Technical University of Varna
Annual Journal
DOI: 10.29114/ajtuv.vol1.iss1.45
Vol.1 Issue 1 (2017):
Published: 2017-12-28
ISSN 2603-316X (Online)

Researching the change of the operating frequencies in the case of inequality of the output voltages of the comparator within the structure of an integrating measuring strain gauge converter

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Abstract. One of the major errors directly influencing the metrological characteristics of the integrating measuring strain gauge converter is the inequality of the output voltages of the comparator. The current paper explores the effect of the voltages variation at the output of the comparator in the case of a bipolar power supply of the converter. The output data is obtained by modeling the equation of conversion in the MATLAB environment. The fore-mentioned problem is investigated assuming up to 20% inequality of the output voltages compared to the supply voltage and a bilateral change of the load on the strain gauges. A regression analysis is performed checking the suitability of a linear, quadratic and cubic model. It shows that the coefficient of determination is highest for the cubic model and relevant conclusions are made.

Keywords: comparator, converter, modeling, regression analysis, strain gauges

1 Introduction.

Strain gauges measuring converters are intended to amplify and convert the small output voltages that are obtained in disbalance of strain gauges bridge, which is known as "Wheatstone bridge". Every "Wheatstone bridge" consists of two or four strain gauges that are connected in half bridge or full bridge. The output voltage is proportional to the deformation of the strain gauges sensors. Depending on the mode of guidance (method of orientation) for bonding, the strain gauges can measure forces, moments, weight, etc.

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: (Шахов, 1986) , (Mochizuki,1996), (Kaliyugavaradan, 2000), (Madhu, 2009), (Гигов, 2013), (Станков, 2014) 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 (Мильченко, Романов, 1980), (Гигов, Гутников, 1981), (Гигов, Янков, 1986), (Glimert 1994), (Василев, Громков, 2009) and many others.

Here is investigated a converter of the disbalance of the resistance of a strain gauge bridge into frequency deviation; its block scheme is given in Figure 1 as well (Stoyanov, 2014).

The converter in Fig. 1 comprises as follows: integrator 4, comparator 1, strain-gauge resistive bridge 2, a differential amplifier 3 and a voltage divider 5 and 6. 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 DA, whose output is connected to the inverting input of the integrator I. The output of the integrator is connected to the inverting input of the comparator C, whose non-inverting input and output are associated with the output of the converter F.

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The output frequency is determined by the following equation:

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

where:

-T – the output period of the converter;

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

-k_{DA} – 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).

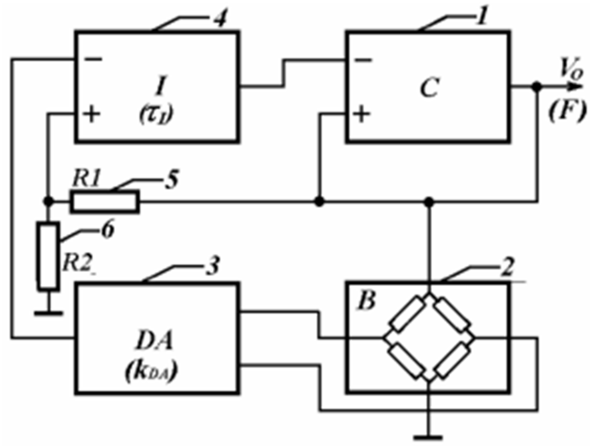

Fig. 1. Block scheme of the investigated converter

The proposed converter has very good metrological characteristics in bilateral change to the load. A prototype has been developed, and a patent application has been made (№111382, made on 25.01.2012). (Гигов, Станков, Стоянов, 2014).

On the basis of the main metrological characteristics of the converter, which have been received up to this moment, there is need of further analysis of the errors that determine the appearance of non-linearity and that change the output frequency (Гигов, 2013).

One of the main errors that influence directly the metrological characteristics is the inequality of the output voltage of the comparator. This leads to adding or subtracting the value of the error of the output voltage ΔU_{out} to the values of the positive or negative output voltages U^{+}_{out} and U^{-}_{out} [Гигов, 2013].

The values of the output voltages of the comparator U^{+}_{out} and U^{-}_{out} are as follows:

$$U^{+}_{out} = U_{out} - \Delta U_{out} \quad (2)$$

$$\left|U^{-}_{out}\right| = U_{out} + \Delta U_{out} \quad (3)$$

For the corrected period T * the following is obtained:

$$T^{*} = T * \left(\frac{U^{+}_{out} + \left|U^{-}_{out}\right|}{U^{+}_{out}} + \frac{U^{+}_{out} + \left|U^{-}_{out}\right|}{\left|U^{-}_{out}\right|} \right) \quad (4)$$

After substitution with 2 and 3 in 4 the following is obtained:

$$T^{*} = T * \left(\frac{U_{out} - \Delta U_{out} + U_{out} + \Delta U_{out}}{U_{out} - \Delta U_{out}} + \frac{U_{out} - \Delta U_{out} + U_{out} + \Delta U_{out}}{U_{out} + \Delta U_{out}} \right) \quad (5)$$

Here the following designation is introduced:

$$\frac{\Delta U_{out}}{U_{out}} = \delta U_{out} \quad (6)$$

After substitution of (6) and (5) in (1) and the conversion, the corrected output frequency f * of the equation of the conversion is obtained (7):

$$f^{*} = \frac{1}{T^{*}} = \frac{1}{T}\left(\frac{1-\delta U^{2}_{out}}{1}\right) = \left(\frac{\beta}{4\tau_I(1-\beta)} + \frac{k_{DA}}{8\tau_I(1-\beta)}\delta R\right)\left(1-\delta U^{2}_{out}\right) \quad (7)$$

where δU_{out} is the relative error of the output voltage

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Table 1 shows the data from the change of the output frequency of the comparator in modeling the equation of conversion and the influence of error in MATLAB environment (Stoyanov, 2014). A chart is built too, and it shows the time of changing of the values under load ΔR in 0,1 Ω and voltage variation ΔU in the interval from 0 to 1V. At the output voltage of the converter 5 V, the change of 1V represents 20% of the change of the output voltage. This amendment is sufficient to research the behavior of the converter at the specified input parameters.

Table 1. Modification of the output frequency Δ*f* depending on the amendment to ΔU and ΔR

ΔU	ΔR										
	-0,5	-0,4	-0,3	-0,2	-0,1	0	0,1	0,2	0,3	0,4	0,5
0	0	0	0	0	0	0	0	0	0	0	0
0,1	0,225989	0,310734	0,39548	0,480226	0,564972	0,649718	0,734463	0,819209	0,903955	0,988701	1,073446
0,2	0,903955	1,242938	1,581921	1,920904	2,259887	2,59887	2,937853	3,276836	3,615819	3,954802	4,293785
0,3	2,033898	2,79661	3,559322	4,322034	5,084746	5,847458	6,610169	7,372881	8,135593	8,898305	9,661017
0,4	3,615819	4,971751	6,327684	7,683616	9,039548	10,39548	11,75141	13,10734	14,46328	15,81921	17,17514
0,5	5,649718	7,768362	9,887006	12,00565	14,12429	16,24294	18,36158	20,48023	22,59887	24,71751	26,83616
0,6	8,135593	11,18644	14,23729	17,28814	20,33898	23,38983	26,44068	29,49153	32,54237	35,59322	38,64407
0,7	11,07345	15,22599	19,37853	23,53107	27,68362	31,83616	35,9887	40,14124	44,29379	48,44633	52,59887
0,8	14,46328	19,88701	25,31073	30,73446	36,15819	41,58192	47,00565	52,42938	57,85311	63,27684	68,70056
0,9	18,30508	25,16949	32,0339	38,89831	45,76271	52,62712	59,49153	66,35593	73,22034	80,08475	86,94915
1	22,59887	31,07345	39,54802	48,0226	56,49718	64,97175	73,44633	81,9209	90,39548	98,87006	107,3446

The chart in Figure 2 shows the dependencies of the change of the output frequency on the difference of the output voltages of the comparator at a fixed disbalance.

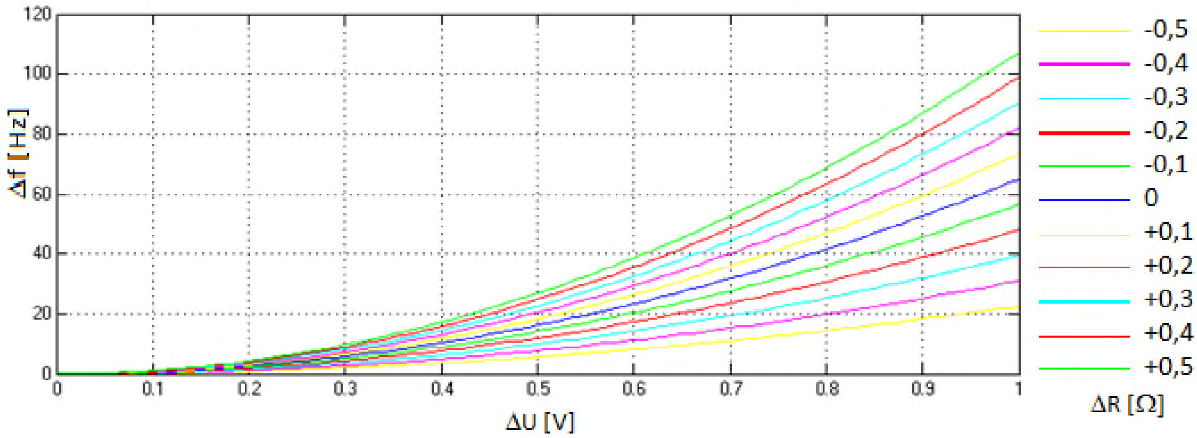

Fig. 2. Modification of the output frequency Δ*f* depending on the amendment to ΔU and ΔR.

The conducted modeling shows that the created simulation model of the measurement converter is highly dependent on the inequality of the absolute values of the output voltages of the comparator. The received non-linearity influences strongly the metrological characteristics of the converter.

A more precise estimate of the impact of the changing tensions could be made with the aid of mathematical statistics.

It is necessary to establish the relationship with a change of the voltage difference when working with a certain load (disbalance of the system) of the change of the output frequency. In the converter all of the control factors are quantitative, and the links between them are described and analyzed mathematically by the methods of regression analysis (Митков, 2011).

2 Main part

The object of research is presented in Fig.1. In this case there is a manageable factor x, one output parameter Y and disturbing influence ε. Since the value of the parameter Δf is formed both by ΔU and disturbing factors w_i, the following equation can be written:

$$Y = \eta(x) + \varepsilon \tag{8}$$

Where: $Y=\Delta f$ $x=\Delta U$

ε – aggregate disturbing influence, which is caused by the uncontrollable factors w_1, w_2, w_i

$\eta(x)$ – function of the factor x

The theoretical model of the researched converter will have the following form:

$$\Delta f = \eta(\Delta U) + \varepsilon \tag{9}$$

at ΔR=const.

The general appearance of the regression model is selected on the base of geometric submitted experimental data. Searched regression model can be written as follows:

$$\tilde{y} = f(x, \beta_0; \beta_1; \beta_2; \beta_i) \tag{10}$$

Where $\beta_0;\beta_1;\beta_2;\beta_i$ are the regression coefficients and $\tilde{y}=\eta(x)$

It is necessary that the function f(x) be approximated to one or several functions in order to determine the most reliable regression model:

$$\tilde{y} = f(\beta_0; \beta_1 x; \beta_2 x^2; \beta_3 x^3; \beta_n x^n) \tag{11}$$

Because of the random error ε in the experimental data and because of the final number of such data, one does not receive the exact values of the parameters $\beta_0;\beta_1;\beta_2;\beta_I$ but their ratings b_0; b_1; b_2; b_i, which are defined as experimental regression coefficients. Thereby the experimental model is obtained on the basis of the theoretical model.

$$\tilde{y} = f(x; b_0; b_1; b_2; b_3; b_i) \tag{12}$$

Where i = 1, 2, 3 ... .N is the number of points of the experiment

In the deduced formulas of the metrological analysis one can see that the influence of the change of the tension is of the second degree. Taking into account dependencies of mathematical modeling and type of the chart, it is expected that the presentation of the regression model $\hat{y}$ will be a second order polynomial, nonlinear internal to the factor ΔU.

$$\hat{y} = b_0 + b_1 x + b_2 x^2 \tag{13}$$

The type of the curves of the experimental chart assumes verification of the suitability of a linear model – Formula 14, and verification of the suitability of the cube model – Formula 15.

$$\hat{y} = b_0 + b_1 x \tag{14}$$

$$\hat{y} = b_0 + b_1 x + b_2 x^2 + b_3 x^3 \tag{15}$$

By means of statistical analysis it is necessary to determine the degree of definiteness of the researched model, to determine the portion of change of the parameter Y, which describes the model, the determine the adequacy of the regression models, to determine the significance of the regression coefficients b_0 b_1,b_2, to perform analysis of the residues $\varepsilon_j = y_j - \hat{y}_j$, and then to specify the final form of the model on the base of a comparative analysis of the three proposed models.

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Table 2. Degree of definiteness of the researched regression model

Parameter/ Model	R = –0,5Ω			R = 0Ω			R = +0,5Ω		
	Linear	Quad.	Cubic	Linear	Quad.	Cubic	Linear	Quad.	Cubic
Coef. of determin. R	0,963	0,99	0,095	0,963	0,99	0,996	0,963	0,99	0,996
Coef. of determin. R^2	0,927	0,979	0,991	0,928	0,98	0,991	0,928	0,98	0,991
Adjusted R^2	0,918	0,973	0,986	0,92	0,974	0,987	0,92	0,974	0,987
Stad. Error of the Estimate	0,087	0,05	0,035	0,94	0,053	0,037	0,94	0,053	0,037

In Table 2 are given the calculated coefficients of determination ***R*** and $\boldsymbol{R^2}$ for the three models. The value of the coefficient indicates the percentage of change in the frequency of Y from tension factor and the remainder to 100% due to other unmanageable factors. Generally, the closer $\boldsymbol{R^2}$ is to 1, the better is the selected model`s description of the change of the output value of the investigated factors (Митков, 2011). Variations of the researched variable (Adjusted R^2), as well as the standard error in the calculations (Stad. Error of the Estimate), are very small, which confirms the right choice of regression model.

In Table 2 it is seen that the coefficients of determination are weakly influenced by the change in resistance, and at values 0Ω and 0,5Ω are identical. This suggests regression analysis to be performed only maximum and minimum value of change of resistance (load) of the sensors of the converter.

In Figure 3 is shown a regression model at maximum negative load; in Figure 4 it is shown under zero load; and in Figure 5 it is shown at maximum positive load. There are given the lines of regression of the calculated values for linear,

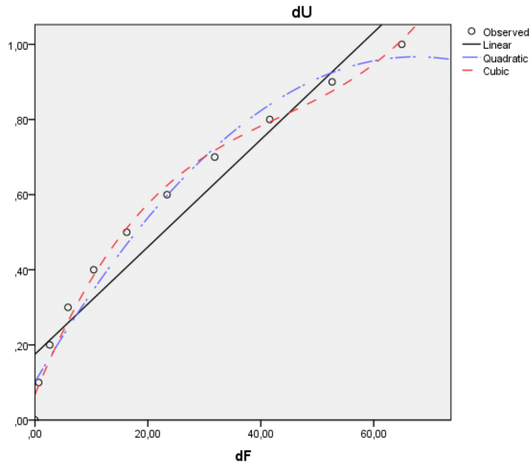

Fig. 3. Regression model at R= - 0,5Ω

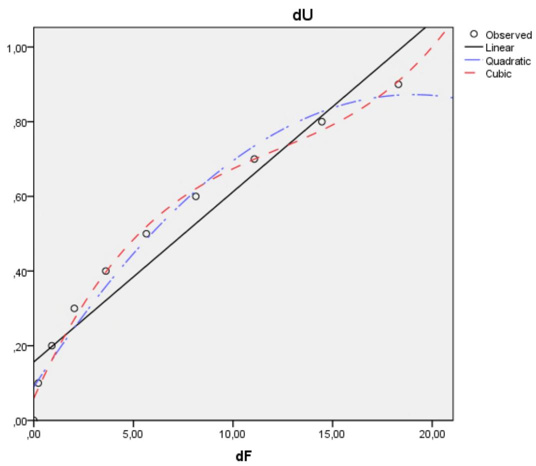

Fig. 3. Regression model at R= 0Ω

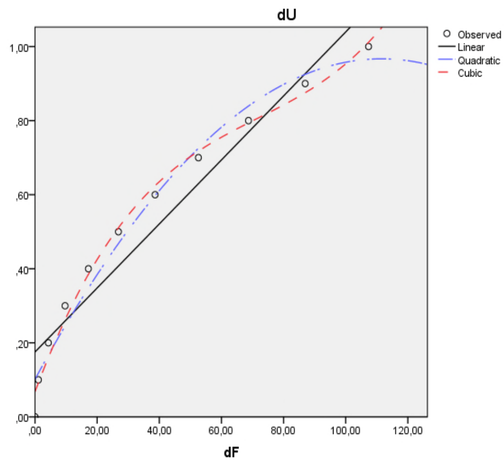

Fig. 5. Regression model at R= +0,5Ω

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quadratic and cubic model. It is seen that the cube model best describes the changes in frequency under the influence of confounding factors.

Table 3. Evaluation of adequacy by Fisher‘s criterion

Parameter/ Model	R = –0,5Ω			R = +0,5Ω		
	Linear	Quadratic	Cubic	Linear	Quadratic	Cubic
Criterion of Fisher F	115,385	192,263	261,246	115,385	192,263	261,246
Critical value of Fisher – F_{kr}	4,96	4,46	4,07	4,96	4,46	4,07

Evaluation adequacy of the regression models is done using the criterion of Fisher, which is the ratio of residual dispersion in relation to the dispersion of the reproducibility for each model-table 3. The greater the value of the criterion of Fisher, the more adequate the model is [10]. It is necessary, however, to compare initially the calculated value with the critical value of the criterion of Fisher – F_{kr} at significance level $\alpha = 0,05$. If the value is lower than critical, the model is not adequate.

Table 4 gives the values that characterize the significance of the coefficients (parameters) of the model $\boldsymbol{b_0, b_1, b_2 b_3}$ and the regression coefficients $\beta_0, \beta_1, \beta_2, \beta_3$.

The calculated value of the criterion of Student, for t_i – in these cases where N on number of experiments – is compared with data references particular for the degrees of freedom $k = N\text{-}1$ and $\gamma = 1\text{-}\alpha$, while $\alpha = 0,05$ – level of significance (Митков, 2011). A verification is made that $t_i > t_{kr}$. If this inequality is satisfied, that means that the respective coefficient of linear, quadratic or cubic model is significant.

Table 4. Significance of the coefficient of the criterion a Student

Parameter/ Model	R = –0,5Ω			R = +0,5Ω		
	Linear	Quadratic	Cubic	Linear	Quadratic	Cubic
b_0 b_1 b_2 b_3	0,175 0,09	0,102 0,016 6,959.1 0^{-5}	0,068 0,022 0,000 1,187.1 0^{-6}	0,175 0,41	0,102 0,074 -0,002	0,068 0,107 -0,006 0,000
β_0 β_1 β_2 β_3	0 0,963	0 1,73 -0,8	0 2,505 -2,93 1,408	0 0,963	0 1,73 -0,8	0 2,505 -2,93 1,408
t_0 t_1 t_2 t_3	4,230 10,742	3,558 9,735 -4,501	2,967 8,805 -4,107 3,033	4,230 10,742	3,558 9,735 -4,501	2,967 8,805 -4,107 3,033
t_{kr}	2,26	2,31	2,36	2,26	2,31	2,36

3 Results:

- The developed model of measurement converter is highly dependent on the inequality of the absolute values of the output voltages of the comparator.
- The coefficient of determination is the highest for the cube model, i.e. it most accurately describes the changes in frequency under the influence of confounding factors.

- Assessment evaluation of the adequacy of regression models is performed using the criterion of Fisher. Fisher‘s criterion is highest for cube model and does not depend on the load value on the strain gauges.
- The coefficient of determination and values of Fisher‘s criterion are identical across the whole measuring range. Thus, the high linearity of the converter in the research range is confirmed.
- Student‘s criterion does not run for negative values of t_i. All positive values t_i are significant. This results in a further simplification of regression models and a proof for the significance and relevance of the created models.
- The obtained results are the basis for further improvement of the converter and guaranty of the linearity in the whole measurement range.

4 Conclusion

The usage of the regression analysis turns out to be an appropriate decision for testing converter work in different modes. The proven capability to cube model suggests an extremely precise execution of power and measuring circuits.

It is important and necessary condition for the normal operation of the converter is to avoid differences in the output of the comparator tensions, especially due to their strong influence in the equation of transformation and their combined disturbance influence caused by unmanageable factors w_1, w_2, w_i.

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