CALCULATION OF DEVICES AND ELECTRONIC EQUIPMENT OWN NOISE (ACTIVE RC FILTER, RAUKH'S CIRCUITS)

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REZUMAT. Actuala lucrare este dedicată metodei de calcul a zgomotului propriu al dispozitivelor şi echipamentelor electronice de selecție a semnalelor prin frecvență. Drept obiect ale acestor calcule sunt utilizate filtrele active *RC* , în varianta practică schemelor de realizare *Raukh*. Aceste scheme de realizare permit obținerea filtrelor active cu diferite funcții de transfer, ca trece-jos (FTJ), trece-sus (FTS) şi trece-bandă (FTB). Metoda de calcul propusă în această lucrare este bazată pe un şir de elemente din teoria generală a cuadripolilor „zgomotoşi". Astfel, filtrul activ *RC* este prezentat ca o conexiune a doi cuadripoli, elementul activ (amplificatorul operațional) – sursă de tensiune comandată prin tensiune – STCT şi circuitul pasiv *RC* , iar proprietățile lor de zgomot sunt prezentate ca un generator sumar $I_{\Sigma\Sigma}$ (figure 5, *a* şi *b*) . Lucrarea conține rezultatele calculului teoretic conform metodei propuse şi ale măsurărilor experimentale care confirmă posibilitatea utilizării acestei metode practica inginerească (figure 8).

Cuvinte cheie: filtre active, funcție de transfer trece-jos, trece-sus, trece-bantă, amplificator operațional, cuadripol, zgomot propriu, zgomot termic, caracteristici de zgomot, densitatea spectrală, circuit echivalent, generator echivalent de zgomot.

ABSTRACT. This paper is dedicated to the method of calculation to its own noise of electronic devices and equipment for selection of signals by frequency. As the concrete object of the calculations presented in this paper are active *RC* filters in practice *Raukh* version. This scheme allows the realization of active filters to obtain the transfer function high-pass (HPF), low-pass (LPF) and pass-band (PBF). The calculation method proposed in this paper is based on elents of the general theory of quadripoles „noisy". Thus, active *RC* filter is presented as a sumary quadripole obtained from connecting the active element (operational amplifier) – voltage - controlled voltage source – VCVS and passive *RC* circuit, and a his noise properties – through a summary generator noise, $I_{\Sigma\Sigma}$ (figure 5, *a* and *b*). The paper containe the results of theoretical calculations and experimental measurement, which confirm the possibility to utilize thise methode of calculation in engineering practice (figure 8).

Keywords: active filter, pass-low, pass-high, pass-band transfer function, operational amplifier, quadripoles, own noise, termal noise, noise caracteristics, spectral density, equivalent circuit, noise equivalent generator

1. INTRODUCTION

Electronic noise can rightly be considered an obstacle to advanced technologies. From the category of „Advanced Technologies..." is part of Information Technology – perhaps even the most advanced technologies at the end this century and the beginning of the millennium!

We can say with certainly that at present there is no other sphere of science and modern technology, which is experiencing a kind of rapid development. We are witness eyes of process that took place in the last decades of the twentieth century, a process that no one can by considered as an exaggeration....the computer revolution, a process which reached its magic wing in absolute every human activity: economic and military, social and cultural, scientific and production activity.

This revolution is still ongoing and not long ago has entered a new phase, related to the WWW – W*orld* W*i-de* W*eb*, or already used – *Internet*, spider's web.

Everything goes to the situation, it can in about 5 –7 years throughout the world there will be no people to whom fate and life would not be influenced by the pre-sence of this field world information or how far man should by computer and personal computers (PC).

The work began several generations of young professionals who were born, they mature and mental enters formed in the century of personal computers. These generation can not imagine to life without a PC, as without a refrigerator, television or car.True is the fact that neither the car nor the TV do not occur as changes, modifications and even radical changes such compute: the operating methods or procedures of these devices or machines does not change significantly for decades.

Completely different things work for the computer: the computers entirely renewed about two years leads to a fundamental change in working methods and processes it. Who claims to meet the accelerated development of computer technology means constant selftraining needs and improve oneself. But for to use this technique to a genuine professional level it's required and more: a diligence work and constant effort, perseverance and unfailing desire to know what happens in the world of **information technology** [1].

The core of information technology is the working from electrical signals: a selection and receivertion of these signals, processing and theirs transmission. Of particular importance in the information transmission and processing issues (which in tum is nothing more then data processing, id est of signal using appropriate mathematical instruments) the methods of calculation or mathematical modeling of both signal itself and the caracteristics of itens and devices, used in this purpose.Their-making process component characterizes the scientific and technical information of the technical means of calculation that is – without exageration – the foundation of progress worldwide.

Among the basic characteristics of computer components directly involved in signal pricessing it is considered the **sensitivity threshold** – at least that level of input signal , which can by plainly (and processed), the background **noise** – bath foreign and **self**. This paper is dedicated to method of calculation to its own noise of the devices by selecting of signal for frequency, based on **active *RC* filters**.

These devices and electronic circuits are widely used in radio engineering, radio electronic and telecommunications, for the selection of signals by frequency, in equipments for multiplexing in plant liaison channels and in many other cases, when the frequency signal is in range of sound waves rather than of 1 MHz.

In this paper the author uses the `notion of signal` given in [2]: the `signal` is colled a measurable physical quantity, carrier of information that can be remotely transmitted, received and/or processed.

2. CUADRIPOL „NOISY" ELEMENTS FROM THE GENERAL THEORY

In the paper is presents a method of noise analysis and calculation of its active *RC* filters (for *Raukh* realization circuit), in the construction version compatible with new technologies and requirements, using computer calculation methods.

The main idea of this method is that many of the elements, devices and even electronic assemblies – components of modern computing resources middle – may be regarded as dipoles, threepoles, quadri- and multipoles.

In the following are presented evidence of the general noise theory of linear quadripoles. On this basis are estabilished the relations that allow determination of the summary noise property (the total effect of noise) as a summary and equivalent generator of current ($\boldsymbol{I}_{Z\Sigma}$) or tension ($\boldsymbol{E}_{Z\Sigma}$) of any quadripol, autonomous passive or non-autonomous activities, expressed by parameters $\boldsymbol{Y}$ or $\boldsymbol{Z}$.

All liniar amplification devices are part of non-autonomous active quadripols, that is why the analysis and calculations of these equivalent noise schemes quadripol's is of particular importance. The more so that in thise class of quadripols are also and active *RC* filters.

The amplifiers and filters usually have a common input and output terminal, so that corresponding of general case of quadripol active, linear and non-autonomous.

For quadripols passive, as active and autonomous quadripols (Fig. 1) can write the following equality [3] :

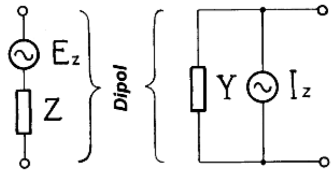
$$Z_{12} = Z_{21}\,; \quad Y_{12} = Y_{21}\,; \quad H_{12} = -H_{21}\,, \tag{1}$$

characterizing simmetry (reversibility) them.

Therefore, to characterize such quadripol only three electrical parameters are enough. In the case of quadripols active but non-autonomous, bicause of inequalities

$$Z_{12} \neq Z_{21}\,; \quad Y_{12} \neq Y_{21}\,; \quad H_{12} \neq -H_{21}\,, \tag{2}$$

it's necessary (are required) four electrical parameters to describe their.



$$E_z = \sqrt{4kT\,\mathrm{Re}Z\,\Delta f}$$
$$I_z = \sqrt{4kT\,\mathrm{Re}Y\,\Delta f}$$
$$Y = Z^{-1}$$

Fig. 1. Equivalent presentation noise properties of a dipol.

This condition is also valid for noise parameters: the minimum set of statisticaly independent noise parameters characterizing the time schedule, it is generaly equal to the minimum set of independet electric parameters.

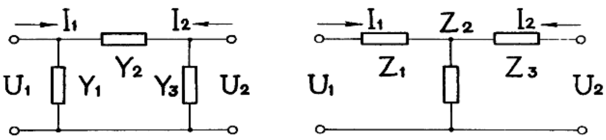
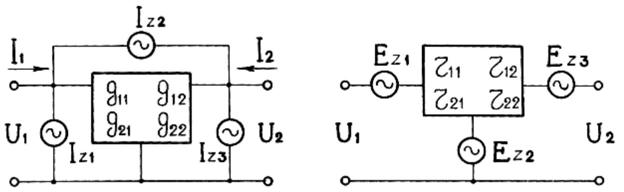


Fig. 2. П- and **T-**type schemes of the quadripols.

From the theory of circuits and systems is well known that any electrical circuit, how complicated it but that does not contain energy sources (*ie* passive) can by equivalently transformed into a scheme with a pair (di-pole, figure 1) or pairs (quadripole, figure 2) terminal.

If the circuit contains complex elements consisting of resistors, capasitors and in the general case - coils, then the properties of the noise can by described using the **thermal noise** equivalent generators.

So, for exemple the dipole can by presented as a generator equivalent of noise tension in series with the ideal (no noisy) resistance, or an equivalent current generator in parallel with the ideal conductance, as shown in figure 1.



a *b*

Fig. 3. Equivalent presentation noise properties of a quadripol.

The noise properties of autonomous quadripol with a common side (or terminal) can be externalized by three statisticaly independent noise parameters in the form of **generators noise voltages** or **noise currents**.

In a concordance with those set out, in figure 3 shows the noise equivalent scheme of passive circuit. The electrical itself scheme in a form of quadripol with common terminal (and so...threepol) is given by parameters ***Y*** and ***Z***. Given that in the „noisy" process real parties ***Y*** and ***Z*** are involved only, in figure 3 is presemted the quadripol with her g and r parameters.

The equations system, which connects the currents and voltages of input and output, if the scheme in figure 3 is:

$$I_1 = g_{11}U_1 + g_{12}U_2;\ I_2 = g_{21}U_1 + g_{22}U_2\,, \tag{3}$$

and for diagram of figure 3, *b*

$$U_1 = r_{11}I_1 + r_{12}I_2\,;\quad U_2 = r_{21}I_1 + r_{22}I_2\ . \tag{4}$$

A particularly important concern in the calculation of noise have the equivalent transformation of the noise scheme, which ultimately simplifies the calculation and their analysis [4].

The equivalent noise generators in figure 3, *a* and *b* can by shown analytically (as thermal noise generator):

$$\overline{I_{Zi}^2} = 4\,k\,\mathrm{T}\,g_i\,\Delta f\,; \tag{5}$$

$$\overline{E_{Zi}^2} = 4\,k\,\mathrm{T}\,r_i\,\Delta f\,, \tag{6}$$

where $i = 1 \div 3$,

$$\begin{gathered} g_1 = g_{11} + g_{12}\,;\ g_2 = -g_{12}\,;\ g_3 = g_{22} + g_{12}\,; \\ r_1 = r_{11} + r_{12}\,;\ r_2 = r_{12}\,;\ r_3 = r_{22} - r_{12}\,. \end{gathered} \tag{7}$$

The ratio of noise parameters of the schemes in figure 3, *a* and figure 3, *b* is given by the relation [4]:

$$\overline{E_{Z1}^2} = \Delta r \cdot \overline{I_{Z3}^2}\,;\ \overline{E_{Z2}^2} = \Delta r \cdot \overline{I_{Z2}^2}\,;\ \overline{E_{Z3}^2} = \Delta r \cdot \overline{I_{Z1}^2}\,. \tag{8}$$

Voltage or current noise value from the corresponding equivalent generator can by calculated to using the equations (5) – (8). Practically, however, is more important to assess the effect of summary noise of any specific circuits. Thise summary noise effect in a form a brief summary current or a summary voltage can by determined to way consistent simplification of the schemes in figure 3, *a* and figure 3, *b id est* to moving from one equivalent scheme to another, more simpler.

An efficient method for simplifaying analysis and calculations for the property noise of various schemes is the *method of transposition* of noise generators of voltage or current, from one sector of scheme to another, without changing the external noise effect of the scheme, in accordance with Thevenen well known theorem [4].

3. OWN NOISE CALCULATION OF RAUKH ACTIVE FILTERS *RC*

Anyc activec filter *RC* (AF–*RC*) can by considered as a connection to *threepol*, passive and active. Where it follow the principles of the general theory of noise analysis and calculation of threepol considered above, are applicable in the case of own noise AF–*RC*.

For own noise analysis and calculation for AF–*RC* is required to achieve short-circuit condition or traveling in the van on the input terminals. Although these conditions carry a load abstract, they are still a convenient tool that simplifies the analysis and facilitate the noise calculation. The more so that all idealizations gravity that can by evaluated.

A dynamics (succession) of its noise calculation *RC* active filters will be presented on a particular case, the concrete acheme for practical realization, what is colled „scheme Raukh”, as the name of author *W. Raukh.* This scheme is frequently utilized in design and construction practice of active filter, with different functional characteristics [5]: HPF; LPF; PBF.

In figure 4 we can see the electrical scheme of active filter that carry low-pass function (LPF); HPF and PBF correspond to high-pass and band-pass function.

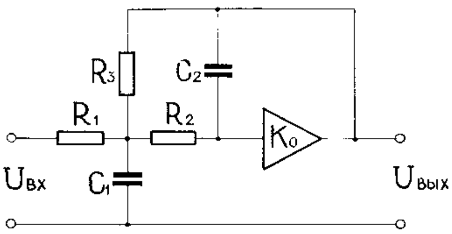


Fig. 4. Scheme of LPF Raukh.

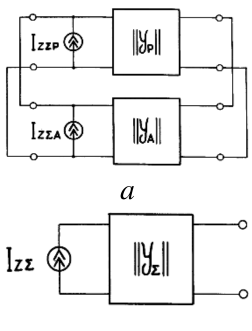
From this scheme it is obvious that if the input terminals to provide a short-circuit regime, LPF can by considered as a parallel connection of two threepol, one of which is passive (*RC* circuit), the other – active (transistor, operational amplifier and for general – active element, figure 5, *a*).

Because each threepol may be presented by matrix of parameters $\|y\|$ and a properties of noise – with a summary equivalent noise generator $\boldsymbol{I}_{Z\Sigma}$, LPF filter may look to like as in figure 5, *b*.

The such presentation of LPF as a parallel connection of two threepol is convenient in the analysis phase of the circuits, but also indispensable for the calculation of noise takingm into account also the presence of feedback loop.

It is worth - while to note apart, even in not many works devoted for analysis and calculation of AF–*RC* noise, the presence of feedback loop or is not taken into account in general, or is specified in a form so relaxed, that it is equivalent with...ignored by her presence. Of course, it sinplifies to a great extent the calculations, but not without injury to the degree of accuracy.

This presentation is more convenient from the point of view : allows the calculation of noise properties of active filters to employment of all possible means of matriciale algebra, which are widely used in various spheres of science and technology, allow computer resources tend implementation. Thia means (*software* packages) enjoys thesame succes, as for the case of synthesis of active *RC* filter as characteristics of amplitude-frequency and phase-frequency.



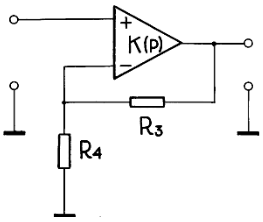


Fig. 5. Prezentation of the LPF as connection of two threepols. **Fig. 6.** Operation amplifier as active element.

Thus, the active filter can be seen (and considered) as being one the active threepol generalised non-autonomouse (figure 5, *b*), for which we can write:

$$\|y_\Sigma\| = \|y_A\| + \|y_P\|, \tag{9}$$

$$\overline{I^2_{Z\Sigma}} = \overline{I^2_{Z\Sigma A}} + 2\xi I_{Z\Sigma A} I_{Z\Sigma P} + \overline{I^2_{Z\Sigma P}} , \tag{10}$$

where ξ is the coefficient (or degree) of correlation bitween noise genarators, $I_{Z\Sigma A}$ and $I_{Z\Sigma P}$.

Mean square current $\overline{I^2_{Z\Sigma P}}$ – the summary effect of noise current of the passive threepol – depends entirely on the parameters $\|y\|$ of this threepol. The determination of these parameters does not present any difficulties in the terms of principle, although in some cases these expressions may be bulky and cumbersome. But...that‘s reality.

To calculation the current $\overline{I^2_{Z\Sigma A}}$ can be used the analytical relations obtained [4]. It should be mentioned that there is a serious difficulty: the calculation, and even the measuring of y parameters of the active threepol presents a uniquely process and in some cases it‘s simply impossible. Using an amplifier with two or three transistors as the active element its at actual cash is already an indication of bed taste, an aberration; is used as this the special integrated circuits – **operațional amplifiers** (figure 6).

The basic advantages of an operational amplifiers (OA) is the high degree of stability and reproductive parameters and multiple functionality, a possibility to builde the active filter in a version of extreme microminiaturization, which is particularly important in the light of the problems they solve a modern microelectronic.

A two-transistor amplifier floor can be presented as an equivalent scheme which is described by squar matrix, of order 6, to operat such a matrix is quite difificult. This is great complexity in the presentation of the operational amplifier through as one equivalent scheme and to execute equivalent transformation and calculation need later. On the other hand, the use of OA (woridwide occur in large series, for about...40 years) in the design and construction of active filter has bicom an imperative.

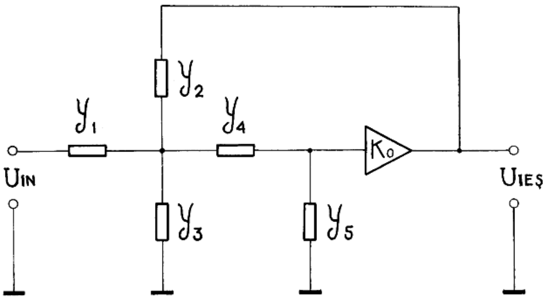


Fig. 7. General scheme to carry out the transfer function order 2, with *VCVS*.

Usually the technical sheet (or passport) accompanying the new OA not contain Y parameters, measuring of their encounters some experimental difficulties (a wide variety of these electronics devices and the absence instruments and universal method of measu-rement).

For the reasons stated above, the Y parameters are calculated in advance based on other technical data. For exemple, a typical data of every one OA (this store marking of similar devices in its original form, Russian and American – in backets) mark КР544УД1 "Регата" (μA741, company *Faichild Ins. Com.*):

– input rezistence $Z_{IN} = 2 \cdot 10^{5}\ \Omega$;
– the transfer tension coeficient (or amplifiere), with disconnected feedback ~ $2 \cdot 10^{4}$;
– feedback coeficient equal to 0;
– output rezistence $Z_{OUT} = 2 \cdot 10^{2}\ \Omega$.

The physical meaning of these parameters are closer to the system h parameters of quadripol. Therefore, we can write:

$$h_{11A} = Z_{INAO} = 2 \cdot 10^{5}\Omega;\quad h_{12A} = 0;$$
$$h_{21A} = 2 \cdot 10^{4}\ \Omega;\ h_{22A} = 1/\,Z_{OUTAO} = 5 \cdot 10^{-3}\ \text{S}.$$

Using the matrices transformation, one can easily switch matrix Y, for which:

$$Y_{11A} = 5 \cdot 10^{-6}\text{S};\quad Y_{12A} = 0;$$
$$Y_{21A} = 2 \cdot 10^{4}\Omega;\ Y_{22A} = 5 \cdot 10^{-3}\ \text{S}. \qquad (11)$$

Based on these data, using a methode of calculation the own noise of active *RC* filters proposed in this paper and the experimental measurements were obtained satisfactory results in practical engineering design and construction of devices for selection of signals by frequence. In figures above are the results of analytical calculations and experimental measurements [6] of its own noise spectaral density $S_U = \varphi\ (f)$: LPF, scheme Raukh (figure 8).

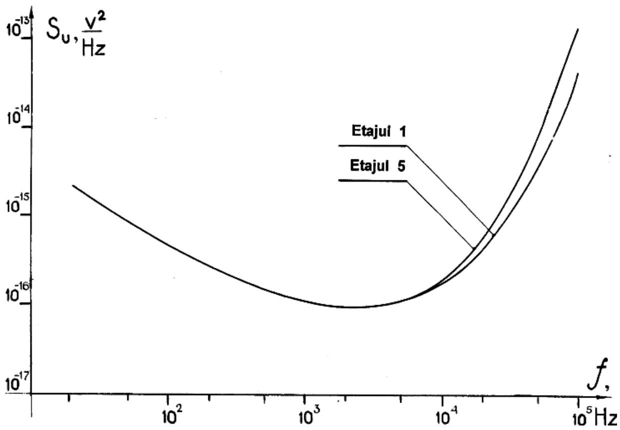


Fig. 8. Characteristics S_U (*f*) of LPF Raukh.

The general scheme shown in figure 7, which carries transfer functions of order 2 is based on sources that when conductance *VCVS* $Y_3 = 0$ and Y_1, Y_2, Y_4, Y_5 are *RC* elements, such a scheme made LPF, HPF and PBF different versions, without signal inversion – *Sallen-Key* schemes [4], $K_0 > 0$; if $Y_3 \neq 0$ and $K_0 < 0$ we obtain the rings of order two, *Teyla* schemes. A special feature of these schemes is the fact that a single element made of the reaction loop and thus are schemes with a single feedback loop. But if the element Y_5 of passive *RC* circuit (figure 7) is not bonded but connected to the output of operational amplifier, thus obtained scheme already contains two elements of reaction Y_2 , Y_5 and is colled *multi-loop* reaction scheme.

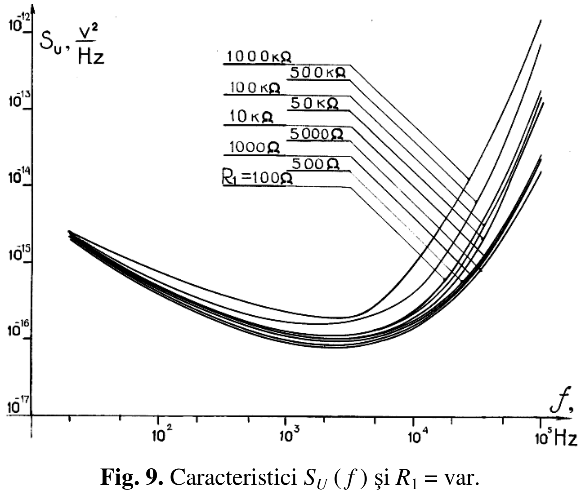


Fig. 9. Caracteristici S_U (f) şi R_1 = var.
(LPF Raukh, $K_0 < 0$, f_t = 4,4 kHz, $U_{Z\Sigma ieş}$ = 15 μV)

Active *RC* filter with multiple loop *VCVS* reaction that made LP, HP and BP transfer function with complex-conjugate pair of poles and zeros are in the complex plane axes origin or infinity, are known in engineering practice that the schemes *Raukh* (figure 4, 10 and 12). Operational amplifier in this case is reversed, noninverting input is connected to ground and $K_0 < 0$. Principal advantage of these schemes is very low output rezistance, meaning that floors can be connected in cascade, without any mutual influence. But to obtain
high values of quality factor Q is necessary a large scale sizes of scheme elements.

Of those exposed is obvious that in order to increase stability as well as to decrease sensitivity to changing circuit elements is reasonable that *Raukh* schemes to achieve limited amounts of quality factor ($Q \le 5$, figure 14).

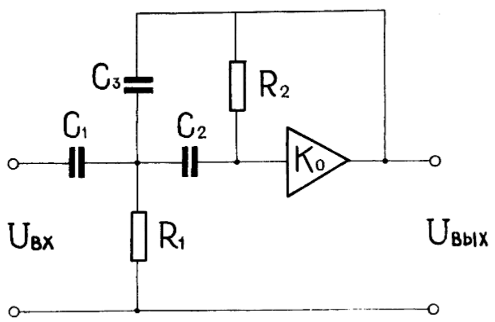


Fig.10. Scheme of HPF Raukh.

Computerized calculation mrthod developed in this work and broadly described above allows to determine its dependence on the AF-*RC* own noise both the parameters and values of *RC* passive circuit elements ($y_1 \div y_5$), and the parameters of active elements (*VCVS*). In [4] is motivated choice of the noise spectral density S (f) as an integral feature of the noise properties of active *RC* filters.

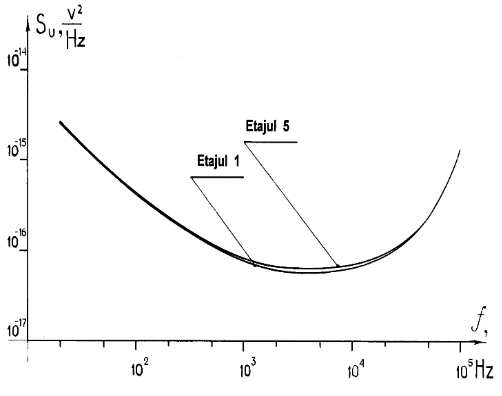


Fig. 11. Characteristics S_U (f) of HPF Raukh.

Very important in the study of noise properties of active filters is to determine the dependence of these properties of R and C values of passive circuits from figure 4. Voltage noise spectral density S_U (f) depends, as is well shown in figures 9, 13 and 15, for concrete values of rezistive element, this dependence is a quasi-parabolic with an extremum faintly.

On the other hand, a certain distribution and position of the set *PZ* (poles and zeros) of the transfer function can be achieved with different ratios of R and C passive elements, important as their product is constant: $R \cdot C =$ const. Thus, there is a real opportunity to choose an optimal ratio of R and C in terms of noise properties, which allows less arbitrary and intuitive a choice the standardized resitance, $\overline{R}$ [4].

For this is necessary to comply with certain requirements, according to [4] is reduced to the following conditions: any changes in *RC* parameters can take place only if

$$\left.\begin{aligned} \omega_0 &= \text{const} \\ 2\eta &= \text{const} \end{aligned}\right\}, \qquad (12)$$

where

$$\omega_0 = \frac{1}{\sqrt{R_1 C_1 R_2 C_2}}$$

is the filter cutoff frequence;
R_1, C_1, R_2, C_2 – *RC* passive circuits elements (figure 4);

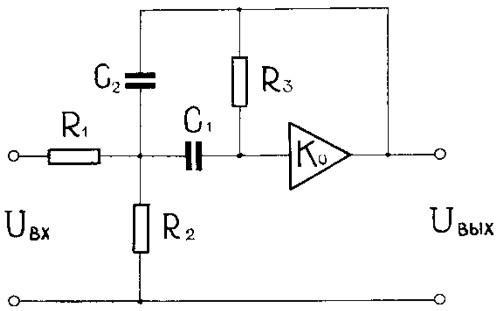


Fig. 12. Scheme of PBF Raukh.

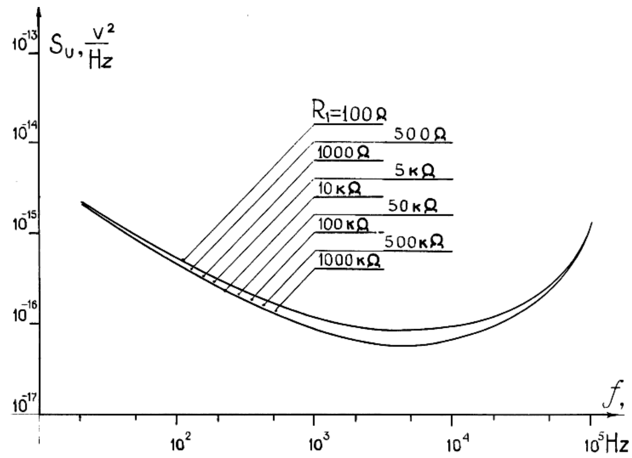


Fig.13. The characteristics S_U (f) for R_1 = var.
(HPF Raukh, $K_0 < 0$, f_t = 4,4 kHz, $U_{Z\Sigma ie\c{s}}$ = 10 μV)

$$2\eta = \sqrt{\frac{R'}{C'}} + \frac{1}{\sqrt{R'C'}} + (1 - K_0)\sqrt{R'C'};$$

$$R' = \frac{R_1}{R_2}; C' = \frac{C_1}{C_2}.$$

Given these conditions, we performed theoretical calculations and computer analysis (Matlab `function`)of the FA's own noise-*CR* based schemes of achieving *Raukh*.
The results are prezented in figures 8 and 9 (LPF), in figures 11 and 13 (HPF)and in figures 14 and 15 (PBF).

4. CONCLUSIONS

A study of the noise properties of Raukhala filters to reveled a some their peculiarities, namely:

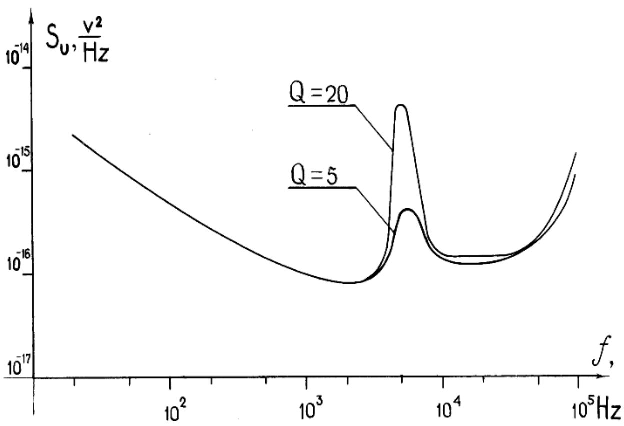


Figure 14. Characteristics S_U (*f*) of PBF Raukh.

1. In the limited of band-pass, the output noise spectral densiti LPF (figure 8) and HPF (figure 11) does not depend on total from quality; the less noticeable depen-dence is observed for LPF on frequencies > 10 kHz, he can no only find the explanation in the *Q* factor of the stage, but in the frequency properties of the OA.

2. The most convenient in terms of noise values of R_1 , for Raukh LPF is 500 Ω - 10 kΩ. Values than thos rise to a considerable increase in noise (figure 9).

3. The results obtained in the realization process of the PBF Raukh schemes, presents a contrast to thos of *Sallen-Key* and *Teyla* schemes. Indeed, their LPF, HPF and PBF in the short circuit input terminals conditions, withim the transition band did note (sharp) any increase of noise curves $S_U = \varphi\ (f\,)$ are smooth, without jumps. And these results are correct as long, as a quality of floor continuous low (Q = 1,5 − 2). Since only the quality of the floor begins to grow, takes place and growth (may be sudden) of noise, on cutoff frecvency f_t (for LPB or HPF), or control frequency (for PBF). This is for PBF Raukh to notes: it is enough quality value Q = 5 − 6, granting that the frequency (f_0 = 4,4 kHz) show a jump of $S_U = \varphi\ (f\,)$. If further Q increases, for example 4 times, this leads to increase in prividing noise on control frequency by 10 times!

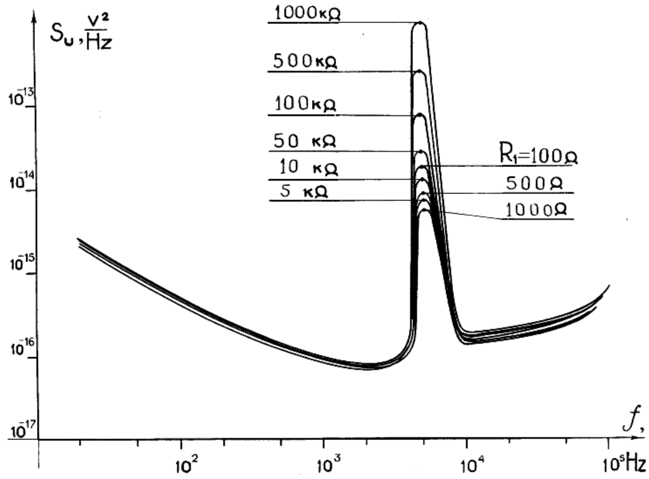


Fig. 15. The characteristics S_U (*f*) for R_1 = var.
(PBF Raukh, $K_0 < 0$, f_0 = 4,4 kHz, $U_{Z\Sigma ie\c{s}}$ = 18 µV)

4. From the characteristics $S_U = \varphi\ (f\,)$ depending on the values of passive circuit, that shows the output noise floor spectral density PBF does not depend basicaly of R_1 , only within the band crossing (figure 15). Within the band pass this dependence becomes significant and can reach 2 – 2,5 orders of magnitude (figure 15). The minimum amount of noise within the pass band, as well as the frequency range 20 Hz – 100 kHz corresponding to value R = 1 kΩ.

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