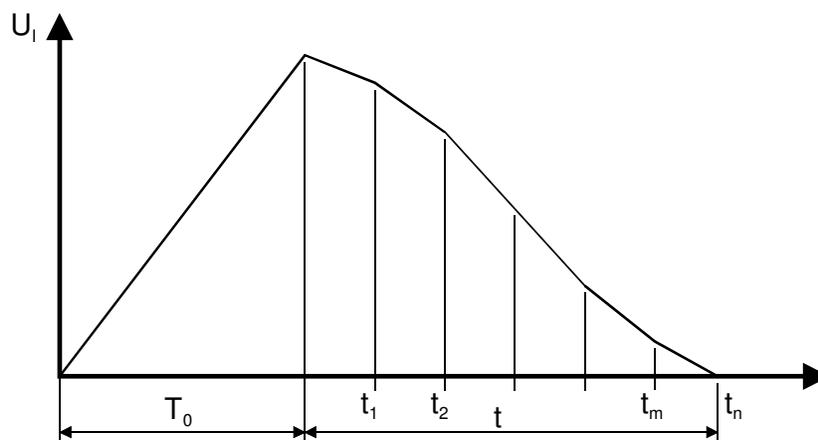


Fig. 3.7. Voltage waveform at integrator's output of double integral converter.

Taking into account that $U_{REF} = U_o$ in the formulation (16), the following is obtained:

$$U_x = \frac{1}{T_0} \left(\sum_{i=0}^{m-1} \int_{t_i}^{t_{i+1}} U_{oi} dt + \int_{t_m}^t U_{om} dt \right) \quad (20)$$

where: U_{oi} - reference voltage in the $t_i - t_{i+1}$ time interval
 t - moment of completion of reference voltage integration phase.

After integration, the relation is obtained:

$$U_x = \frac{1}{T_0} \left(\sum_{i=0}^{m-1} U_{oi} (t_{i+1} - t_i) + U_{om} (t - t_m) \right) \quad (21)$$

Since time slices $t_i - t_{i+1}$ are the same throughout the entire reference voltage generating time and amount to Δt , and the integration time t of reference voltage ends in moment t_n , the formulation (21) can be presented in the following form:

$$U_x = \frac{1}{T_0} \left(\sum_{i=0}^{m-1} U_{oi} \times \Delta t + U_{om} \times \Delta t_n \right) \quad (22)$$

The formulation (22) is a record of a range-linear function in which Δt determines the range length, U_{oi} – inclination of function in i -th range. Because time slices T_0 and Δt are determined in the transducer by dividing frequency f_n of the clock generator, then, taking account that :

$$T_0 = \frac{k}{f_n} \quad \Delta t = \frac{p}{f_n} \quad t = \frac{N}{f_n} \quad t = m \times \Delta t + \Delta t_n \quad (23)$$

the formulation (22) can be presented in the following form:

$$U_x \times k = p \times \sum_{i=0}^{m-1} U_{oi} + U_{om} \times (N - m \times p) \quad (24)$$

where: N – value of input signal processing result.

Taking into consideration that the reference voltage is equal:

$$U_o = R4 \times \left(\frac{U_{REF}}{R3} + \frac{U_g}{R2} \right) \quad (25)$$

the formulation (24) takes the form:

$$U_x \times k = \frac{R4}{R3} U_{REF} (N - p) + \frac{R4}{R2} \left(p \sum_{i=0}^{m-1} U_{gi} + U_{gm} (N - m \times p) \right) \quad (26)$$

Because, as it seems from the above-mentioned formulations, the function describing the output signal on the integrator in the phase of reference voltage integration is a range-linear function, the measuring transducer's characteristics should also be approximated by a range-linear function:

$$U(x) = \sum_{i=0}^{m-1} \alpha_i \times (x_i - x_{i+1}) + \alpha_m (x - x_m) \quad (27)$$

where: α_i – coefficients of section inclination in i -th range
 x_i – range points

Formulations (24) and (27) lead to believe that to obtain a linear relation:

$$N = c \times x \quad (28)$$

the condition must be fulfilled:

$$p \cdot U_{oi} = c \cdot k \cdot \alpha_i \cdot \Delta x \quad (29)$$

where: Δx – range length.

Range-linear function inclination coefficients obtained from the generator of function containing the C/A transducer, have finite values with discretization corresponding to D/A

converter's output signal resolution. That fact should be considered when calculating the function approximating the measuring transducer's characteristics. In addition, the number of values that the approximating function coefficients can have is equal to the number of values generated by the D/A converter. In addition, due to simplicity of the shaping circuit's structure, the approximation ranges should have the same length, and, if possible, the number of ranges should be the power of number 2.

The range of changes in coefficient values of approximating sections' inclination is determined by the following relation:

$$\alpha = R4 \left(\frac{U_{REF}}{R3} + \frac{U_g}{R2} \right) \quad (30)$$

From formulations (17) and (23), it seems that accuracy of double integral converter depends on the reference voltage stability. Therefore, also in the transducer with adjusted characteristics, the processing accuracy will depend on voltage generation accuracy U_o , with the assumption that the approximation error of the measuring transducer's characteristics by a range-linear function is negligibly small.

The formulation (30) shows that maintaining the assumed coefficient α accuracy depends on the stability of resistors R2, R3, R4 and voltage U_{REF} as well as on the accuracy of generating voltage U_g by D/A converter. The currently available parameters of resistors and sources of reference voltages are such that their impact on the accuracy of coefficients α may be omitted. Thus, the main source of errors will be D/A converter's errors.

The most important D/A converter's errors which should be factored in when determining the generated reference voltage accuracy include: characteristics linearity error, characteristics inclination change error and zero drift. D/A converter characteristics zero drift reduction as well as other analog blocks of slotted line can be performed by means of cyclical zeroing of the slotted line.

The method of adjusting transducer processing characteristics described above is one of the most effective, especially for converters of high non-linearity. An example may be the methane concentration meter with a measuring transducer TGS 22611 E00 manufactured by Figaro USA Inc. (TGS 2611). That is a resistance transducer and it measures methane concentration ranging from 300 ppm to 10000 ppm. Its characteristics, determining the relation of output resistance R_s to reference resistance R_o depending on methane concentration has been presented in figure 3.8. Resistance R_o , defined at concentration 5000 ppm, depending on a specific transducer may vary from 0.68 k Ω to 6.8 k Ω . The transducer used in the described meter, had 1.2 k Ω . Thus, transducer output resistance changes were ranging from 0.9 k Ω to 3.6 k Ω .

The currently available integrated A/D converters do not provide the feature of adjusting their processing characteristics. That is why analog elements that can be found in microcontroller internal structures were used in the structure. The MSP430FG4618 microcontroller manufactured by Texas Instruments was used in the meter for measuring methane concentration. Its structure contains three operational amplifiers, a 12-bit D/A converter, resistors and a set of analog switches. The circuit of dual slope converter, containing those elements, has been presented in figure 3.9.

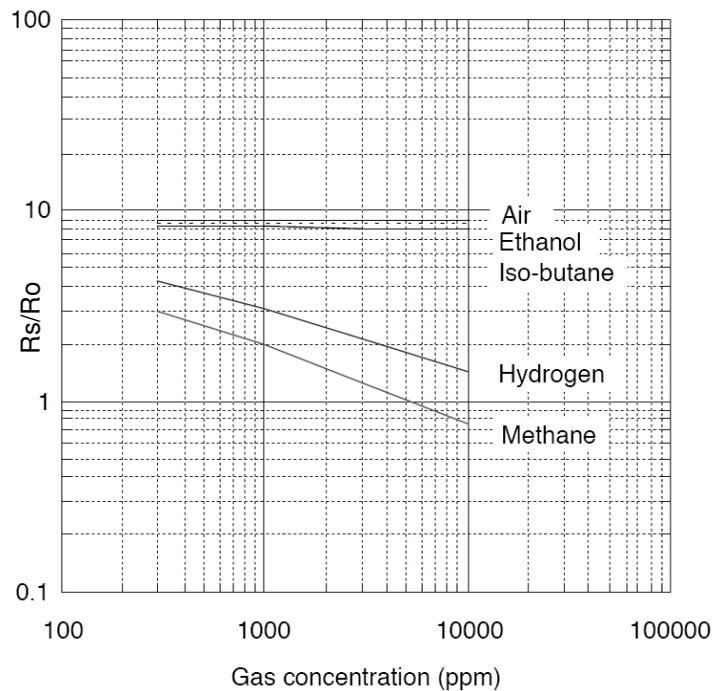


Fig. 3.8. Characteristics of transducer for measuring methane concentration.

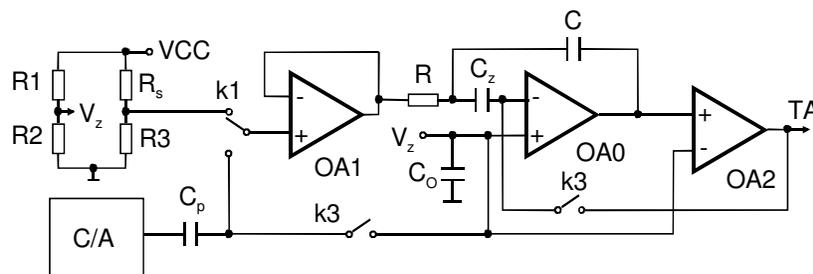


Fig. 3.9. Scheme of dual slope converter.

The integrator with amplifier OA0 and comparator OA2 is enclosed by the zeroing circuit with a capacitor C_z storing offset voltage. Voltage V_z produces artificial mass, in relation to which the input voltage and the reference voltage received from D/A transducer is determined. The capacitor C_p provides an appropriate shift of the output signal level from the D/A converter. Resistors inside the micro-controller have been used as resistor R of the integrator. The measuring transducer is included in the divider circuit, which simplifies the measuring circuit. Since voltage VCC , supplying the divider, is, at the same time, the reference voltage for the D/A converter. Changes in that voltage do not affect the accuracy of measurement. The transducer control circuit has been based on the structure of module Timer A and an appropriate program.

The simplified scheme of the meter circuit has been presented in figure 3.10. It is clear, that almost the entire transducer structure is located inside the micro-controller. Only capacitors and divider resistors are located outside. The diagram has omitted the heater activation circuit and the meter's keyboard.

For selected concentration values, voltage values on bridge diagonal have been calculated and for points obtained in such way, the second-degree approximating polynomial $U(s)$ has been calculated. Its waveform have been specified in figure 3.11.

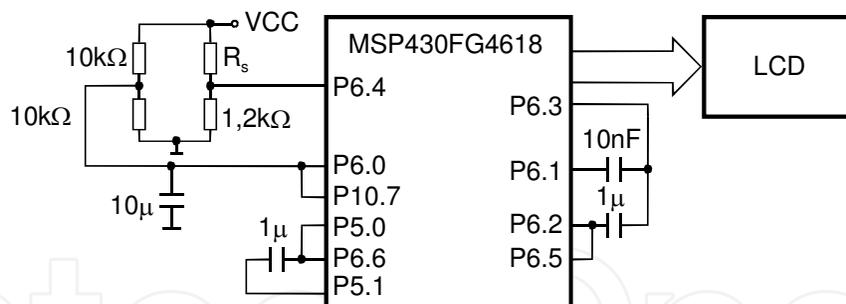


Fig. 3.10. Simplified scheme of meter for measuring CO concentration.

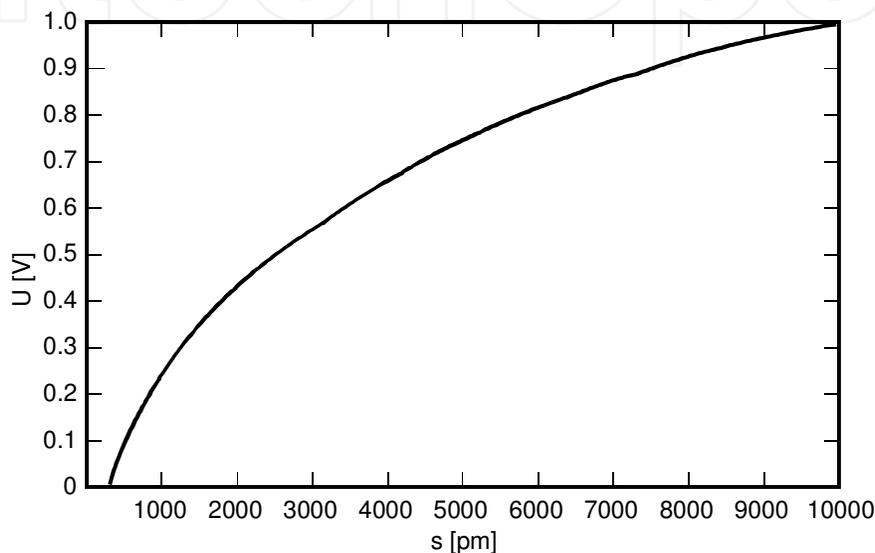


Fig. 3.11. Relation of voltage U on divider output to value of concentration s .

Then, the obtained function $U(s)$ has been approximated by a range-linear function. 10 sections have been obtained. Inclination values of those sections were used to calculate the values entered into the controlling register of the C/A transducer.

Testing of errors produced by the shaping circuit took place in such way that the transducer output resistance, for selected concentration values, was simulated by a resistance decade and the difference between the theoretical concentration value and the value indicated by the meter was defined. The value of relative error d , calculated with respect to the maximum range value, has been shown in figure 3.12.

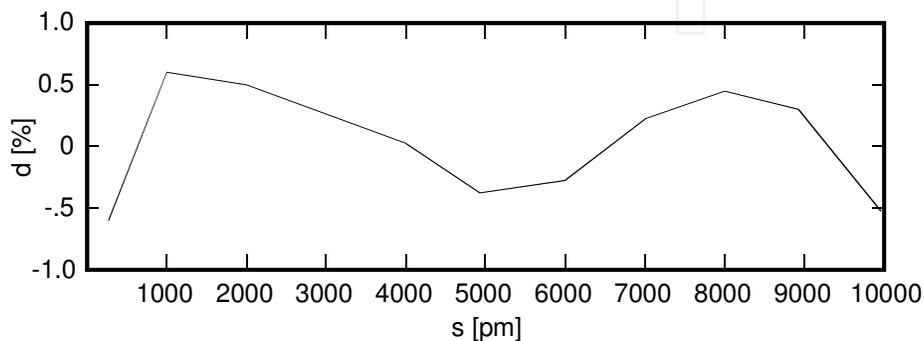


Fig. 3.12. Chart of relative error of carbon monoxide concentration meter.

As it stems from the error chart, its maximum value does not exceed 0.6% and is present at the beginning of the range.

4. Transducer with impulse feedback

Transducer with impulse feedback is also classified into integrating transducers. Its great advantage is that it is a very simple circuit, but it processes signals of just one polarity, although that limitation generally is not disturbing in the case of cooperation with measuring transducers. Especially since it is very well suited for cooperation with measuring resistance transducers. Due to that simplicity and easy control, they are used in measuring devices cooperating with different measuring transducers. Block diagram of a transducer with impulse feedback has been presented in figure 4.1, and voltage waveforms in selected points of the transducer in figure 4.2.

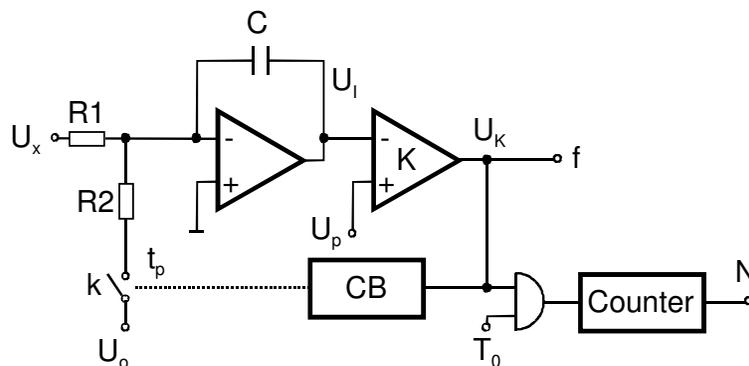


Fig. 4.1. Block diagram of transducer with impulse feedback.

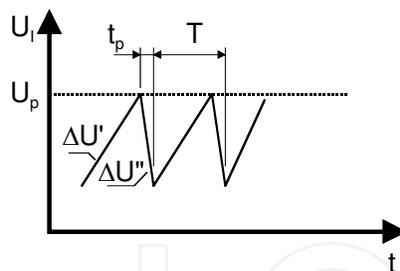


Fig. 4.2. Voltage waveforms in selected transducer points.

The transducer circuit consists of an integrator with operational amplifier, capacitor C and resistors $R1$, $R2$, comparator K , control block CB , key k and reference voltage source U_o . The output signal of frequency f being the function of the processed input voltage U_x is obtained at the comparator's output. If numeric values are to be obtained from the transducer, then the meter calculates output signal impulses for a given time T_0 .

The circuit operates in the following manner: processed voltage U_x is supplied to the integrator, through resistor $R1$, at all times. As a result, voltage U_I at integrator's output continues to increase until it reaches the reference level U_p . At that time, the comparator is activated and, as a consequence, control block CB is activated which, for time t_p , closes key k supplying the integrator with reference voltage with polarization opposite to the polarization of input voltage U_x through resistor $R2$. That results in change of voltage

waveform at the integrator's output. After time t_p , key k is turned off and the processing cycle starts over. In the first phase of transducer operation, voltage increase at the integrator's output can be described by the relation:

$$\Delta U'(t) = \frac{1}{R_1 \times C} \int_0^{T-t_p} U_x(t) dt \quad (31)$$

In the second phase of transducer operation, in which reference voltage is added to the integrator, voltage increase at the integrator's output can be described by the following relation:

$$\Delta U''(t) = \frac{1}{R_1 C} \int_{T-t_p}^T U_x(t) dt - \frac{1}{R_2 C} \int_{T-t_p}^T U_o(t) dt \quad (32)$$

In the steady state, voltage increases at the integrator's output are equal:

$$\Delta U' + \Delta U'' = 0 \quad (33)$$

Thus, summing up the integrals from formulations (31) and (32) the following is obtained:

$$\frac{1}{R_1 \times C} \int_0^T U_x(t) dt = \frac{1}{R_2 \times C} \int_0^{t_p} U_o(t) dt \quad (34)$$

If voltages U_x and U_o are constant, then after transforming the relation (34), a formulation determining the frequency of transducer output signal is obtained:

$$f = \frac{1}{T} = \frac{U_x \times R_2}{U_o \times R_1 \times t_p} \quad (35)$$

and the number of impulses calculated during processing time T_0 is:

$$N = T_0 f = \frac{U_x \times R_2 \times T_0}{U_o \times R_1 \times t_p} \quad (36)$$

Formulation (34) shows that in a one processing cycle, the charge supplied to the integrator from voltage U_x source is equal to the charge transferred from the integrator under the influence of reference voltage U_o . Measurement time of processed voltage U_x , namely the time of impulses counting in the meter is T_0 and over the entire period there is balance between the supplied and the transferred charge. Taking that into consideration, the formulation (34) can be presented in the following form:

$$\frac{1}{R_1} \int_0^{T_0} U_x(t) dt = \frac{1}{R_2} \int_0^{N t_p} U_o dt \quad (37)$$

Assuming that the processed voltage U_x and reference voltage U_o are constant over processing period T_0 , then after transforming, formulation (37) takes the form:

$$U_x \frac{T_0}{R_1} = U_o \frac{N \times t_p}{R_2} \tag{38}$$

On the other hand, when the reference voltage U_0 is a variable voltage over the processing period, but it maintains constant value over period t_p , figure 4.3, then that condition can be described by relation (39) arising from formulation (37)

$$U_x \frac{T_0}{R_1} = \frac{N \times t_p}{R_2} \sum_{i=0}^{N-1} U_{oi} \tag{39}$$

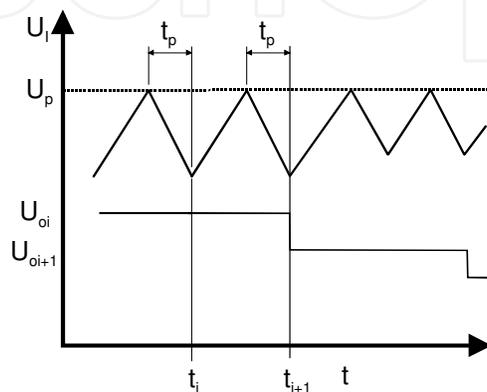


Fig. 4.3. Waveforms at integrator's output at variable voltage U_0 .

If voltage U_{oi} is constant over p long ranges, then for the m -th range the relation (39) may be expressed in the form:

$$U_x = \frac{R_1 \times t_p}{R_2 \times T_0} \left(p \sum_{i=0}^{m-1} U_{oi} + U_{om} (N - m \times p) \right) \tag{40}$$

Formulation (40) corresponds to formulation (30) for double integral converter and, as a result, shows that the characteristics of a transducer with impulse feedback can be adjusted in a similar way as it has been presented for a double integral converter. Also, all presented considerations are also valid here with one reservation concerning time t_p .

In the transducer circuit presented in figure 4.1, time t_p is generated by a monostable circuit which does not provide too high accuracy. It may be remedied by introducing modifications in the transducer circuit, presented in figure 4.4. (Janiczek, 1992)

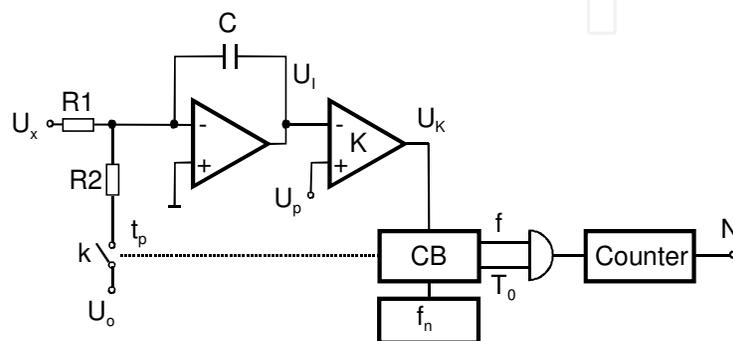


Fig. 4.4. Modified version of transducer circuit with impulse feedback.

The modification of transducer operation involves generation of time t_p – it begins not when the comparator is activated, but synchronically with the first impulse of generator f_n , which comes when the comparator is activated. That is illustrated in figure 4.5.

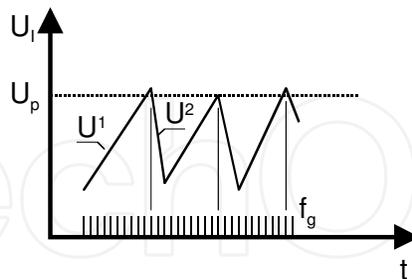


Fig. 4.5. Voltage waveforms in modified transducer circuit.

As a result, time slice t_p may be generated by division of frequency f_n in the divider. That results in a certain deviation of transducer output signal frequency, but after averaging over time interval t_0 , that does not affect the processing accuracy. Also, time interval T_0 may be obtained in the same manner. Thus, times t_p and T_0 can be identified as:

$$T_0 = \frac{k}{f_n} \quad t_p = \frac{q}{f_n} \quad (41)$$

where q, k – frequency f_n division coefficients.

Taking into consideration the relations (41) in formulation (40) the following is obtained:

$$U_x = \frac{R_1 \times q}{R_2 \times k} \left(p \sum_{i=0}^{m-1} U_{oi} + U_{om} (N - m \times p) \right) \quad (42)$$

Thanks to such solution, the processing accuracy of a transducer depends only on the constancy of relation R_1/R_2 and accuracy of generating voltage U_o . In addition, there is a possibility to adjust transducer characteristics in the above-mentioned circuit by changing duration time t_p of the feedback impulse.

Assuming, in formulation (37), that both the values of processed voltage U_x and reference voltage U_o are constant, the following is obtained:

$$U_x \frac{T_0}{R_1} = \frac{U_o}{R_2} \sum_{i=0}^{N-1} t_{pi} \quad (43)$$

After considering the relations (43) and transformation, the following formulation is obtained:

$$U_x = \frac{R_1 \times U_o}{R_2 \times k} \sum_{i=0}^{N-1} q_i \quad (44)$$

from which it can be concluded that the characteristics of a transducer with impulse feedback can be adjusted by changing the degree of meter division specifying impulse duration t_p .

Assuming, as previously, that values q_i are constant over p long ranges, the following relation is obtained:

$$U_x = \frac{R_1 \times U_0}{R_2 \times k} \left(p \sum_{i=0}^{m-1} q_i + q_m (N - m \times p) \right) \quad (45)$$

which shows that in such circuit of a transducer with impulse feedback, measuring transducers characteristics approximated by a range-linear function may be adjusted in a very wide range. Moreover, in that transducer, a very high processing resolution and accuracy can be obtained, which practically depends on the offset voltage constancy of integrator's amplifier, the constancy of R_1/R_2 resistors' relation and the constancy of reference voltage source U_0 .

The above-mentioned method of adjusting processing characteristics of transducer with impulse feedback has been applied in the meter for measuring carbon monoxide concentration. A transducer TGS 203 manufactured by Figaro Engineering Inc. (Japan) whose simplified scheme has been presented in figure 4.6. was used in the meter. (Janiczek, 2009)

The A/D converter circuit consists of an integrator, comparator, keys $k_1 - k_5$, voltage divider R_2, R_3 and R_4 and reference resistor R_1 . R_s is the measuring transducer's resistance. Particular phases of transducer operation are controlled by the micro-controller manufactured by Texas Instruments - MSP430F415. Additionally, to improve transducer resistance to changes in temperature and supply voltage, the phase of zeroing the integrator's amplifiers and comparator has been introduced. The zeroing voltage is stored on capacitor C_z . In order for the circuit to be supplied with one voltage, a divider of voltage $R_2/R_3, R_4$ providing the reference voltage U_z for the integrator has been introduced. That voltage is equal approximately to half the supply voltage. As a result, voltages applied to resistors R_1 and R_s , through keys k_1 and k_2 , have opposite polarizations in relation to voltage U_z . The reference voltage U_p for the comparator is obtained from divider $R_2, R_3/R_4$.

The circuit is zeroed over the T_z time, figure 4.7. Keys k_1 and k_2 , are open and keys k_3, k_4 and k_5 are closed. The integrator's and comparator's amplifiers are enclosed by the feedback loop, and capacitor C_z is charged up to the integrator's amplifier offset voltage. After zeroing the circuit, keys k_4 are opened and key k_1 is closed for the entire duration of processing and the transducer operates in regular mode of transducer with impulse feedback.

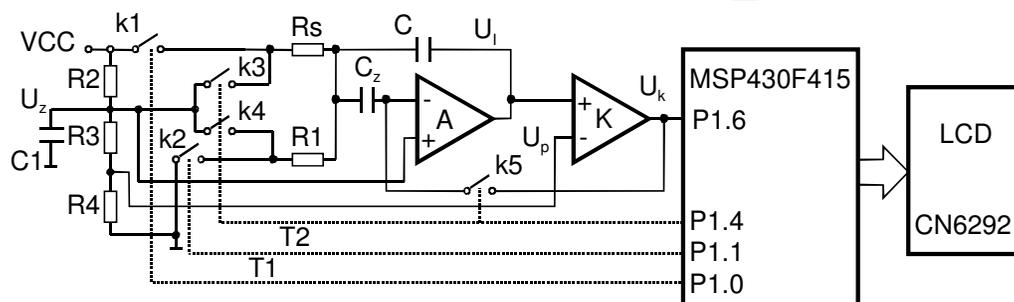


Fig. 4.6. Scheme of carbon monoxide concentration meter.

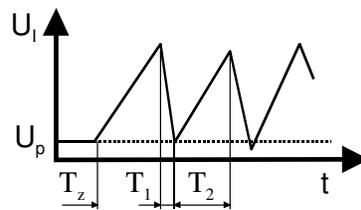


Fig. 4.7. Voltage waveform at integrator's output.

Comparator's output impulses are counted in one of the meter's micro-controllers and a different meter unit generates time slices T_2 of feedback impulse duration. Using the basic relation (38) describing transducer operation and taking account of relation (4.4) describing the measuring transducer's characteristics, the following is obtained:

$$N = \frac{(VCC - U_z) \times R1 \times s^{0.95}}{245.66 \times U_z \times T_2(N)} \times T_0 \quad (46)$$

where: N - number of impulses counted in the meter,
 T_0 - processing duration,
 U_z - artificial mass voltage.

Figure 4.8 shows the required voltage-frequency transducer characteristics.

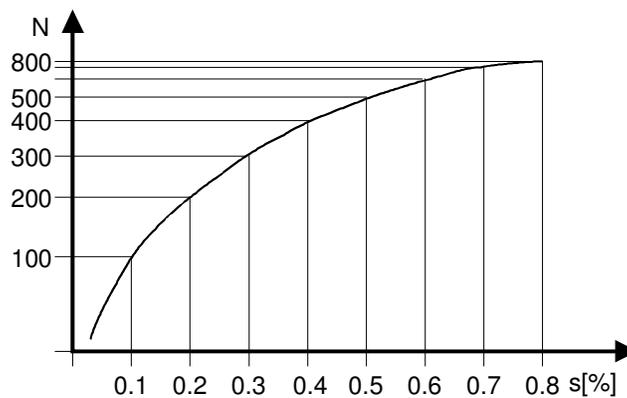


Fig. 4.8. Characteristics of voltage-frequency transducer.

For proper charge balance over the T_2 period, it has been assumed that resistor $R1=150 \Omega$ and $U_z=VCC/2$, hence the formulation (45) takes the form:

$$N = 0.61 \frac{s^{0.95}}{T_2(N)} T_0 \quad (47)$$

In order to obtain a linear relation between the number of counted impulses N and concentration s , the following condition must be fulfilled:

$$T_2(N) = c \cdot s^{0.95} \quad (48)$$

The measuring transducer's characteristics has been approximated with ten sections, which ensured approximation error not greater than 0.3%. Using relation (45), coefficient values determining times T_2 have been calculated.

Conducted tests have indicated that a stable resolution of so constructed A/D converter was reached at the level of 14 bits. The impact of temperature changes in the range 0 – 30° C did not exceed 0.02%. The main factor of that error was changes of R1 resistor values and change of R2/R3, R4 divider's pitch. Change of supply voltage VCC within +/-10% was not noticed. Those parameters significantly exceed the requirements necessary to measure carbon monoxide concentration but they show the capabilities of the measuring circuit.

Conducted meter characteristics tests, in which the measuring transducer was simulated with a variable resistor, indicated that the relative measuring error d (with regard to the range endpoint) did not exceed the value 0.3%, figure 4.9.

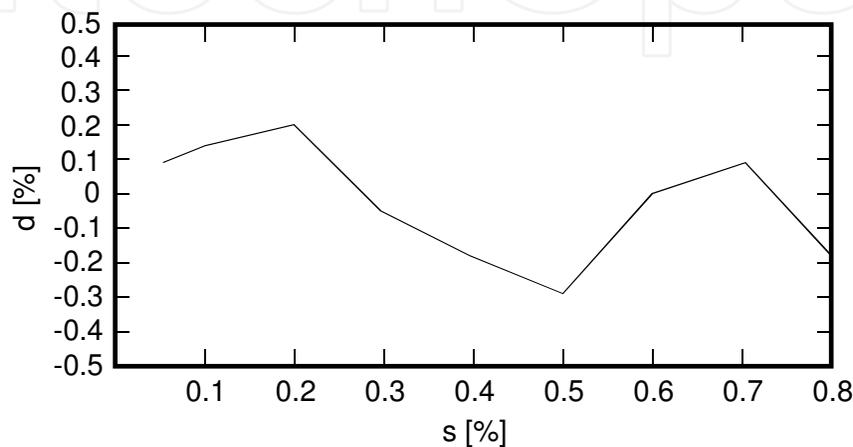


Fig. 4.9. Error chart of transducer for measuring carbon monoxide concentration.

5. Conclusion

This chapter presents a method for digital adjustment of analog-to-digital converter transfer function. If the measuring transducer's characteristics is non-linear, it is necessary to use suitable correction methods. When the measuring transducer's characteristics is very non-linear, for example in the case of certain transducers for light intensity measurement, a problem with selecting a relevant A/D transducer may occur.

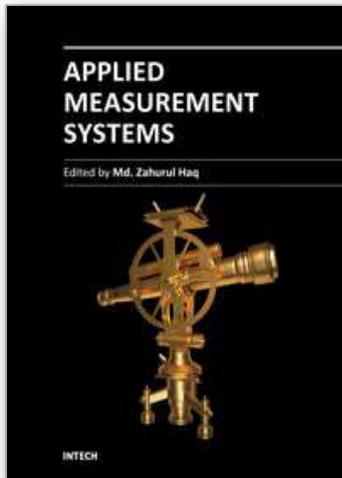
A converter with digital adjustments is a useful tool for correcting non-linearity of transducers, especially those with high linearity, in case of which the numerical correction would lead to the lost of resolution. The conducted experiments proved the suitability of the proposed new solution of converter. Such designed analog-to-digital converter achieves a stable resolution and small error of the approximation function.

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