AMPLIFICATION STRUCTURES WITH ADDITIVE ERROR COMPENSATION

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For two classes of amplification structures with additive error compensation, the authors calculated the sensitivity of gain to changes in elements of the structures and formulated conditions for the observance of stability. The results obtained are analyzed on the basis of comparison with an amplification structure with overall negative feedback.

Amplification structures with additive error compensation (AS with AC), which were discussed in [1-3], contain, besides the main one, a compensating channel that forms an error signal. The error signal is introduced into the main channel in such a way that the error is compensated in the output signal. It has been suggested [4] that such AS make it possible to avoid the trade-off of increased accuracy for a corresponding loss of amplification, which is characteristic of AS with overall negative feedback (AS with NFB).

The purpose of the present work is to calculate the sensitivity of gain for an AS with AC to variations in elements of the AS, determine the working range of frequencies from considerations of stability, and to evaluate the efficiency of the trade-off of the compensating channel's surplus gain for accuracy in an AS with AC in relation to a reference AS with NFB.

Figure 1 represents generalized structural diagrams of AS with AC related to each other by N-transformation [4]. The transfer function of AS with suppression of an error signal [1] (Fig. la) is determined by the relationship:

$$A_1 = \frac{U_{вых}}{U_{вх}} = \frac{G_1 + G_2(aG_1 + b)}{1 + \beta G_2(aG_1 + b)}$$

and for a structure with isolation of the error signal [2,3] (Fig. 1b):

$$A_2 = \frac{U_{вых}}{U_{вх}} = \frac{G_1 - bG_2(\beta G_1 - 1)}{1 + aG_2(\beta G_1 - 1)}$$

The value of the feedback circuit's transfer ratio $\beta = 1/G_1$ is chosen from the condition of equality of the main channel's gain G_1 and that of the AS with AC as a whole (A_1, A_2).

The sensitivity of the gain A_1 of an AS with suppression of an error signal to changes in G_1 is written in the form:

$$S_{A1}[G_1] = \frac{G_1(1 + G_2(a + \beta b))}{(G_1 + G_2(aG_1 + b))(1 + \beta G_2(aG_1 + b))} . \quad (1)$$

The sensitivity $S_{A1}[G_1]$ tends to zero from the right with a rise in the compensating channel's gain G_2 . For active error-signal FB with input summation [1] ($a = 1, b = 0$), (1) is rewritten in the form $S_{A1}[G_1] = \frac{1}{1 + \beta G_1 G_2} \approx \frac{1}{1 + G_2}$. The derived expression coincides with the gain sensitivity of an AS with NFB the direct-transmission circuit of which contains amplification channels with gains G_1 and G_2 connected in series, and the FB circuit has the transfer ratio $\beta = 1/G_1$ [5]. For active error-signal FB with output summation [1] ($a = 0, b = 1$):

$$S_{A1}[G_1] = \frac{1}{1 + G_2} \approx \frac{1}{1 + \beta G_2}$$

which corresponds to application of an FB loop with transfer ratio $\beta = 1/G_1$ to the compensating channel.

For an AS with isolation of an error signal $S_{A2}[G_1]$ is determined by the expression

$$S_{A2}[G_1] = \frac{G_1(1 - G_2(a + \beta b))}{(G_1 - bG_2(\beta G_1 - 1))(1 + aG_2(\beta G_1 - 1))} \quad (2)$$

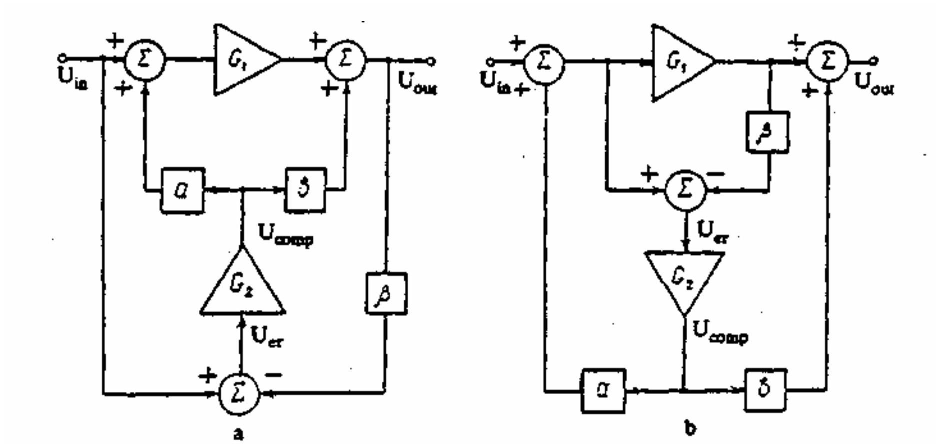

Fig.1

The numerator of (2) is equal to zero if the condition $G_2(a+\beta b)=1$ is fulfilled, i.e., if the possibility theoretically exists of obtaining zero sensitivity of A_2 to changes in G_1. In the case of "error correction" [2] ($a=1, b=0$), (2) takes the form $S_{A2}[G_1]=\dfrac{1}{1+\beta G_1 \dfrac{G_2}{1-G_2}} \approx 1-G_2$, and the least value of sensitivity is attained when G_2 tends to 1. With error compensation of an AS by feedforward [3] ($a=0, b=1$),

$$S_{A2}[G_1]=\frac{1}{1+\dfrac{G_2}{G_1(1-\beta G_2)}} \approx 1-\beta G_2$$

and $S_{A2}[G_1] \rightarrow 0$ when $G_2 \rightarrow 1/\beta$. Thus, an AS with isolation of an error signal has close to zero sensitivity S_{A2} to variations in G_1 when $G_2=1/(a+\beta b)$. The amount of deviation of G_2 from the exact value entirely determines $S_{A2}[G_1]$; therefore, G_2, in turn, must be stabilized, for example, with the help of a local FB loop. In the case of "error correction" ($a=1, b=0$), the minimum sensitivity of $S_{A2}[G_1]$ is attained when $G_2=1$. We will assume that this condition is fulfilled by means of application of local FB to the compensating channel's amplifier, with gain G_2^* of 100%. The compensating channel, in this case, represents a voltage follower with galvanically uncoupled feed circuits [4] and $G_2=G_2^*/(1+G_2^*)$, $G_2^*=G_2/(1-G_2)$ and $G_2 \rightarrow 1$ when $G_2^* \rightarrow \infty$. Combining with (2), we get $S_{A2}[G_1]=\dfrac{1}{1+\beta G_1 G_2^*} \approx \dfrac{1}{1+G_2^*}$, which coincides with the expressions derived for AS with suppression of an error signal and for AS with NFB. When the error is compensated by feedforward ($a=0, b=1$), we will take $G_2=G_2^*/(1+\beta G_2^*)$ and $G_2 \rightarrow 1/\beta$ when $G_2^* \rightarrow \infty$, which corresponds to application of local FB with the transfer ratio β to the compensating channel's amplifier. Carrying out analogous substitution, we get $S_{A2}[G_1]=\dfrac{1}{1+G_2^*/G_1} \approx \dfrac{1}{1+\beta G_2^*}$, which also coincides with the expression for an AS with suppression of an error signal. Thus, none of the structures considered above possesses sensitivity to changes in the gain of the main channel G_1 less than for the corresponding AS with NFB. What is more, in deriving (1) and (2) we assumed that the adders connected at the AS's input and output possess zero multiplicative error.

We will consider the sensitivity to changes in the compensating channel. For the AS in Fig. la,

$$S_{A1}[G_2]=\frac{G_2(aG_1+b)(1-\beta G_1)}{(G_1+G_2(aG_1+b))(1+\beta G_2(aG_1+b))} \qquad (3)$$

In the limiting cases,

$$S_{A1}[G_1] = \frac{G_2(1-\beta G_1)}{(1+G_2)(1+\beta G_1 G_2)} \approx \frac{1-\beta G_1}{1+G_2}$$

with $a = 1, b = 0$; and $S_{A1}[G_1] = \frac{G_2(1-\beta G_1)}{(G_1+G_2)(1+\beta G_2)}$ with $a = 0, b = 1$. For the AS in Fig.1b,

$$S_{A2}[G_2] = \frac{G_2(aG_1+b)(1-\beta G_1)}{(G_1 - bG_2(\beta G_1 - 1))(1 + aG_2(\beta G_1 - 1))} \quad (4)$$

In the limiting cases,

$$S_{A2}[G_2] = \frac{G_2(1-\beta G_1)}{1+\beta G_1 G_2 - G_2} \approx 1-\beta G_1$$

with $a = 1, b = 0$, and

$$S_{A2}[G_2] = \frac{G_2(1-\beta G_1)}{G_1 + G_2 - \beta G_1 G_2} \approx 1-\beta G_1$$

with $a = 0, b = 1$. For all of these expressions, $S_{A2}[G_2]$ is proportional to $1-\beta G_1$, the amount of deviation of the main channel's gain G_1 from the nominal value $1/\beta$. This is connected with the absence of a signal at the compensating channel's output when the condition $G_1 = 1/\beta$ is fulfilled.

For correct comparison of AS with AC to AS with NFB, we have to determine the operating range of frequencies at which the sensitivities determined by (l)-(4) will be less than unity. The band of operating frequencies is determined from considerations of the stability of AS with AC. FB theory [5] enables us to draw a conclusion in relation to the behavior of a closed FB loop, considering signal transmission along an open loop, i.e., loop amplification L. It is convenient to choose the point of the loop's break for AS with AC at the output of the compensating channel. In this case, loop amplification L, or the ratio of $G_2 U_{ERR}$ to U_{COMP} (Fig. 1), is naturally divided into two parts: the gain of the compensating channel G_2 and the transfer ratio of the active FB circuit around the compensating channel.

The problem of synthesizing AS with AC, when seen in this way, is reduced to the question of proper behavior of the frequency response $L(j\omega)$ on a complex plane near the point ($-1,+j0$). The restrictions imposed on $L(j\omega)$ express the Nyquist criterion. For AS with suppression of an error signal (Fig. la), the loop amplification L

$$L_1 = -\frac{G_2 U_{ERR}}{U_{COPM}} = \beta G_2(aG_1 + b)$$

In the limiting cases $L_1 = \beta G_1 G_2$ ($a = 1, b = 0$) and $L_1 = \beta G_2$ ($a = 0, b = 1$), loop amplification and sensitivity $S_{A1}[G_1]$ correspond in accuracy to an AS with NFB. The amount of $S_{A1}[G_1]$ and the effective frequency band (for which $S_{A1}[G_1] < 1$) for an AS with suppression of an error signal do not differ from the values for AS with NFB. For an AS with isolation of an error signal (Fig. 1b), loop amplification is

$$L_2 = -\frac{G_2 U_{ERR}}{U_{COPM}} = -aG_2(1-\beta G_1)$$

In the limiting cases, $L_2 = -G_2(1-\beta G_1)$ with $a = 1, b = 0$, and $L_2 = 0$ with $a = 0, b = 1$. With error compensation of the AS by feedforward, there is no explicit stability criterion. However, finite output resistance of the main channel with the use of an output resistive adder or connection of a load between the outputs of the main and compensating channels leads to formation of a parasitic FB loop around the compensating channel [1]. This shortcoming can be eliminated by the use of a matched bidirectional adder of the three-winding transformer type, or a balanced bridge [3].

In the case of "error correction" [2], positive FB with a transfer ratio $1-\beta G_1$ is applied to a compensating channel with gain $G_2 \approx 1$ through an input adder. According to the principle of compatibility of negative and positive FB [4], for a nonautonomous active multiport network connected to a passive circuit and covered by negative FB, in relation to any direction of transmission there is always another transmission direction in relation to which it will be covered by positive FB.

The case to be analyzed ($a = 1, b = 0$) $L_2 = -G_2(1 - \beta G_1)$ $G_2 \approx 1$, belongs to the class of closed circuits with positive FB constructed on the basis of voltage followers and can be transformed to the class of closed circuits with negative FB constructed on the basis of inverting voltage amplifiers. After the transformations, we get an AS in which a parallel FB circuit with transfer ratio βG_1 is applied to an inverting amplifier with gain $G_2^* = G_2/(1 - G_2)$. In this case, G_2^* corresponds to the previously introduced value, and loop amplification $L_2^* = \beta G_1 G_2^*$ coincides with the value for an AS with NFB.

The AS with AC under consideration behaves analogously to AS with NFB with two degrees of freedom [5], allowing an independent choice of the transfer function A and sensitivity to variations of the controlled object (the main amplification channel). Simultaneous fulfillment of the requirements for A and $S_A[G_1]$ is provided by the same means as in AS with NFB, and in this sense AS with AC do not have any fundamental advantage. The sensitivity $S_A[G_1]$ and operating frequency band determined from the conditions of maintaining stability (with the exception of AS with error compensation by feedforward) do not surpass the corresponding values for AS with NFB. The trade-off of the compensating channel's amplification for a decrease in $S_A[G_1]$ occurs to the same degree as in AS with NFB, and in this sense AS with AC are inefficient.

On the other hand, AS with suppression of a noise signal do possess less sensitivity to variations in G_2, and both variants of AS with AC have a wider band of frequencies with which $S_{A1}[G_2]$ and $S_{A2}[G_2]$ is less than unity. This makes it possible to choose the characteristics and parameters of channels for AS with AC. For example, in order to get an accurate, fast AS, it is sufficient to supplement a high-speed main channel with a highly accurate compensating channel, which can have relatively low speed. In this case, the conditions linking the range of the active amplification mode for each of the AS's cascades to the transfer ratio of the preceding cascade, which are characteristic of highly accurate, fast AS with NFB, are removed [6].

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