Direct Integrating Converter realized as Strain Gauge Bridge with Frequency Deviation and Low Power Supply

Svilen Stoyanov[1] and Desislava Mihaylova[2]

Abstract – ***In* this paper a scheme of bidirectional integrating converter with frequency deviation is developed, featured by low power supply voltages and low power consumption. The scheme works on the method of a right ramp conversion. A mathematical and simulation model of the converter is created. The practical implementation proves the performance and functionality of the scheme, which is generally designed for measuring forces and torques in different technological processes. The results are presented in table and graphic form and corresponding conclusions are made.**

Keywords – **Low power supply, Measurement, Integrating converter, Strain gauge bridge.**

I. Introduction

The measurement of forces and torques in the technological processes always puts on the agenda issues like accuracy improvement, widening the operating range and decreasing the effect of strain gauges in measurement.

For the exploration of cutting processes during removal of the chips in mechanical engineering it is necessary measuring forces and torques on the different coordinate axes, depending on the type of cutting tool and the corresponding circuit for cutting the material.

In this study the measurement of forces and torques is realized by using foil strain gauges, which are glued and places over the object in the zones of weakened cross-section, known as concentrators of mechanical stresses.

The transformation of the change of the strain gauges deformation into frequency deviation is done by integrating converters working on the method of ramp right conversion. The method itself is well known and reported by many scientists: Kaliyugavaradan S. (2000) [4], Mohan M., J. Kumar (2009) [5], Gigov H. (2013) [3] and many others. Essential advantages of the method are simplicity circuits and high linearity conversion. The main disadvantages are the requirements for using high performance elements, fast operational amplifiers, and accurate selection of measurement ranges. Therefore, there is no coincidence that most schemes of integrating converters have patent protection rights, namely Forehand G. (1994) [7], Vassilev V. Gromkov H. (2009) [6] and many others.

When working with measuring circuits including instrumental amplifiers supply voltages are typically bipolar in the range of 12-18 volts [2]. When operating the scheme on the ramp right conversion method with frequency output, the strain gauges are supplied with a voltage ranging 8-14 volts. This leads to additional heating and variable temperature operation. When working with instrumental amplifiers reducing the supply voltage is difficult to implement and usually leads to a strong deterioration of the regime parameters respectively increasing the reduced nonlinearity error.

The scheme of the measuring strain gauges transducer with instrumental amplifier is given in Fig. 1 [1], [2].

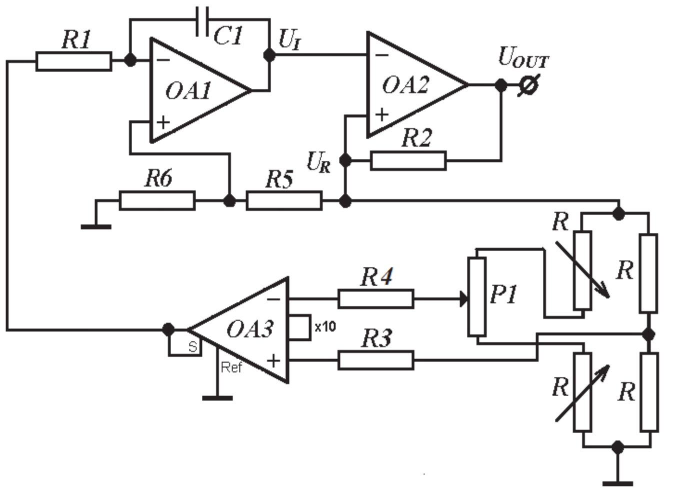


Fig. 1. Circuit diagram of strain gauge converter into frequency deviation with instrumental amplifier

The scheme assembly includes an instrumental amplifier (OA3), an integrator (OA1), a comparator (OA2) and a strain-gauge resistive bridge R. 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 instrumental amplifier whose output is connected to the inverting input of the integrator OA1. The output of the integrator is connected to the inverting input of the comparator whose non-inverting input is combined with the output of the converter. The resistors R5 and R6 realize a voltage divider, the middle point of the divider is connected to the non-inverting input of the integrator. The resistive load P1 is used to set accurate values of the disbalance of the strain gauges bridge, realized as a differential scheme with a half bridge circuit.

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

$$f = \frac{1}{T_1 + T_2} = \frac{1}{T} = \frac{\beta}{4\tau_I(1-\beta)} + \frac{k_{IA}}{8\tau_I(1-\beta)}\delta R \qquad (1)$$

where:

[1]Svilen Stoyanov is with the Technological College of Dobrich at Technical University of Varna, 1 Studentska Str, Varna 9010, Bulgaria, E-mail: svilen.stoyanov@tu-varna.bg

[2]Desislava Mihaylova is with the Technological College of Dobrich at Technical University of Varna, 1 Studentska Str, Varna 9010, Bulgaria, E-mail: de_c@abv.bg

-T – the output period of the converter;

-T_1 and T_2 – half periods of the converter, and T_1=T_2

- $\beta = \frac{R_2}{R_1 + R_2}$ – coefficient of the voltage divider;

-k_{IA} – the gain of the instrumental amplifier;

- τ_I – time constant of the integrator;

-δR – relative change of the resistance of the strain gauges load (deformation).

The first part of the equation represents the base frequency, and the second part is the change of the base frequency under bidirectional load. From Eq. (2), the output frequency needs to meet the following condition:

$$\frac{k_{IA}}{8\tau_I(1-\beta)}|\delta R| < \frac{\beta}{4\tau_I(1-\beta)} \tag{2}$$

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

In operating mode it was found that bilateral converting deformation of strain gauges is possible only at the smallest gain of the instrumental amplifier k = 10 V/V. In the other ranges, a number of limitations exist in terms of the gain due to non-compliance with condition 2. The scheme with instrumental amplifier has stable performance only when bipolar voltages above 15 volts [2] are applied, which leads to localized heating of the strain gauges and certain change of temperature regimes of the test objects.

II. Development of Bilateral Integrating Converter with Reduced Supply Voltages

The proposed scheme in Fig. 2 avoids most disadvantages. The scheme represents a linear integrating converter realized by strain gauge bridge with frequency deviation and reduced supply voltages.

The main difference in the scheme is the replacement of the instrument amplifier INA110 of a precise operational amplifier. The last is adjusted for leveling the values of the voltages at the two inputs at zero disbalans of the bridge by the potentiometer P_2.

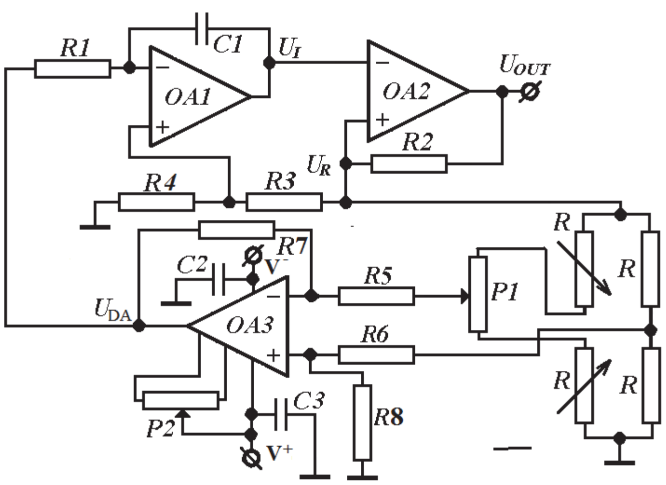


Fig. 2. The circuit diagram of the proposed direct integrating converter with low power supply

III. Metrological Analysis of the Errors of the Differential Amplifier

A. Metrological Analysis of Errors due to the Tolerance of the Values of the Resistors

The amplification of small changes in input voltage at disbalans of the strain gauge bridge of the converter is realized using differential amplifier. The deviations of the values of resistors R5, R6, R7 and R8 of the differential amplifier from their nominal values cause multiplicative and additive error.

The output voltage of the differential amplifier can be determined by the following formula [3]:

$$V_{out} = \frac{R_8}{R_6} \frac{1}{1+\frac{R_8}{R_6}} \left(1 + \frac{R_7}{R_5}\right) V_{in1} - \frac{R_7}{R_5} V_{in2} \tag{3}$$

After conversion of formula 3 and applying the superposition principle for the input differential voltage V_D of the strain gauge bridge and its input in-phase voltage V_{CM} it is obtained:

$$V_{out} = V_D \frac{2R_7R_8 + R_5R_8 + R_7R_6}{2R_5(R_6+R_8)} + V_{CM} \frac{R_5R_8 - R_7R_6}{R_5(R_6+R_8)} = K_D V_D + \Delta_a \tag{4}$$

From (3) it can be concluded that the inaccuracy of the coefficient K_D leads to a multiplicative error, and the expression $\Delta_R = R_5R_8 - R_7R_6$, when unequal to 0, leads to additive error Δ_a.

Additive error is determined by the method of logarithmic differential. The absolute value of the additive error caused by errors of the resistors is obtained:

$$\Delta_a = V_{CM} \frac{R_8}{R_6+R_8}(\delta R_5 + \delta R_7 - \delta R_6 - \delta R_8) \tag{5}$$

In case of differential amplifiers additive error is caused from the common mode rejection ratio Mc (CMRR) as well. The absolute value of this error relevant to the input V_1 can be calculated by the following formula [3]:

$$\Delta_a(M_c) = \frac{V_1}{M_c} \frac{R_8}{R_6+R_8} \tag{6}$$

The scheme in Figure 3 requires the use of resistors with a tolerance of 0.1%. The inaccuracy of the coefficient K_D is determined about 0.007 at normalized gain of value 30, which corresponds to 0.022932 %. The absolute value of the additive error as described in formula 5 is 0,0193548*V_{CM}. The absolute value of additive error caused by the common mode rejection ratio using operational amplifier type OPA134PA [9] is 0,000332226*V_{CM} and can be ignored.

B. Analysis of the Error of the Input Offset Voltage of the Differential Amplifier

The residual voltage has a great impact on the accuracy of measurement due to the low values of the voltages coming from the two diagonals of the strain gauge bridge. This tension cannot be compensated in any way. In the circuit of the converter it is necessary to use operational amplifiers with very low values of the input offset voltage. Further equalizing the voltages of the two inputs of the differential amplifier is reached by using trimmer potentiometer P_2 and the split beam oscilloscope.

IV. Mathematical Modelling the Equation of Conversion

The equation of conversion (1) is modeled in the environment of MATLAB [1]. The values of the elements significant in the equation of conversion are: resistor of the integrator R_I = 10kΩ, the capacitor of the integrator C_I = 1,7nF, strain gauges with resistance R = 120Ω, and a coefficient of the voltage divider β= 0,115. Default bilateral amendment resistance ΔR of strain gauges from -0,5 Ω to + 0,5Ω with step 0,1Ω. The initial frequency of the converter at ΔR = 0 is 1910,934 Hz, but its change is a linear function – Table I.

TABLE I
RESULT FROM MODELING

ΔR, Ω	T, ms	*f, Hz*	ΔR, Ω	T, ms	*f, Hz*
0.5	0.33904	2949.49	-0.1	0.58712	1703.22
0.4	0.36473	2741.78	-0.2	0.66867	1495.51
0.3	0.39462	2534.06	-0.3	0.77652	1287.8
0.2	0.42986	2326.35	-0.4	0.92585	1080.09
0.1	0.472	2118.64	-0.5	1.14629	872.383
0	0.5233	1910.93			

V. Simulation Modeling of the Converter

In Fig. 3 a simulation model of the converter is shown, developed in the MULTISIM interface.

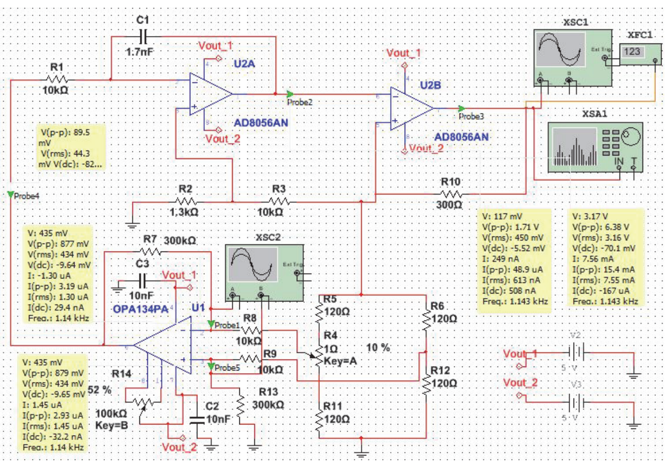


Fig. 3. Simulation model of the converter

The values of the components are the same as for mathematical modeling. In line with the integrator and comparator a dual voltage feedback amplifiers AD8056 are used [8] with the following important parameters: 5V power supplies, 5mA typ/amplifier power supply current, 300 MHz −3 dB bandwidth, 1400 V/µs slew rate, 0,02° differential phase error, 0,01% differential gain error, temperature range of −40°C to +125°C. For the differential amplifier High Performance Operational Amplifiers OPA134PA are selected [9] with the following important parameters: supply range ±2,5 V to ±18V, slew rate 20 V/µs, bandwidth 8 MHz, common-mode rejection 100dB, input offset voltage ±0,5V, temperature range of −40°C to +85°C.

The operation of the converter is examined at a voltage of 2.5 to 6 volts. Initially, the amplitudes of the two input signals of the differential amplifier are equalized via the potentiometer R_{14}, and dual beam oscilloscope XSC2. Two strain gauges R_5 and R_{11} are simulated, differentially connected with values variation ± 0,5 Ω. This is performed by means of the potentiometer R4 step 0,1 Ω. Additionally connected are a dual beam oscilloscope XSC1, frequency counter XFC1 and spectrum analyzer XSA1. The resulting output frequency is given in Table II.

TABLE II
OUTPUT FREQUENCY OF THE CONVERTER

ΔR [Ω]	*f_{out}, Hz при Ucc=, V*					
	6	5	4	3	2.5	2
0.5	3046	3074	3121	3239	3407	4289
0.4	2834	2860	2904	3014	3169	3983
0.3	2622	2646	2687	2788	2932	3676
0.2	2410	2432	2470	2562	2694	3368
0.1	2198	2218	2252	2336	2456	3059
0	1985	2003	2034	2110	2217	2748
-0.1	1772	1788	1816	1883	1978	2434
-0.2	1560	1574	1598	1657	1739	2117
-0.3	1346	1359	1379	1429	1499	1796
-0.4	1133	1143	1161	1202	1258	1467
-0.5	919.8	927.9	941.7	974.1	1017	1127

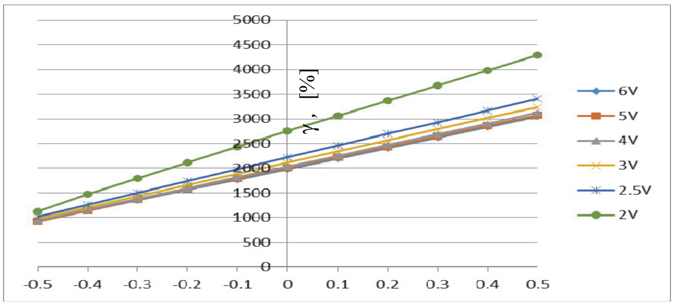
The results obtained were processed and the corresponding points of linearized frequency $f_{out\text{-}lin}$ were calculated (not shown herein) and the reduced error of non-linearity γ in % as per formula (7) [3] - Table III:

$$\gamma = \frac{f_{out} - f_{out\_lin}}{f_{out\_max} - f_{out\_min}} 100\% \tag{7}$$

TABLE III
THE REDUCED ERROR OF NON-LINEARITY γ IN %

ΔR [Ω]	*γ, % при Ucc=, V*					
	6	5	4	3	2.5	2
0.5	0	0	0	0	0	0
0.4	0.0292	0.0284	-0.1097	-0.4841	-0.9209	-4.2584
0.3	0.0292	0.0284	-0.1097	-0.5307	-0.8751	-4.305
0.2	0.0292	0.0284	-0.1097	-0.5307	-0.9209	-4.3516
0.1	0.0292	0.0284	-0.1556	-0.5307	-0.9209	-4.3982
0	-0.0179	-0.0182	-0.1556	-0.5307	-0.9668	-4.4914
-0.1	-0.0179	-0.0182	-0.1556	-0.5773	-0.9668	-4.6312
-0.2	0.0292	0.0284	-0.1556	-0.5307	-0.9668	-4.771
-0.3	-0.0649	-0.0182	-0.2014	-0.6239	-1.0127	-4.9574
-0.4	-0.0179	-0.0648	-0.1556	-0.5773	-1.0586	-5.3301
-0.5	0	0	0	0	0	0

The results obtained from the simulation are presented graphically in Figs. 4 and 5. The maximum reduced error at Ucc≤4V is 0,2014%, and in case of Ucc 2,5÷3V is about 1%.



Below 3V the circuit does not work stably.

Fig. 4. Output frequency at different supply voltages

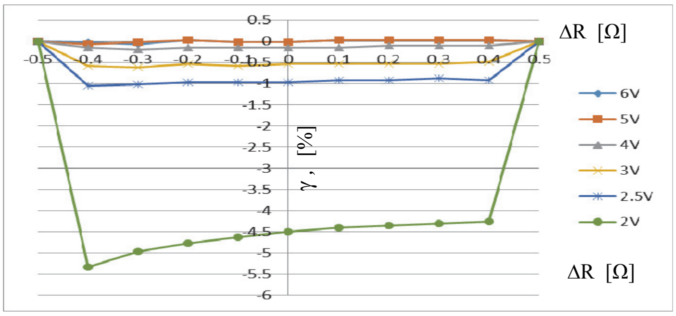


Fig. 5. The reduced error of non-linearity γ in %

VI. Experimental Result

Experiments were performed under the same conditions as in the simulation. Modification of the resistance with step of 0,1Ω is performed by means of an exemplary pair with accuracy 0.02%. The resistors R_7, R_8 R_9 and R_{13} have tolerances ± 0,1% and TCS ± 100ppm, and the rest ones ± 1% and ± 100ppm TCS. The capacitor with value 1,7nF is pre-selected and tested (2 capacitors in the kit).

The obtained experimental results are given in Table IV. For the mentioned supply voltages the corresponding output frequency f are included as well as the calculated reduced error of non-linearity from formula 7 [3].

Table IV
Experimental result

ΔR, Ω	*Ucc=3V*		*Ucc=4V*		*Ucc=5V*	
	f_{out}, Hz	γ, %	f_{out}, Hz	γ, %	f_{out}, Hz	γ, %
0,5	2701	0	2877	0	2879	0
0,4	2496	-0,005	2678	0,1044	2676	-0,05
0,3	2285	-0,298	2477	0,005	2475	0,0495
0,2	2079	-0,054	2276	0,005	2273	0
0,1	1868	-0,298	2077	0,1044	2075	0,198
0	1664	0,0439	1868	-0,393	1867	-0,297
-0,1	1448	-0,542	1667	0,005	1662	-0,149
-0,2	1232	-0,542	1468	0,1044	1460	0
-0,3	1013	-0,688	1267	0,005	1259	0,0495
-0,4	752	-2,738	1063	-0,144	1053	-0,198
-0,5	652	0	866	0	859	0

The scheme shows a stable work at Ucc=3÷5V. The maximum reduced error at Ucc=4÷5V is 0,393%, and at Ucc=3V it is 2,738 %.

VII. Conclusion

An integrating strain gauge convertor is developed operating with low power voltages by using the ramp right conversion method.

The accomplished metrological analysis of the differential amplifier and the converter simulations prove the high metrological characteristics if correct selection of the electronic components is made.

Experimentally, the schematic shows a robust operation at 4-5V supply voltages with an error of less than 0.5%. For supply voltages ranging from 3-4V the error of non-linearity is increased to 2.8%, which must be taken into account when a battery or rechargeable power supply is utilized. In case of supply voltages below 3 V and above 5 V the device cannot operate appropriately.

The main application of the developed transducer is to study mechanical forces and torques of technological processes in real-time.

Acknowledgement

The work has been performed under the contract number НП17/2017 with Technical University of Varna, Bulgaria.

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