A linear converter of strain-gauge bridge bidirectional disbalance into frequency deviation

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The measurement of mechanical force and torque magnitudes by means of strain gauges based on a new method for "transforming resistance into frequency" is the object of investigation in this paper. It presents the development of a converter with frequency output using the method of unfolding transformation. An original design is proposed for researching and measuring the non-electrical force and moment values in some technological processes. The equation of conversion is obtained which proves to be invariant from some transformation parameters including the power supply voltage. The advantages of the scheme proposed are measurement of bilateral load, improved linearization of the measuring range, high sensitivity, working with both a half bridge and a full bridge, and the simplicity of the scheme implementation. Computerized simulation has been made and experimental measurement confirms the theoretical formulation, as well.

Линеен преобразувател на двупосочен разбаланс на тензорезистивен мост в честотна девиация (Свилен Х. Стоянов).
В работата е представено създаване на тензометричен преобразувател с честотен изход по метода на разгъващото преобразуване. Предложено е оригинално схемно решение за изследване на неелектрическите величини: механична сила и момент при различни технологични процеси. Изведено е уравнението на преобразуване и е показано, че то е инвариантно към някои параметри на преобразуване, включително и към захранващото напрежение. Използваната схема дава възможност за измерване на двустранно натоварване при подобрена линейност на измервателния диапазон. Тя се характеризира с проста реализация и осигурява висока чувствителност при работа с полумост и пълен мост. Направените симулационни и експериментални измервания потвърждават теоретичната постановка.

Introduction

The big attention to the converters in question is owing to many advantages they have using schemes with a frequency output. The advantages are higher accuracy of measuring, higher sustainability against noise of frequency signals, low sensibility to the resistance of connecting conductors, non-sensibility to the contact resistance and easy detecting the frequency signal.

The scheme decision gives possibility for easy regulation of sensibility of the basic frequency, exclusion of the additive errors caused by the driftage of zero in the DC amplifier and in the integrator, and work within wide temperature limits in case the source of power is unstable [6].

Another feature is a low number of composed elements which is an additional advantage of this kind of converters.

The task for elaborating and testing the convertors is very heavy, and the requirements to the elements to achieve stable work under very low input signals are high, as well.

Analysis of the existing schematic solutions

There are many technical solutions for converters from voltage to frequency, with total conversion. They are all built on the basis of the relaxation oscillator and include two main blocks: integrator and comparator which are covered by the respective positive and negative feedback. The basic scheme of the converter of the resistive imbalance in the bridge frequency [5] is shown in Fig. 1.

The proposed scheme decision includes a differential amplifier (DA), an integrator (I), and a comparator (C). The power diagonal of the bridge is connected between the output of the comparator and the common ground. Measuring is done diagonally to the inputs of the differential amplifier whose output is connected to the inverting input of the integrator OA1. The latter's non-inverting input and output are connected to a common ground and inverting input of the comparator OA2 whose non-inverting input and output are associated with the output of the converter f.

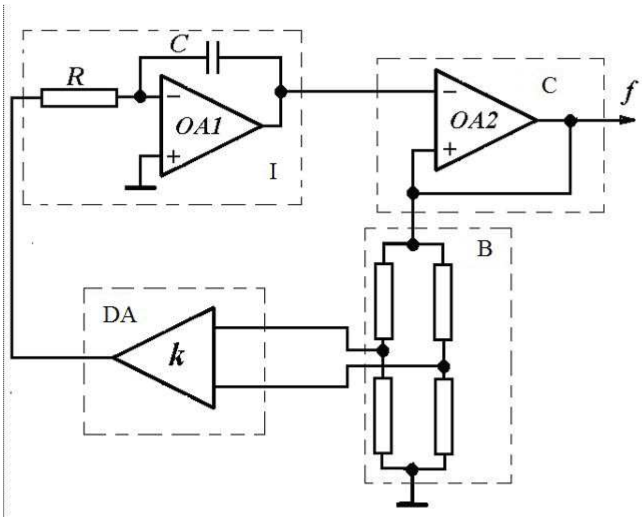

Fig.1. Signal conditioning circuit for resistive bridge with frequency output.

The output frequency is determined by the following equation:

$$F = \frac{n.k.\varepsilon}{4\tau} , \qquad (1)$$

where n = 1, 2, 4 respectively for 1, 2 and 4 working arm of the measuring bridge B, k is gain of the differential amplifier DU; $\varepsilon = \Delta Rx/Rx_0$ is relative change in resistance of the strain gauges; τ = RC is time constant of the integrator.

On the basis of the scheme in Figure 1, a new scheme of the measurement transducer has been developed. Fig. 2 illustrates a schematic view of the transducer with resistance deviation in frequency [1], and Fig. 3 illustrates timing diagram of the operation.

The scheme including the integrator is made on the basis of R1, C1 and OA1, a comparator designed on the basis of OA2 with positive feedback composed of R2 and the equivalent resistance R of the power diagonal of the bridge, and a differential amplifier designed on the basis of OA3.

The analysis of the operation of the converter [1] shows that when using two or four strain gauges as a working sensor connected differentially [7], the output frequency is a linear function of the change in resistance of the sensor:

$$F_{OUT} = \frac{K_{DU}}{4R_1C_1U_R}\frac{U_R}{2}\delta R = \frac{K_{DU}}{8R_1C_1}\delta R \qquad (2)$$

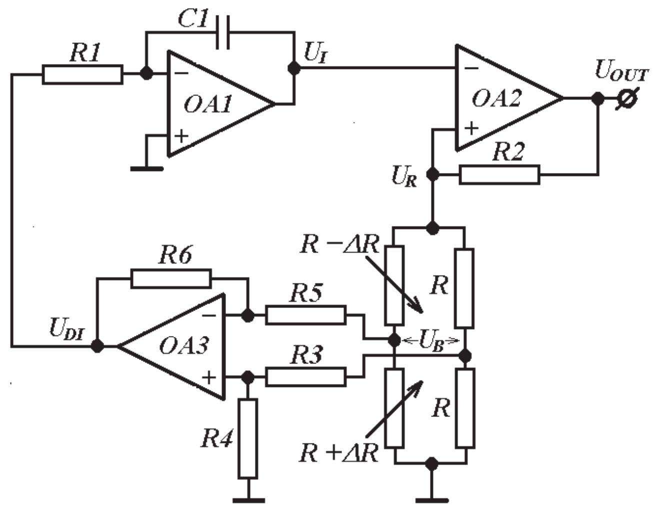

Fig.2. Circuit diagram of the proposed resistance deviation bridge to frequency converter.

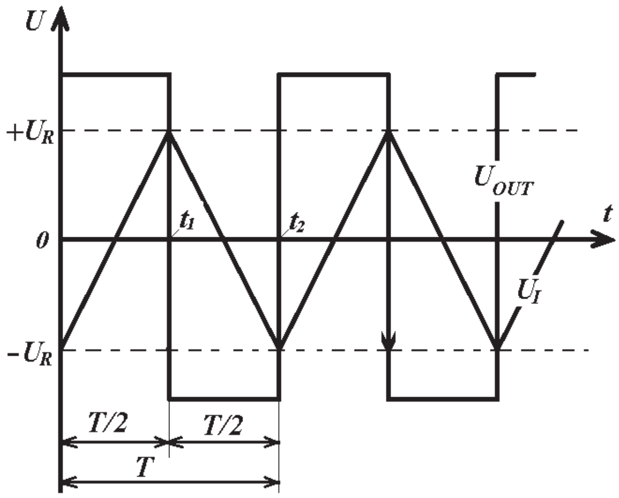

Fig.3. Timing diagram of operation.

Eq. (2) shows that the parameter U_R (a function of the output voltage of the comparator and the resistors R2 and R) is not included in the equation of the conversion and, thus, the converter is invariant from it. This is an important feature of the converter, as in the classical circuit solutions supply voltage of the bridge comes with a unit weighting factor in the equation of transformation to bring it particularly stringent requirements.

A major shortcoming in the converter in Fig. 2 is that the transformation equation is valid only for one-sided load sensors modified to their resistances with a sign marked in the figure. To have the output frequency reset to zero load (ΔR = 0) and reloading strain gauges should become negative is obviously impossible. Therefore, for the correct operation of the converter it is necessary to observe the signs of changes in the resistances of the working sensors, as shown in Fig. 2. Furthermore, the output frequency is reduced substantially below for the sake of accuracy of its measurement, which means the resistive bridge should be unbalanced in advance to about 10% of the output range of the converter.

The Fig. 4 shows a circuit diagram that eliminates these shortcomings.

The scheme of Fig. 4, analogous to that of Fig. 1, contains an integrator based on R1, C1 and OA1, a comparator (Schmitt trigger) based on OA2 with positive feedback consisting of R2 and equivalent resistance R of the power diagonal of the bridge, and a differential amplifier designed on the basis of OA3. Additionally, an inverting amplifier designed on the basis of the operational amplifier OA4 and resistors R7, R8 and R9 is introduced. Its output is connected through a resistor R10 to the inverting input of OA1, and its input - to the supply voltage U_R of the bridge [2].

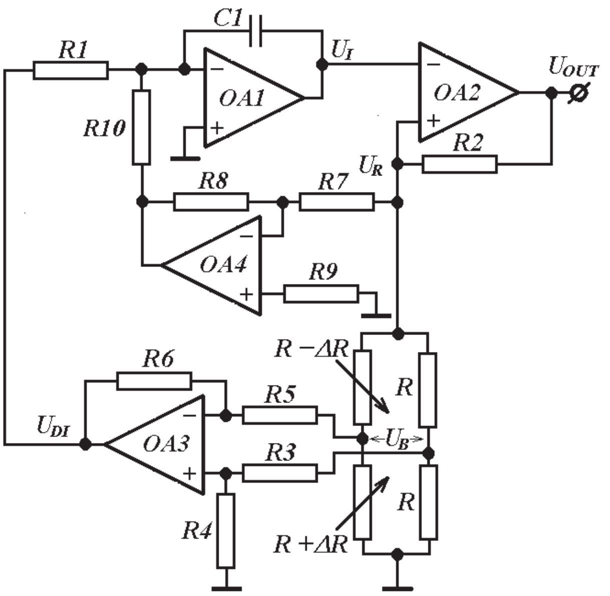

Fig.4. Circuit diagram of the bilateral resistance deviation bridge with regard to a frequency converter.

The timing diagram of the bilateral converter is shown in Fig. 2. As well, a complete symmetry of the processes in the two time intervals is available in the circuit there.

For the output frequency of the converter, the following is obtained:

(3) $$F_{OUT} = \frac{1}{2t_1} = \frac{K_{DU}}{8R_1C_1}\delta R + \frac{1}{4}\frac{R_8}{R_7}\frac{1}{R_{10}C_1} = S_R\delta R + F_0$$

(4) $$S_R = \frac{K_{DU}}{8R_1C_{10}}$$ (5) $$F_0 = \frac{1}{4}\frac{R_8}{R_7}\frac{1}{R_{10}C_{10}}$$

where Eq. (4) presents the sensitivity of the converter, and Eq. (5) gives starting frequency of the converter with $\delta R = 0$.

The Eq. (3) shows that the susceptibility S_R specifies a maximum, and a module change of Strain gauges $|\delta R|_{max}$ is sufficient to set the initial frequency $F_0 > S_R|\delta R|_{max}$, wherein, in the entire input range of up $-\delta R_{max}$ to $+\delta R_{max}$ output frequency of the converter will remain positive.

The presented converter of bilateral deviation strain gauge resistive bridge to frequency has potentially high metrological characteristics and works sustainably in the normal range of strain-gauge measuring bridges.

The main disadvantages of the presented scheme implementation are heightened complexity and relatively high values of reduced error of nonlinearity which during simulations reach a value of 0,413%, and for practical realization 0,52% [2].

Main part

The converter in Fig. 5 consists of: integrator 4, comparator 1, strain-gauge resistive bridge 2, a differential amplifier 3 and a voltage divider 5 and 6.

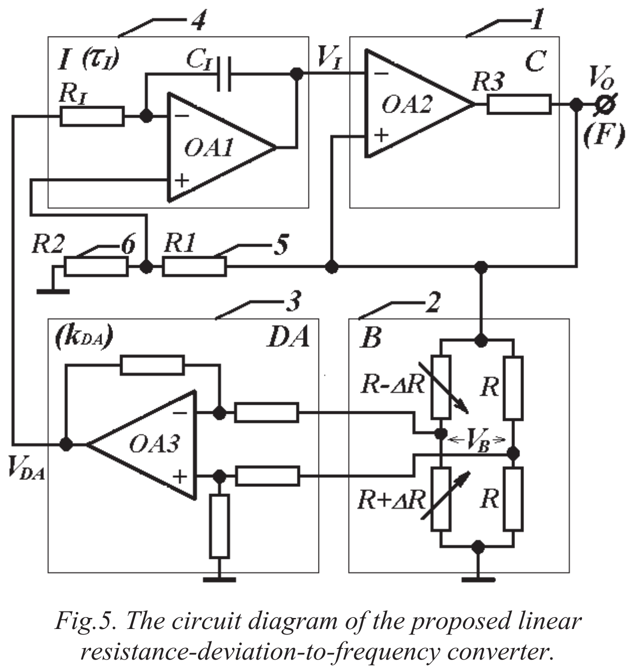

Fig.5. The circuit diagram of the proposed linear resistance-deviation-to-frequency converter.

The timing diagrams of the operation are shown in Fig. 6, where the output voltage V_{out} is obtained at the output of comparator 1 as V_0, and V_I is at the output of the integrator 4.

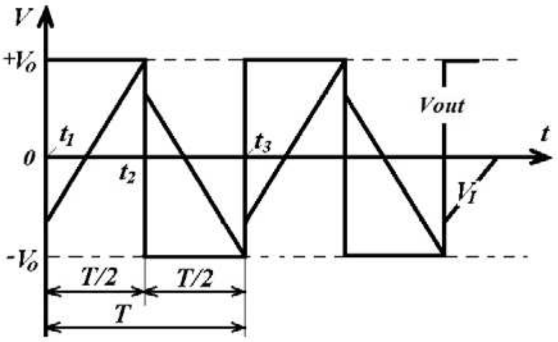

Fig.6. Timing diagrams of linear converter.

The analysis of the converter's work will be conducted assuming operational amplifiers for ideal. The principle of operation of the converter is as follows: in the steady state, the output voltage of the comparator 1 takes one of two states $+V_0$ or $–V_0$ (Fig.6); this voltage goes simultaneously as threshold voltage comparator 1 supply voltage resistive bridge 2 and input voltage of the resistive voltage divider comprising a first resistor 5 and a second resistor 6. Assuming that the voltage V_0 is positive (interval $t_1 \div t_2$) and the output voltage of the resistive bridge 2 is linear to the relative change in resistance δR (δR = ΔR/R) and in particular for two differential sensors related work for the output voltage of the bridge 2 output:

(6) $$V_B = \frac{V_o}{2}\delta R$$

For the output voltage of the differential amplifier 3, the following equation is obtained:

(7) $$V_{DA} = -k_{DA}\frac{V_o}{2}\delta R$$

However, the non-inverting input of the integrator 4 goes from the output voltage V_β the voltage divider composed of a first resistor 5 and a second resistor 6:

(8) $$V_\beta = V_o\frac{R_2}{R_1 + R_2} = \beta V_o$$

Considering Eqs. (7) and (8), on the principle of superposition in the time interval $t_1 \div t_2$, for the output voltage V_I of the integrator 4 the following equation can be written:

(9) $$V_I = -V_o + 2\beta V_o + \frac{1}{\tau_I}\int_{t_1}^{t_2}\beta V_o dt - \frac{1}{\tau_I}\int_{t_1}^{t_2}(-k_{DA}\frac{V_o}{2}\delta R)dt$$

The comparator switches its output from + V_0 to - V_0 at the moment t = t_2, when the output voltage V_I (t_2) of the integrator 4 becomes equal to the trigger voltage V_0. Considering the symmetry of the two time intervals ($t_1 \div t_2$ and $t_2 \div t_3$), for the first time interval it is displayed: $t_2 \div t_1$ = T /2, where T = 1/F is the period of the output voltage. Taking into account that the values of the integrands in Eq. (9) are constants in the time interval, the same equation can be transformed as follows:

(10) $$-V_o + 2\beta V_o + \frac{1}{\tau_I}\beta V_o\frac{T}{2} + \frac{1}{\tau_I}k_{DA}\frac{V_o}{2}\delta R\frac{T}{2} = V_o$$

From Eq. (10), for the frequency F = 1/T the following equation is obtained:

(11) $$F = \frac{1}{T} = \frac{\beta}{4\tau_I(1-\beta)} + \frac{k_{DA}}{8\tau_I(1-\beta)}\delta R$$

The first part of the equation represents the base frequency, and the second part is the change in the base frequency under bidirectional load. From Eq. (11), the output frequency can be seen to be subject to the following condition:

(12) $$\frac{k_{DA}}{8\tau_I(1-\beta)}\left|\delta R\right| < \frac{\beta}{4\tau_I(1-\beta)}$$

According to this condition, the converter is linear for both positive and negative δR.

The scheme combines the most of the advantages of the circuit solutions considered here and has very good metrological characteristics under bilateral variable loading [3].

A prototype of the proposed scheme has been implemented [4].

Simulation results

For confirmation of the analysis, the converter in Fig. 5 has been simulated by the values of the elements as shown in Fig. 7.

In Table 1, the results of simulation research are given. The strain gauges are represented by the resistors R4 = 100.0 ... 100.5 Ω, R3 = 100.0 ... 99.5 Ω, varying with step 0.1 Ω (column 1). In columns 2 and 3, the period T in ms and the f_{out} output voltage frequency in kHz are respectively shown. In column 4, corresponding points are calculated concerning the linearized rights $f_{out\text{-}lin}$ in kHz and drawn between the first and last points of the output frequency f_{out}. In column 5, reduced error of nonlinearity is calculated according to the following equation:

(13) $$\gamma_{lin} = \frac{f_{out} - f_{out\_lin}}{f_{out\_max} - f_{out\_min}}100\%$$

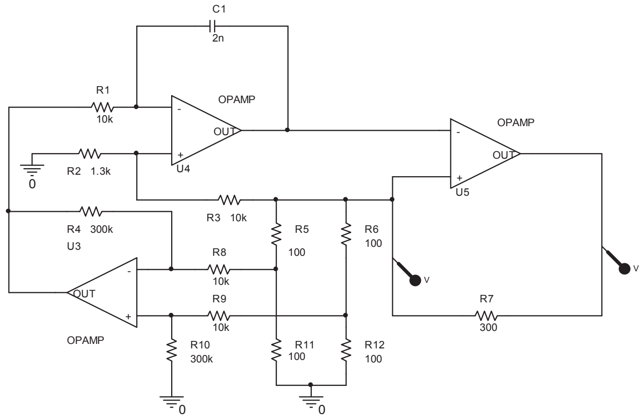

Fig.7. Circuit of the converter for the simulation experiment.

Table 1

Simulation results

R_{11}/R_{13}, Ω	*T, ms*	f_{out},*kHz*	f_{out_lin},*kHz*	γ_{lin}, %
1	2	3	4	5
99,5/100,5	1,8598	537,7	537,7	0
99,6/100,4	1,3344	749,41	749,409	-0,00013
99,7/100,3	1,0405	961,11	961,118	0,000832
99,8/100,2	0,8526	1172,82	1172,827	0,000597
99,9/100,1	0,7223	1384,53	1384,536	0,000433
100,0/100,0	0,6265	1596,27	1596,245	-0,00157
100,1/99,9	0,5531	1807,94	1807,954	0,000774
100,2/99,8	0,4951	2019,65	2019,663	0,000644
100,3/99,7	0,4482	2231,35	2231,372	0,000986
100,4/99,6	0,4093	2443,11	2443,081	-0,00119
100,5/99,5	0,3767	2654,79	2654,79	0

Experimental results

To check of the function of the converter in Fig. 8 has been done by means of an experimental model using the following components: a comparator - operational amplifier LF357N; differential amplifier and integrator - operational amplifier LF356N; resistors with a tolerance of ± 1% and a capacitor with a tolerance of ± 2%. The following values of the elements have been selected: R = 100Ω - initial resistance of the sensor, R1 = RI = 10kΩ, R2 = 1,3kΩ, CI = 2,2nF, gain differential amplifier K_{DA}=30. At these values of the components and unbalance of the resistive bridge ΔR = ± 0,5Ω (set with resistive decade), the following results have been obtained: initial frequency (with a balanced bridge) f_0 = 1446,7 Hz and incremental change in the frequency 181,9 Hz (for ΔR = 0,1Ω) – Fig. 8 and Table 2. When comparing the results with theoretical relative error, δ_{f0} = -1,5% is displayed for the initial frequency. The relative error of the sensitivity of the converter output is δ_k = -5% [4].

Table 2

Experimental results

1	2	3	4	5
R_{11}/R_{13}, Ω	*T, ms*	f_{out},*kHz*	f_{out_lin},*kHz*	γ, %
99,5/100,5	0,42510	2352,3895	2352,38950	0
99,6/100,4	0,46068	2170,7099	2170,46352	0,013543
99,7/100,3	0,50265	1989,4656	1988,53753	0,051013
99,8/100,2	0,55263	1809,5263	1806,61155	0,160216
99,9/100,1	0,61573	1624,097	1624,68557	-0,03235
100,0/100,0	0,69266	1443,7075	1442,75959	0,052104
100,1/99,9	0,79299	1261,044	1260,83360	0,011565
100,2/99,8	0,92648	1079,3541	1078,90762	0,024542
100,3/99,7	1,11364	897,95873	896,98164	0,053708
100,4/99,6	1,39885	714,87223	715,05565	-0,01008
100,5/99,5	1,87572	533,12967	533,12967	0

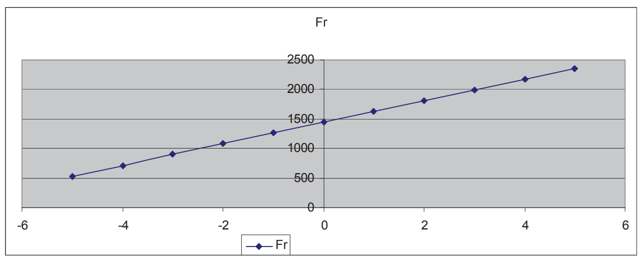

Fig.8. Experimental results.

The results obtained show a coincidence with the deduced analytical expressions. The errors of the converter in the experiments are within the tolerances of the components used.

Conclusion

The present paper shows the elaborated scheme of a linear converter of strain-gauge resistive bridge disbalance into frequency deviation under bilateral load. There have been experiments demonstrating the efficiency of the scheme, particularly in minimizing the non-linearity. The scheme has been simulated with the same values at which the maximum non-linearity error appears as 0,00157%, and scheme’s conversion is 0,05225%.

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