The Design Features of Low-Temperature Radiation-Hardened Instrumentation Amplifiers and Sensor Interfaces

A. E. Titov
Southern Federal University
Rostov-on-Don, Russia
aetitov@sfedu.ru

N. N. Prokopenko, *Member of IEEE*
Don State Technical University
Rostov-on-Don, Russia
prokopenko@sssu.ru

I. V. Pakhomov
Don State Technical University
Rostov-on-Don, Russia
ilyavpakhomov@sssu.ru

***Abstract* – The article gives a theoretical analysis of the generalized structure of precision instrumentation amplifiers (IA) of modern interfaces for sensor and diagnostic systems of robots and unmanned aerial vehicles (UAV), which operate, among others, on exposure to radiation and low temperatures. The main disadvantages of classical IA are determined from the common positions and the possible ways of their clearing are presented. The new architecture of radiation-hardened differential difference op-amp (DDA) based on "folded" cascode is developed for the application in sensor interfaces and its simulation results are given, taking into account the effect of disturbing factors.**

Key words – robot, sensor interface, analog microcircuits, instrumentation amplifier, neutron flux, low temperatures

I. Introduction

One of the problems for the improvement of measuring equipments [1], for example of robots and UAVs, operating on exposure to radiation and low temperatures, is a lack of the necessary nomenclature of interface microcircuits with high generalized parameters, which provide the operation of a great number of intelligent sensors of different nature in the corresponding controlling and diagnosis systems.

The creation of interface microcircuits, oriented towards the interaction with various types of sensors, always involves the application of instrumentation amplifiers (IA) [2, 3, 4, 5]. These devices perform functions of common-mode voltage V_{cm} rejection and amplification of differential voltage V_d [2, 3].

In comparison with the well-known publications [2, 3, 4, 5], this article presents a general error estimation of classical IA on three op-amps and theoretically substantiates the prospects of DDA application and also the problems of application of DDA in this class of interfaces.

II. The Disadvantages of Classical Architecture of Instrumentation Amplifiers

The sufficiently great dynamic range of measuring values and the requirement of high accuracy of signal conversion predetermined the application of precision op-amps in IA (Fig. 1).

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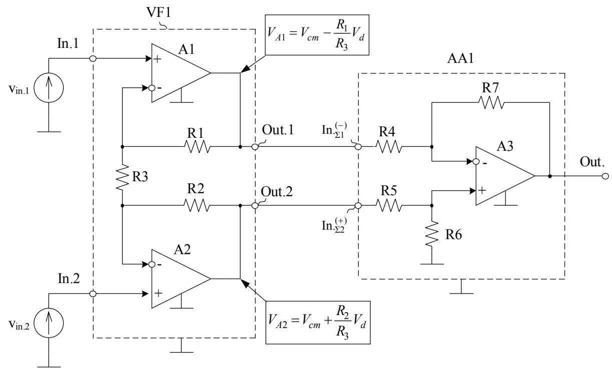

Fig. 1. Classical instrumentation amplifier

However, in many cases the application of IA (Fig. 1) [2, 3, 4, 5] based on three op-amps and seven resistors in the radiation-hardened and low-temperature [1] products occurs not optimal for a number of the following reasons.

The 1-st reason. The common-mode gain (A_{cm}) in the structure of IA of Fig. 1 is determined by the accuracy of manufacturing of the resistors $R_4 - R_7$. When using precisely ideal (identical) op-amps the limits of the coefficient A_{cm} are defined by the relation

$$A_{cm} = \frac{R_6}{R_5+R_6}\left(1+\frac{R_7}{R_4}\right)-\frac{R_7}{R_4}=\frac{R_6-R_5\,R_7/R_4}{R_5+R_6}. \qquad (1)$$

Consequently, the deep common-mode voltage rejection is possible only when the resistors of the output active signal adder (AA1, Fig. 1) are coordinated [3, 4].

The function (1) has a bilinear expansion

$$A_c = \frac{A+\lambda B}{C+\lambda D}, \qquad (2)$$

where λ – is a variable parameter of the circuit.

So, the effect of passive elements on the common-mode gain is determined by the sensitivity function

$$S_{R_i}^{A_{cm}} = \frac{R_i B}{A+R_i B}-\frac{R_i D}{C+R_i D}, \quad i=\overline{4,7}, \qquad (3)$$

which is defined by the relation

$$S_{R_i}^{A_{cm}} = \frac{\Delta A_{cm}/A_{cm}}{\Delta R_i/R_i}, \qquad (4)$$

where $\Delta R_i/R_i = \Theta_{R_i}$ – is a resistance error of the i-th resistor of the circuit.

Influence of each passive element on A_{cm} is estimated by sensibility factor:

$$S_{R_4}^{A_{cm}} = -\left(-\frac{R_5R_7 \cdot 1/R_4}{R_6 - R_5R_7 \cdot 1/R_4}\right) = \frac{R_5R_7}{R_4R_6 - R_5R_7}, \quad (5)$$

$$S_{R_5}^{A_{cm}} = -\frac{R_5R_7}{R_4R_6 - R_5R_7} - \frac{R_5}{R_6 + R_5}, \quad (6)$$

$$S_{R_6}^{A_{cm}} = \frac{R_4R_6}{R_4R_6 - R_5R_7} - \frac{R_6}{R_6 + R_5}, \quad (7)$$

$$S_{R_7}^{A_{cm}} = -\frac{R_5R_7}{R_4R_6 - R_5R_7}. \quad (8)$$

Therefore, the absolute error of the common-mode gain $\Delta A_{cm} = f(\Theta_{R_i})$:

$$\Delta A_{cm} = S_{R_4}^{A_{cm}} A_{cm}\Theta_{R_4} + S_{R_5}^{A_{cm}} A_{cm}\Theta_{R_5} + + S_{R_6}^{A_{cm}} A_{cm}\Theta_{R_6} + S_{R_7}^{A_{cm}} A_{cm}\Theta_{R_7}. \quad (9)$$

If the errors of the resistive elements are equal, we'll get the following:

$$\Delta A_{cm} = \sqrt{\sum_{i=4}^{7}\left(A_{cm}S_{R_i}^{A_{cm}}\right)^2 \Theta_{R_i}^2} = \Theta_R\sqrt{\sum_{i=4}^{7}\left(A_{cm}S_{R_i}^{A_{cm}}\right)^2}, \quad (10)$$

If we choose $R_4 = R_5 = R_6 = R_7 = R$ then, considering the uncertainties of type [0, ∞] disclosure rules

$$\Delta A_{cm} = \Theta_R. \quad (11)$$

From the mentioned relation it is seen that the A_{cm} has a directly-proportional dependence on the resistance error of the circuit resistors Θ_R. Even for precision technologies, when $\Theta_R = 0{,}1\%$, the value A_{cm} is not less -54 dB. In most cases it is not enough. So, when manufacturing IA, a special functional adjustment is used to reach the required magnitude of A_{cm}.

The 2-nd reason – is an effect of common-mode rejection ratio (*CMRR*) of the active elements A1 and A2. To estimate this influence let's analyze a generalized structure (Fig. 2), by which we mean a set of baseline structures and circuits, forming a complete graph (Fig. 3).

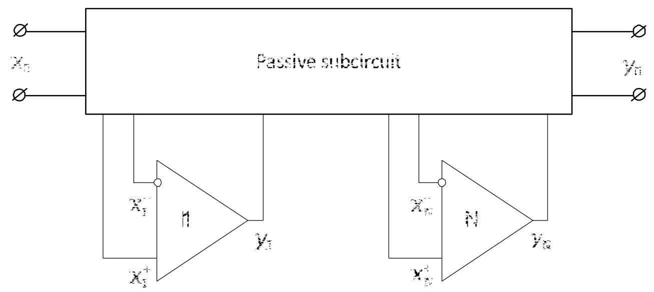

Fig. 2. The generalized structure of IA with nonseparated feedback loops

The generalized structure of Fig. 2 provides a functional and circuitry completeness, which guarantees, that any physically realizable solution of a certain problem of IA design can be obtained from the generalized structure by simple truncation. For this task op-amps are baseline elements of structure Fig. 2.

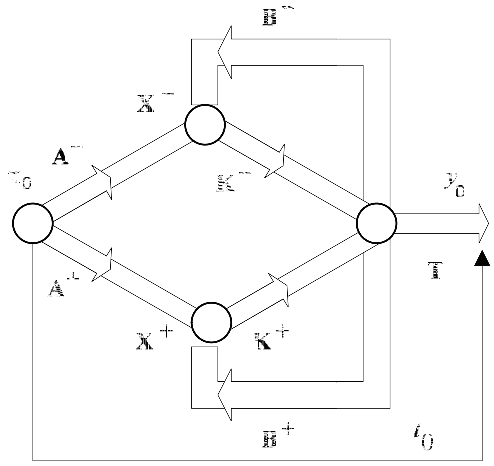
Fig. 3. Vector signal-flow graph of the generalized structure of IA

In [6, 7] it is shown that the generalized structure of IA of Fig. 2 is described by the following matrix-vector system of equations

$$\begin{cases}\mathbf{X}^- = \mathbf{A}^- x_0 + \mathbf{B}^-\mathbf{Y}, \quad \mathbf{X}^+ = \mathbf{A}^+ x_0 + \mathbf{B}^+\mathbf{Y}, \\ \mathbf{Y} = \mathbf{K}^-\mathbf{X}^- + \mathbf{K}^+\mathbf{X}^+, \quad y_0 = \mathbf{T}\mathbf{Y} + t_0 x_0. \end{cases} \quad (12)$$

The meaning of vectors $\mathbf{X}^-$, $\mathbf{X}^+$, $\mathbf{Y}$, $\mathbf{T}$, $\mathbf{A}^+$, $\mathbf{A}^-$, t_0 and matrices $\mathbf{B}^-$, $\mathbf{B}^+$, their structure are explained in Fig. 3.

When defining the local transmissions it is necessary to connect the pins of the unused op-amps with common bus [6, 7]. The active elements are described by diagonal matrices

$$\mathbf{K}^- = \{K_i^-(\mathrm{p})\}, \ \mathbf{K}^+ = \{K_i^+(\mathrm{p})\}, \quad (13)$$

with the dimension $N \times N$, the components of which are gain of op-amp in inverting $K_i^-(\mathrm{p})$ and non-inverting $K_i^+(\mathrm{p})$ inputs. For modern op-amps with low A_{cm}

$$K_i^+(\mathrm{p}) = -K_i^-(\mathrm{p}) = K_i(\mathrm{p}). \quad (14)$$

The transfer function of the generalized structure of Fig. 2 is defined from (12), taking into account (13),

$$\mathrm{F(p)} = t_0 + \mathbf{T}\left[\{K_i(\mathrm{p})\}^{-1} + \mathbf{B}\right]^{-1}\mathbf{A}, \quad (15)$$

where $\mathbf{B} = \mathbf{B}^- - \mathbf{B}^+$, $\mathbf{A} = \mathbf{A}^+ - \mathbf{A}^-$.

For the ideal op-amps $(K_i(\mathrm{p}) = \infty, i = \overline{1,N})$

$$\mathrm{F}_u(\mathrm{p}) = t_0 + \mathbf{T}\mathbf{B}^{-1}\mathbf{A}. \quad (16)$$

However, when the condition (14) is not met, the function (15) is determined by the equation

$$\mathrm{F(p)} = t_0 + \mathbf{T}\left[\{K_i^+\}^{-1} + \mathbf{B} - \{CMMR_i^{-1}\}\mathbf{B}^+\right]^{-1} \cdot \cdot\left(\mathbf{A} + \{CMMR_i^{-1}\}\mathbf{A}^+\right), \quad (17)$$

where $CMRR_i = K_i^+ / A_{cm_i}$ – is *CMRR* of the *i*-th op-amp.

Thus, whatever the structure of matrices $\mathbf{B}^-$ and $\mathbf{B}^+$, which determine the interaction of op-amp in IA, its A_{cm} will be defined by *CMRR* of the used op-amps. This conclusion is substantiated by the analysis of the basic variants of IA of Fig. 1, when $\mathbf{B}^+ = 0$, $\mathbf{A}^- = 0$ or $\mathbf{A}^+ = 0$, $\mathbf{B}^- = 0$. For example, for classical IA (Fig. 1)

$$\begin{cases} b_{11}^- = (R_3 + R_2)/R_\Sigma, \; b_{12}^- = R_2/R_\Sigma, \; b_{33}^- = R_4/(R_4 + R_7), \\ b_{23}^+ = R_6/(R_5 + R_6), \; b_{21}^- = R_1/R_\Sigma, \; b_{22}^- = (R_3 + R_1)/R_\Sigma, \\ b_{13}^- = R_7/(R_4 + R_7), \; \mathbf{A}^- = 0, \; \mathbf{A}^+ = [1 \;\; 1 \;\; 0], \; \mathbf{T} = [0 \;\; 0 \;\; 1], \end{cases} \quad (18)$$

where $R_\Sigma = R_1 + R_2 + R_3$, b_{ij}^+, b_{ij}^- – are parameters of the corresponding matrices [6].

According to (17), with the optimum relationship of resistors $R_4 = R_5 = R_6 = R_7$, $R_1 = R_2$ the limiting value of A_{cm} is defined by the identity of active elements A1 and A2 (Fig. 2) in *CMMR*:

$$A_{cm.\min} = A_d \left(1/CMRR_2 - 1/CMRR_1\right) - 1/CMRR_3 , \quad (19)$$

This may be due to the differential gain of the IA circuit

$$A_d = R_\Sigma / R_3 > 1 . \quad (20)$$

Thus, even the condition $CMRR_1 = CMRR_2$ is met, the minimum magnitude of A_{cm} is not better, than

$$A_{cm.\min} = \Delta A_{cm.\min} \approx A_d \left(\Delta CMRR_1^{-1} - \Delta CMRR_2^{-1}\right). \quad (21)$$

Consequently, the circuitry of the active elements A1 and A2 should provide for special measures, increasing their *CMRR*.

The 3-rd reason. It is shown in [6, 7], that the common-mode voltages V_{cm} in the outputs of the active elements A1 and A2 depend on Θ_R of the resistors R_1, R_2 and R_3 and are determined by the relations

$$V_{cm\_Out.1} = \left[\frac{1 + (1 + k_1 + k_2)}{k_2 + (1 + k_1) A_{c1} / k_1} \right] V_{in} , \quad (22)$$

$$V_{cm\_Out.2} \approx \left[\frac{1 + (1 + k_1 + k_2)}{k_1 + (1 + k_2) A_{c2} / k_2} \right] V_{in} , \quad (23)$$

where $k_1 = R_1 / R_3$, $k_2 = R_2 / R_3$.

Thus, to provide the independence of the A_{cm} of IA on the feedback resistors error it is necessary to increase the CMRR into input differential stages of the active elements A1 and A2.

The 4-th reason. The structure of classical IA of Fig. 1 causes an inefficient use of the gain-transfer characteristic of the active elements A1 and A2. This is due to the fact that the main part of gain-transfer characteristic of A1 and A2 contains a component of the input common-mode voltage

$$V_{A1} = V_{cm} - \frac{R_1}{R_3} V_d , \; V_{A2} = V_{cm} + \frac{R_2}{R_3} V_d , \quad (24)$$

where V_{A1} and V_{A2} – are voltages in the outputs of op-amp A1 and A2, correspondingly, V_{cm} – is a common-mode voltage in the inputs of IA, V_d – is a differential voltage in the inputs of IA.

Thus, the limitation of maximum output voltage occurs due to the effect of V_{cm} in the classical circuit of IA. It doesn't allow using the low-voltage active elements and requires a considerable increase of linearity of the input circuits of the active adder AA1.

The 5-th reason – is the presence of the output offset voltage V_{oo} and its drift, which effect on the dynamic range and the conversion accuracy of physical quantities. For the circuit of IA of Fig. 1

$$V_{oo} \approx A_d \left(V_{io\_A2} - V_{io\_A1}\right)/2 + (1 + R_7/R_4) V_{io\_A3} , \quad (25)$$

where V_{io_Ai} – is an input offset voltage of the *i*-th active element.

Even in case of the precisely identical op-amps and the optimum relationship of resistors the parameter V_{oo} cannot be better, than $V_{oo} = 2V_{io\_A3}$. This magnitude is determined by the structure of the adder A3.

III. The Main Directions of the Precision Increase of the Instrumentation Amplifiers for Sensor Interfaces

In general terms the theoretical findings allow defining the main requirements, applicable to designing of the instrumentation amplifiers which operate on exposure to `the effect of disturbing factors (DF).

1. It is necessary to exclude resistors of the structure of the active adder AA1. It'll allow not only increasing the reachable common-mode rejection ratio in case of the effect of DF, but also increasing the chip yield in the process of manufacturing of IAs and decreasing their offset voltage.

2. It is necessary to achieve the increase of *CMRR* of the input common-mode voltages V_{cm} both in the active elements A1 and A2, and in the adder A3. It'll allow minimizing the common-mode in the output signals A1, A2, AA1, increasing the utilization efficiency of their gain-transfer characteristic and input circuits of the active adder AA1. In addition, the error effect of the resistive elements of IA on the output signals A1 and A2 decreases significantly.

The practical implementation of the abovementioned requirements resolves oneself into the necessity of application of the active elements of the relatively new class in IA – differential difference op-amps [8, 9] with a set of (i) inverting and non-inverting inputs (Fig. 4 ($i = 2$)). Such structure of the input circuits construction of A1 and A2 allows excluding the resistors $R_4 \div R_7$. This partially solves the reviewed above problems in case of the IA designing and also allows providing a simple digital control by the differential gain of IA (Fig. 4).

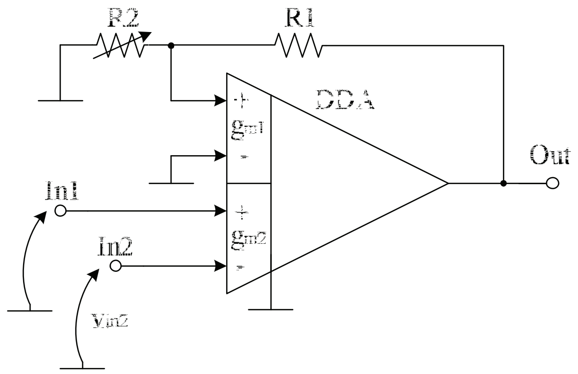

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Fig. 4 Instrumentation amplifier based on DDA

However, the apparent simplicity of such solution is due to the necessity of the further improving of DDA circuitry, the parameters of which dominate in the common error of IA now. In comparison with classical OA, the differential difference op-amp (in case of other equal conditions) has, as a rule, higher values of V_{oo}, lower differential gain and lower *CMRR*, and also it is characterized by other disadvantages [7].

IV. The Examples of DDA implementation

The Fig. 5 presents a new architecture of DDA based on the "folded" cascode [10], which, unlike other well-known solutions, is characterized by higher speed in large-signal operation. This is due to the fact that the intermediate stage of this DDA operates in class AB. As a result in the scheme of Fig. 5 the higher recharge of the balancing capacitor C_b is provided that increases a slew rate of IA to 1000 V/µs (for a BiJFet process [11]).

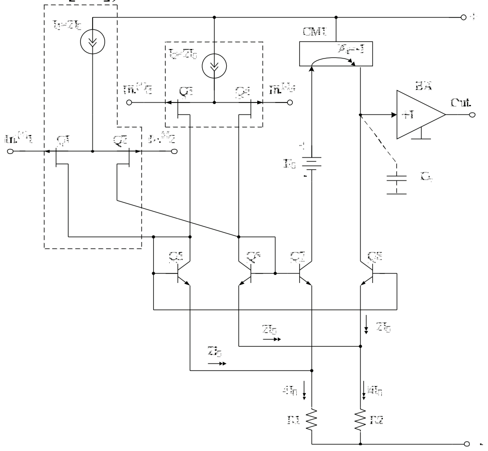

Fig. 5. BiJFet DDA with the non-linear correction circuit in the intermediate stage

The Bode plot of differential voltage gain of DDA (Fig.5) is showed on Fig.6. From Fig.6 it follows, that open-loop gain of DDA above 50 dB.

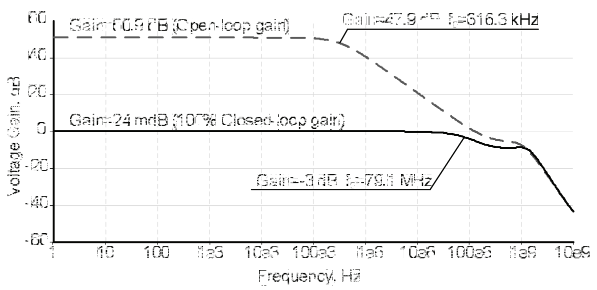

Fig. 6. Bode plot of differential voltage gain of DDA

The suggested architecture of DDA (Fig. 5), in case of its implementation in radiation-hardened BiJFet process (OJSC "Integral" (Minsk)) [11], is also characterised by the low offset voltage V_{oo} on exposure to the temperature (Fig. 7) and radiation.

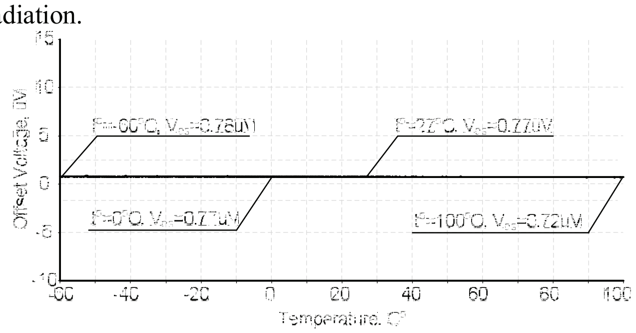

Fig. 7 – The dependence of offset voltage V_{oo} of DDA on the temperature

When the neutron flux $F_n < 5 \cdot 10^{13}$ n/cm^2, the systematic component of the offset voltage V_{oo} (without parameter spread, ideal the current mirror (CM1) and the buffer amplifier (BA)) is lower than 10 µV. It characterizes the limiting parameters of the DDA, which can be pursued. Low values V_{oo} in circuit (Fig. 5) caused a decrease of the influence of temperature and radiation degradation of transistor parameters because of effects of mutual compensation.

Presented results have been obtained using the radiation-hardened models of transistors of technological process ABMK_1.3 [11].

V. Conclusion

One of the creation directions of instrumentation amplifiers with high parameters, resistant to the radiation effect and the low temperatures is an amplification of differential difference op-amps. In this case the qualitative improvement of the IA parameters is due to the DDAs precision increase – their offset voltage decrease, the differential gain and common-mode rejection ratio increase in conditions of the low temperatures and radiation effect, the range extension of linear operation of the input stages, etc. However, the circuitry improvement of these parameters is not a simple task and nowadays it is neglected. Consequently, when constructing IA, based on DDA, the main problem of its precision increasing is transferred to the solving of design issues of more precise DDAs of the new generation.

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