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Bandwidth analysis of low-pass elliptic biquadratic structures OPA–RC

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Abstract. The influence of bandwidth of OPA on frequency characteristics was investigated in this paper. The analysis of frequency properties was carried out for two exemplary structures. For operational amplifier it was assumed a typical frequency macromodel with 1-pole characteristic. Deformation of the frequency characteristic and the structure bandwidth in dependence on amplifiers bandwidth were analyzed. It was proved that shape of the characteristic to some degree depends on some elements values. The procedure was proposed for optimal choice of the values of (RC) elements, that ensures the characteristic is most approached to ideal one. Optimal values of these (RC) elements ensure that the characteristic of structures do not have any distortion in all frequencies, and these structures can be used in high frequency applications.

Key words: frequency limitations, unity gain bandwidth, OPA, biquadratic structures, low-pass elliptic filter.

1. Introduction

The elliptic filter from among all known ones is distinguished by the biggest selectivity [1-6], at the cost of appearing oscillations on the characteristic in pass-band and stop-band. The characteristic of the even order r low-pass elliptic filter is shown in Fig. 1.

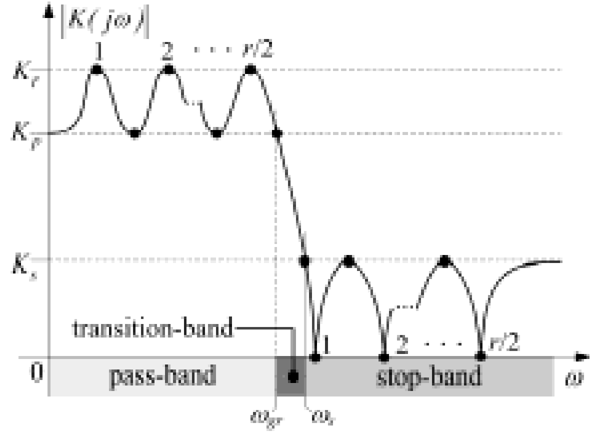

Fig. 1.The characteristic of the even order r low-pass elliptic filter

Low-pass elliptic biquadratic structures, that is type "a" elliptic structures, have the application in construction of low-pass elliptic filters [1,3,6,7-8]. The low-pass elliptic filter of even order r can be built in cascade r/2 of the biquadratic structures of type "a", realizing the suitable biquadratic transmittance and the single proportional structure (1).

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In this paper the structures with operational amplifier (OPA) were tested. Because of the limited bandwidth of real OPA the frequency characteristics differ from assumed ideal ones.

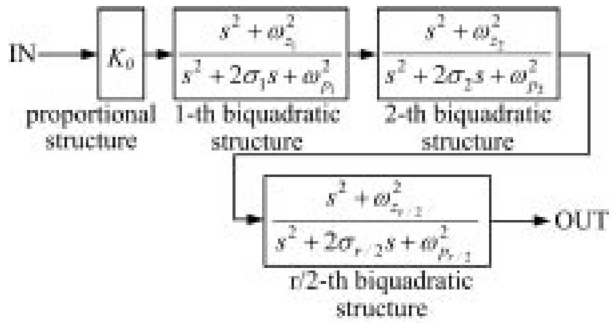

Fig. 2. Even order r low-pass elliptic filter built from the cascade of r/2 type "a" structures and proportional structure

2. Frequency macromodel of OPA

Proposed frequency macromodel of amplifier OPA [5,9] (2a) takes into account the limited bandwidth for a typical 1-pole characteristic, with bend for frequency f_0 (2b).

Transmittance of OPA is determined by a formula:

$$K_D(jf) = \frac{U_0}{U_D} = \frac{K_{D0}}{1 + j\frac{f}{f_0}}, \text{ and, } GBP = K_{D0} f_0 = f_T \tag{1}$$

where:
K_{D0} – DC gain,
f_T – unity gain bandwidth,
GBP – gain bandwidth product.

The macromodel was implemented in SPICE™ 5 simulator as a circuit with controlled sources (Fig. 3c).

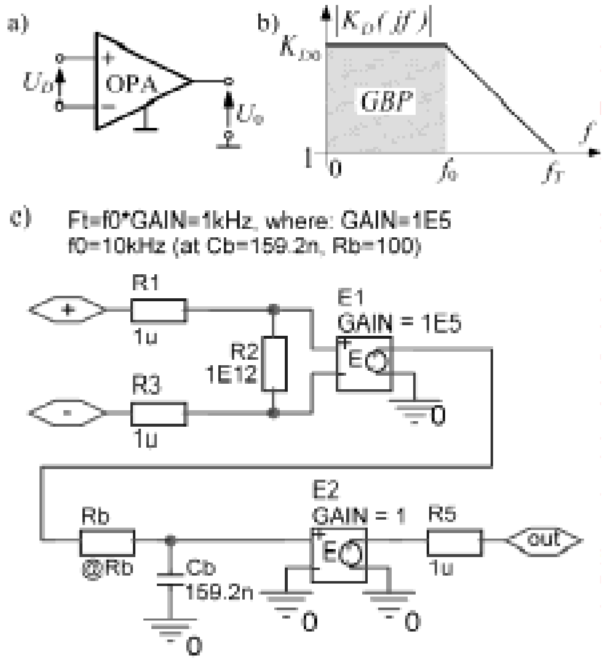

Fig. 3. Frequency model of OPA: a) symbol; b) frequency characteristic; c) SPICE™simulation macromodel

3. Type "a" structures

Operator transmittance of type "a" structures is determined by a formula:

$$K_U(s) = N\frac{s^2+\omega_z^2}{s^2+2\sigma s+\omega_p^2} \quad \text{at} \quad \omega_z > \omega_p . \tag{2}$$

On the frequency characteristic (Fig 4) it possible to distinguish three bands: pass-band $(0, f_p)$, transition band (f_p, f_z) and stop-band (f_z, ∞). For $f \approx f_p$ there is maximum K_{max}, which approximately equals:

$$K_{max} \approx N\left(\frac{f_z}{f_p}\right)^2 Q \quad , \tag{3}$$

where:

$$Q = \frac{\omega_p}{2\sigma}, \; f_p = \frac{\omega_p}{2\pi}, \; f_z = \frac{\omega_z}{2\pi} \tag{4}$$

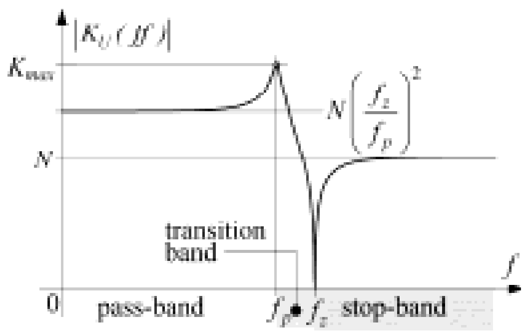

Fig. 4. Frequency characteristic of type "a" structure

4. Bandwidth analysis of type "a" structures

In the paper two exemplary type "a" structures were analyzed: VES OPA–RC "a" - 01 structure was taken from biquadratic structures catalog 5, whereas VES OPA–RC "a" - 02 structure is proposed by the authors 5.

4.1. Analysis of VES OPA–RC "a" – 01 structure. Scheme of the structure was presented in 4.1. transmittance, for ideal amplifiers, is determined by a formula:

$$K_U(s) = \frac{U_{OUT}(s)}{U_{IN}(s)} = N\frac{s^2+\omega_z^2}{s^2+2\sigma s+\omega_p^2} =$$
$$= \frac{s^2 + \dfrac{R_3}{R_4C_1R_2C_5R_6}\left(1+\dfrac{R_2}{R_7}\right)}{s^2+\dfrac{1}{C_1R_7}s+\dfrac{R_3}{R_4C_1R_2C_5R_6}}. \tag{5}$$

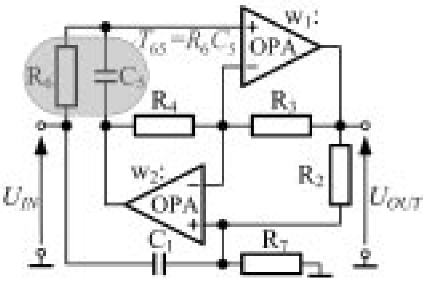

Fig. 5. The VES OPA–RC "a" – 01 structure

Finite bandwidth of amplifiers OPA is a cause of frequency characteristic bend:

a) amplifier w_1 with bandwidth f_{T1} causes a bend for frequency f_{b1},
b) amplifier w_2 with bandwidth f_{T2} causes a bend for frequency f_{b2}.

Frequencies f_{b1}, f_{b2} equal to:

$$f_{b1} = \frac{f_{T1}}{2\pi f_z Q C_5 R_6\left(\dfrac{f_z}{f_p}-\dfrac{f_p}{f_z}\right)} \quad (6) \text{ and } \quad f_{b2} = f_{T2} \quad . \; (7)$$

In 4.1 it was demonstrated the different shapes of the structures' frequency characteristics for three different cases of values f_{b1}, f_{b2}.

Significant influence on the characteristic shape has the time-constant $T_{65} = R_6C_5$. Randomly selected value of constant may produce significant distortions of the characteristic in pass-band and transition band. The good result is obtained, when time-constant T_{65} is chosen as an optimal value, according to:

$$T_{65} = T_{65opt} = \frac{1}{2\pi f_z Q\left(\dfrac{f_z}{f_p}-\dfrac{f_p}{f_z}\right)}, \quad (8) \text{ so that } \; f_{b1} = f_{T1}. \; (9)$$

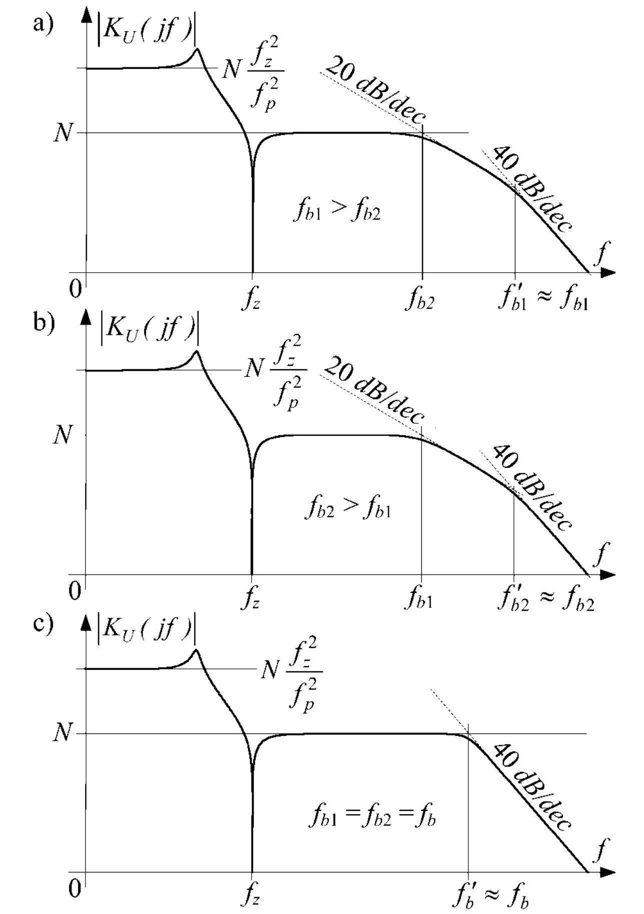

Fig. 6. Characteristic of VES OPA–RC "a" - 01 structure for three cases of values f_{b1}, f_{b2}: a) $f_{b1} > f_{b2}$; b) $f_{b2} > f_{b1}$; c) $f_{b1} = f_{b2}$

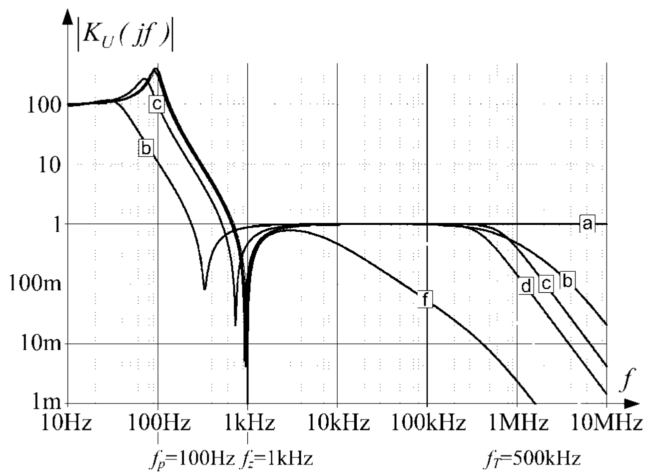

Fig. 7. Characteristic of VES OPA–RC "a" - 01 structure (Q = 4, f_p = 100 Hz, f_z = 1 kHz, f_T = 500 kHz) in dependence on time-constant T_{65}: a) ideal case; b $0.01T_{65\,opt}$; c) $0.1T_{65\,opt}$; d) $T_{65\,opt}$; e) $10T_{65\,opt}$; f) $100T_{65\,opt}$

It means, that if $f_{T1} = f_{T2} = f_T$, the characteristic has one bend for frequency with roll-off equals to 40 *dB*/*dec*. When $T_{65} < T_{65\,opt}$ the characteristic distortions in pass-band and transition band become visible. They are bigger, when T_{65} is lower than $T_{65\,opt}$. The lowest distortions occur for $T_{65} = T_{65\,opt}$ or alternatively when T_{65} is a little bigger than $T_{65\,opt}$. The influence of T_{65} on the characteristic shape was showed in 4.1.

4.2. Analysis of VES OPA–RC "a" – 02 structure. Scheme of the structure was shown in 4.2. For ideal amplifiers transmittance operator is described by the formula:

$$K_U(s) = \frac{U_{OUT}(s)}{U_{IN}(s)} = N\frac{s^2+\omega_z^2}{s^2+2\sigma s+\omega_p^2} = \frac{s^2 + \dfrac{R_5}{R_4C_1R_2C_3R_6}\left(1+\dfrac{R_2}{R_7}\right)}{s^2+\dfrac{1}{C_1R_7}s+\dfrac{R_5}{R_4C_1R_2C_3R_6}}. \tag{10}$$

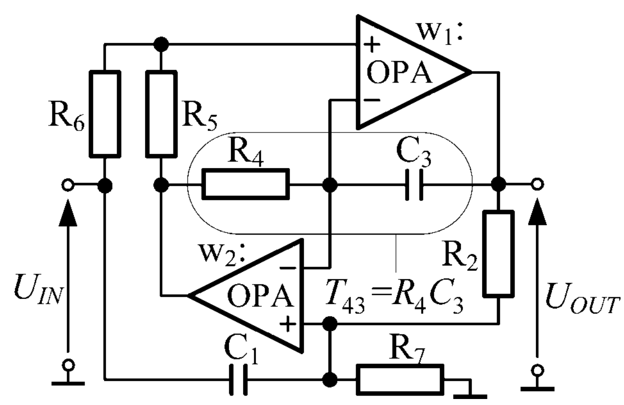

Fig. 8. The VES OPA–RC "a" - 02 structure

If bandwidth of both amplifiers is the same and equals to f_T, then the characteristic bands with roll-off that equals to 20 *dB*/*dec*, exactly for $f = f_T$ (4.2).

The characteristic in pass-band and transition band differs from ideal characteristic. That difference can be minimized by suitable choice of elements values R_4, C_3. The best results are obtained, when the time-constant $T_{43} = R_4C_3$ is optimally chosen, according to the formula:

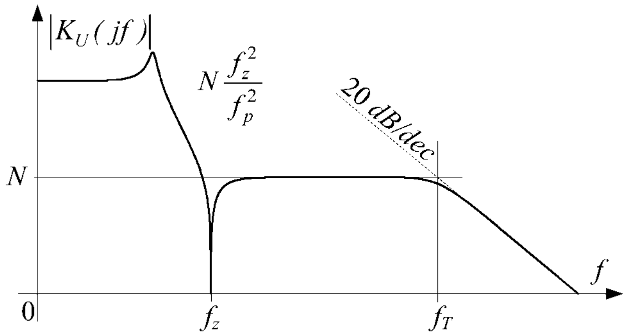

Fig. 9. Characteristic of the VES OPA–RC "a" - 02 structure for unity gain bandwidth both OPAs equalled f_T

$$T_{43} = T_{43opt} = \frac{f_p}{2\pi Q f_z^2}. \tag{11}$$

Influence of the time-constant T_{43} on the characteristic shape was illustrated in 4.2.

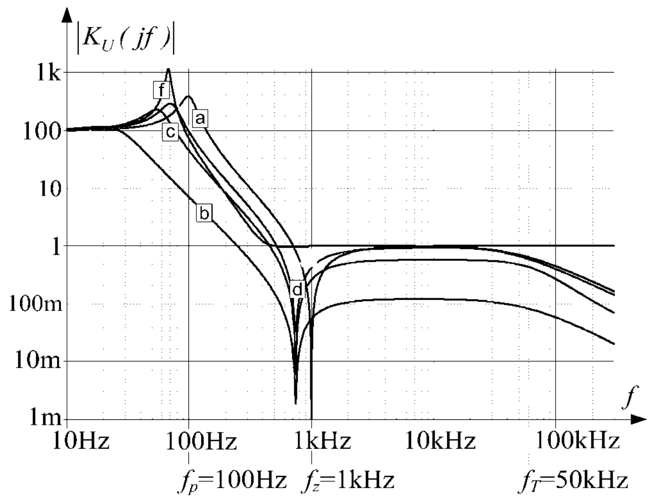

Fig. 10. Characteristic of VES OPA–RC "a" - 02 structure (Q = 4, f_p = 100 Hz, f_z = 1 kHz, f_T = 50 kHz) in dependence on time-constant T_{43}: a) ideal case; b) $0.01T_{43\,opt}$; c) $0.1T_{43\,opt}$; d) $T_{43\,opt}$; e) $10T_{43\,opt}$; f) $100T_{43\,opt}$

4.3. Minimal bandwidth of OPAs in type "a" structures. Analysis of type "a" structures allows to determine the minimal bandwidth $f_{T\,min}$ of OPA amplifiers. The characteristic of amplifier with bandwidth equalled $f_{T\,min}$ covers the structure characteristic in range (0, f_{Tmin}) in minimal way (4.3).

The use of amplifiers with bandwidth $f_T \geq f_{Tmin}$ ensures correct shape of the characteristic in pass-band and transition band. Value $f_{T\,min}$ is dependent on parameters of biquadratic transmittance: f_z, f_p, Q, N and equals:

$$f_{T\,min} = N\, f_p Q \left(\frac{f_z}{f_p}\right)^2. \tag{12}$$

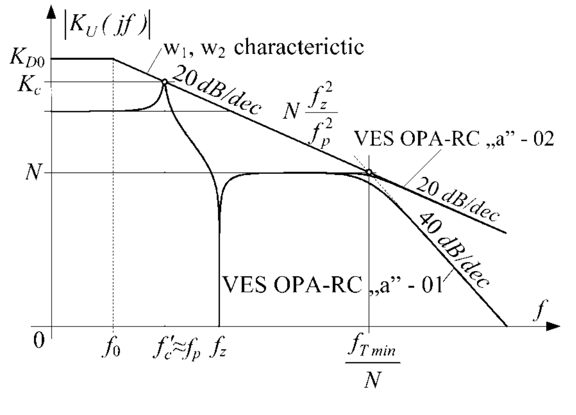

Fig. 11. Minimal unity gain bandwidth of OPAs in type "a" structures

Occurring bend in the characteristic, in stop-band, does not limit at all the structure bandwidth. Furthermore it influences beneficially, because it brings additional attenuation, increasing effectiveness of filtering.

5. Summary

Finite bandwidth of amplifiers unfavourably influences the characteristics of the structures, bringing about deformation of frequency characteristic. However it is necessary to affirm that this deformation does not limit the functionality of the structures, if bandwidth of used amplifiers and elements values is suitably chosen. In dependence on parameters of biquadratic transmittance realized by the structure, it is possible to determine the minimal required amplifiers bandwidth f_{Tmin}. Fulfilment of this condition guarantees that the characteristic is free of bigger distortions in crucial regions, that is in pass-band and transition band. The bend of characteristic appearing in the stop-band does not limit the structure bandwidth, and even influence favourably by increasing additionally the attenuation in this band. Possible distortions of the characteristic are minimized by optimal choice of suitable time-constants: T_{65} in the VES OPA–RC „a" - 01 structure and T_{43} in the VES OPA–RC „a" - 02 structure. For optimal values of these time-constants the characteristic of structures do not have any distortion for all frequencies. Because of that presented structures with optimally chosen suitable time-constant can be used in high frequency applications [11].

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