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# NON – IDEAL PERFORMANCE OF ACTIVE BIQUADATIC FILTER BLOCKS

## Abstract

In the paper a study of the non-ideal performance of operational amplifiers on two well known active filter biquadratic sections is reported. The comparison of real frequency magnitude response of active low – pass filters realized with biquadratic Sallen – Key block and frequency depended negative lossy resistor (FDNR) block is here briefly discussed.

## Introduction

By the frequency filter design, the selection of the proper network topology is one from most important parts which determines real resulting filter parameters. In the area of frequency about MHz and lower is suitable to use the active frequency filter blocks. The active filter design approach use generally two ways: cascade network realization and non-cascade network realization.

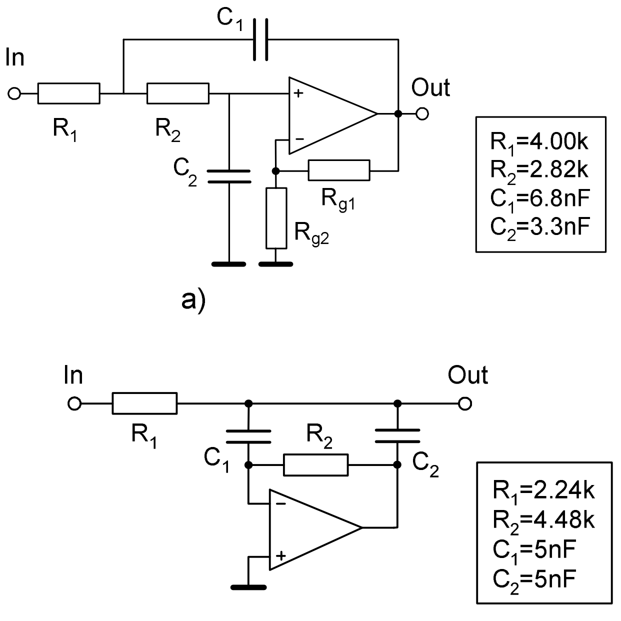
By the cascade network realization is required transfer function decomposed to 1st and 2nd orders transfer functions. As active biquadratic structure very often Sallen – Key circuit with one active element (operational amplifier OA) is used.

By the non – cascade network realizations there are many possibilities in filter design process. Here are very often used the RLC ladder prototypes due their excellent sensitivities. The direct inductance simulation using GIC networks or Bruton´s transformation with FDNR (Frequency Depended Negative Resistor) active elements (the networks are also named as RCD structures) are widely used in area of communication systems. Lossy FDNR active elements with only one operational amplifier can be successfully used namely by low - pass filter realisations with minimised offset [3],[4]. However in practice realised filters designed according both mentioned methods exhibit some important deviations of the filter characteristics from ideal in stop – band at higher frequencies. Therefore by using circuit analysis and computer modelling were the effects of non – ideal performance of both basic biquadratic blocks with one OA (above mentioned Sallen – Key circuit and lossy FDNR active network) investigated and compared.

## 1. ARC LOW – PASS FILTERS WITH BASIC BIQUADRATIC BUILDING BLOCKS

In the technique of active ARC filters many types of different selective biquadratic blocks are used. Usually acording number of active elements (Operational amplifiers – OA) these groups of circuits are divided. From many points of view these circuits was investigated and compared. [3],[4]. Usually an imperfections of performance of biqadratic filter sections due to real OA parameters are investigated by resonant circuit function. There is generally most noticeable effect of the amplifier degeneracy in the pass band well known – a significant shift of both $f_0$ and Q of the sections. These pass band effects have been found to be predominantly due to the finite gain – bandwidth product of amplifiers. In the stop – band, what is very important area namely in case of low – pass filter realizations the performance of filters is influenced by two further degeneracy - finite attenuation at higher frequencies and stop - band transmission zero effect caused limited bandwidth and finite output resistance of active element. These above mentioned imperfections were investigated for two most frequently used circuit configurations of biquadrate blocks used very often in practice to realization of low – pass filters in cascade and non – cascade synthesis design.

To comparison of both above mentioned realisation techniques were designed low – pass filters with Sallen – Key network (Fig.1a) and with lossy FDNR network (Fig.1b) for the identical required low – pass transfer function.



a)

b)

Fig.1. a) Sallen Key low – pass filter, b) Lossy FDNR network (Rg1,Rg2 – DC gain adjusting resistors)

To analysis of both networks the PC simulations using Tina network simulator were made. As active element - operational amplifier- were used in first step ideal operational amplifier, in second step model of real OA.

From the result of analysis (see Fig.2a), with ideal active element we can note the fact, that at the output of network Fig2.b) is realized the band-pass filter transfer. In comparison to the Sallen-Key network tot it means some disadvantage, the OA output at FDNR network generate higher voltage in the stop-band area, what is decreasing possible dynamic range of active filter.

In Fig2 b) there are magnitude transfer characteristics of both networks obtained with real 2-poles model of OA [5]. How we can see from both curves now both circuits exhibit in stop – band significant deviations of responses from ideal in due to form of parasitic transfer zeros and non - monotonic slope of curve at higher stop – band frequencies. Further investigation was focussed to investigate influence of different real active element parameters to above mentioned imperfections. The symbolical and numerical network analysis and modelling of many different network configurations were investigated to determine parasitic transfer zero frequency.

The knowledge of value of this frequency can be used as figure of merit of the real filter properties and their performance at higher frequencies. The usage of a ratio of frequencies $F_{cut-off}/F_{zero}$ can be a comparison of different networks by higher frequency performance made. and valorising the degeneracy of different network structures during the process of the filter design the optimization of synthesis process can be made.

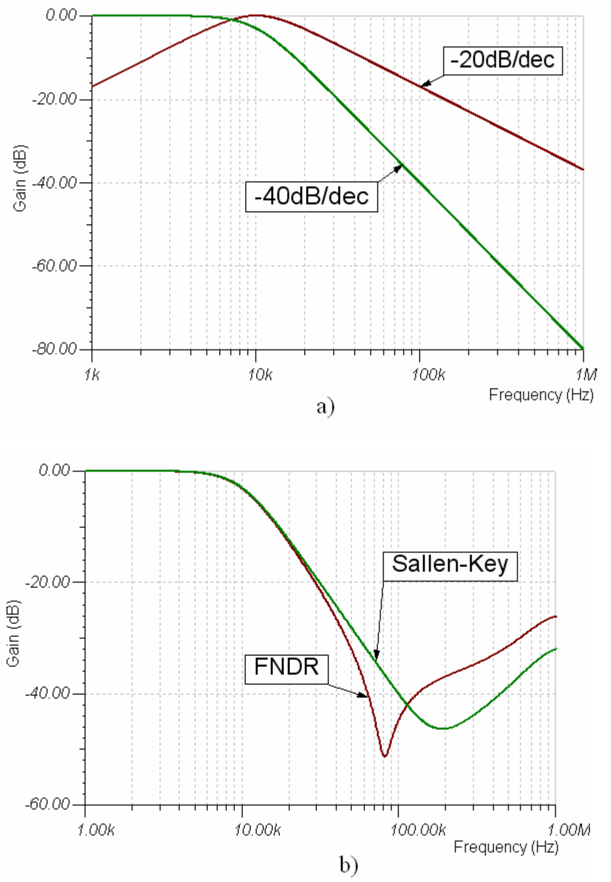
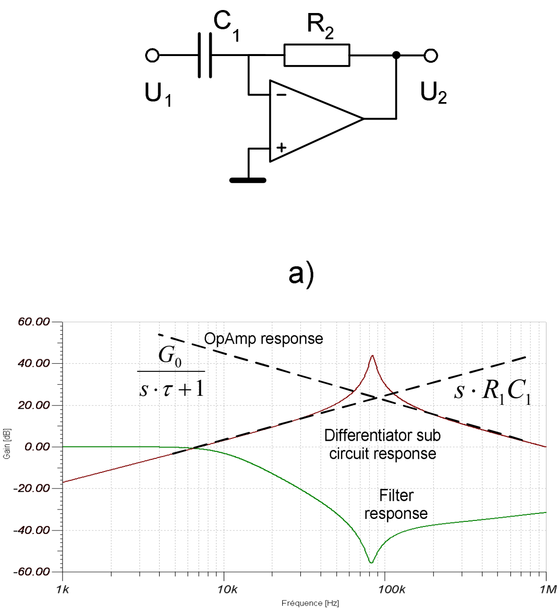


Fig.2. a) Transfer function at output (terms Out) of both networks from Fig.1 (slope -40dB/dec.), transfer function (slope -20dB/dec.) at operational amplifier output of FDNR (Fig.1b) network (OA modelled as ideal).**2.**

## ANALYSIS OF OA DEGENERACY EFFECTS



b)

Fig.3 . a) The sub – circuit of FDNR network, b) transfer functions of investigated networks

From the network analysis is clear, that a condition for the parasitic transfer zero growing is fulfilled in any node of filter structure if there are superposed sum of currents with identical value of magnitudes by inverted phase shift. Thus for example in output node of RCD filter (Fig.2b) can sum of currents expressed as:

$$I_{R1}e^{j\varphi I_{R1}} + I_{C1}e^{j\varphi I_{C1}} + I_{C2}e^{j\varphi I_{C2}} = 0 \qquad (1)$$

From symbolical network analysis have been derived, that by location of parasitic transfer zero frequency major role plays a sub – network of FDNR from Fig.3a) which is working as derivation circuit. Deviation from ideal function network at higher frequency area is given by means frequency response of real OA, what declare modeled transfer function of investigated networks. Using single – pole OA linear model the transfer function of sub - network from figure can be derived in the form:

$$F(s) = \frac{s\,.G_0\,.R_2\,.C_1}{\tau\,.R_2\,.C_1 s^2 + R_2\,.C_1 s - G_0}\,, \qquad (2)$$

where $G_0$ is DC gain and $f_p$ $(f_p = 1/\tau_p)$ is the first pole of modeled operational amplifier OA . From this equation can be very easy derived resulting formula for frequency of parasitic transfer zero of investigated sub – network :

$$f_{ND} = \frac{1}{2\pi}\sqrt{\frac{2\pi f_p\left(G_0 - 1\right)}{C_1 R_2}} \doteq \frac{1}{2\pi}\sqrt{\frac{2\pi GBW}{C_1 R_2}}\,, \qquad (3)$$

where GBW is the gain band – width product of OA.

Similarly the formula of parasitic transfer zero was investigated in the case of Sallen –Key network from Fig.1a). The presence of zero of transfer in the output node allows to ground the output and the capacitor C1 (Fig.4)), what simplifies the solution. Here the symbolical analysis of two most important currents in output node has to be done . The principle of idea is briefly given in by above presented condition (1) (it means here $I_0 = -I_{C1}$). This condition was leading to formulation of the frequency of parasitic transfer zero:

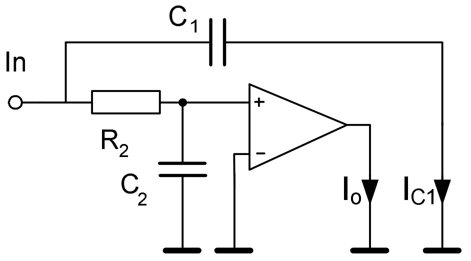
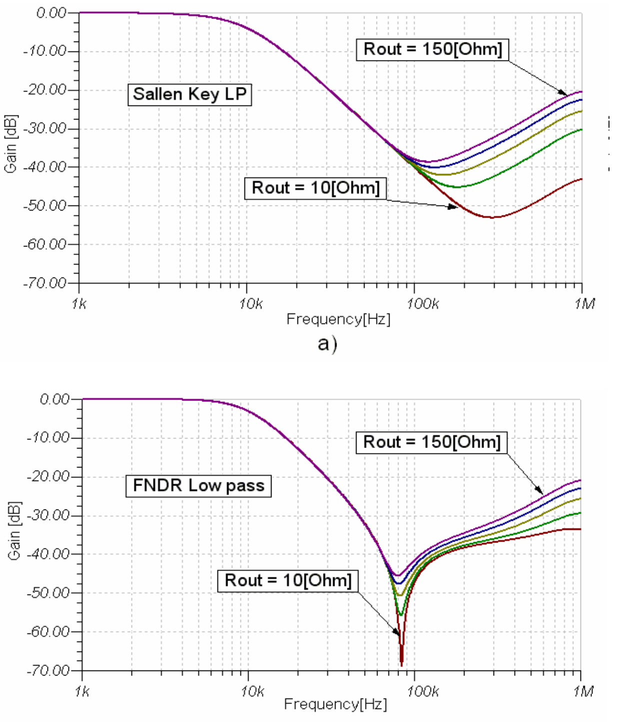


Fig.4 . The principle of Sallen – Key network transfer zero analysis

$$f_{NS} = \frac{1}{2\pi}\sqrt[3]{\frac{2\pi GBW}{R_0 R_2 C_1 C_2}}\,, \qquad (4)$$

where $R_0$ is an output resistance of operational amplifier. From both formulas (3),(4) it is clear, that frequency of parasitic zero is dominantly determined by elements of filter network and by major real parameters of the operational amplifier. From formula (4) is evident, that in the case of the Sallen-Key circuit here is most important parameter an output resistance of amplifier, in contrast to frequency of parasitic transfer zero presented in formula (5) for the FDNR low - pass circuit. The transfer zero frequency of Sallen - Key circuit grows with cubic root of GBW amplifier in contrast to second root of GBW for FDNR low – pass filter. The comparison of the variation of output resistor value of OA for both networks is shown in Fig. 4a,b.



a)

b)

Fig.4 . Frequency responses – OA output resistance stepping a) Sallen – Key, b) FDNR network

These conclusions have been confirmed by measurement of realised low – pass filter networks. It was found that the measured frequency of parasitic transfer zeroes is in close correspondence with frequency calculated according derived formulas (4),(5) as well with computer simulated results. The all presented results declare, that the imperfections of transfer function due the real OA parameters in the stop band of low – pass filters are significant for both investigated networks (Sallen –

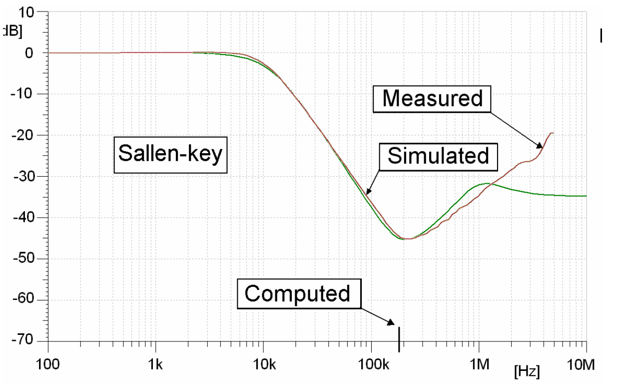


Fig.5 . The comparison of simulated and measured transfer response of Sallen – Key network

Key and FDNR).The PC simulation has been done also with two pole model OA with $f_p$=5Hz, $G_0$=200k and output resistance 75 Ω , which is corresponding with LM741 type of OA, used in the laboratory measurements.

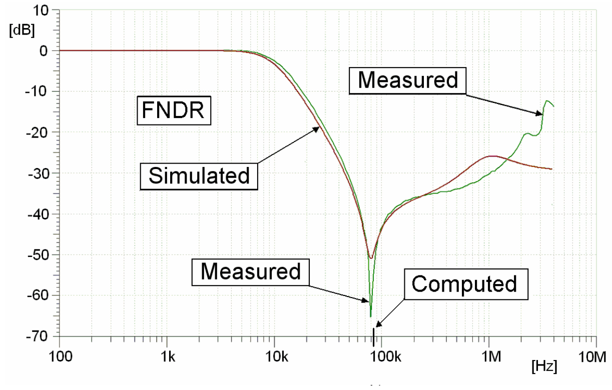
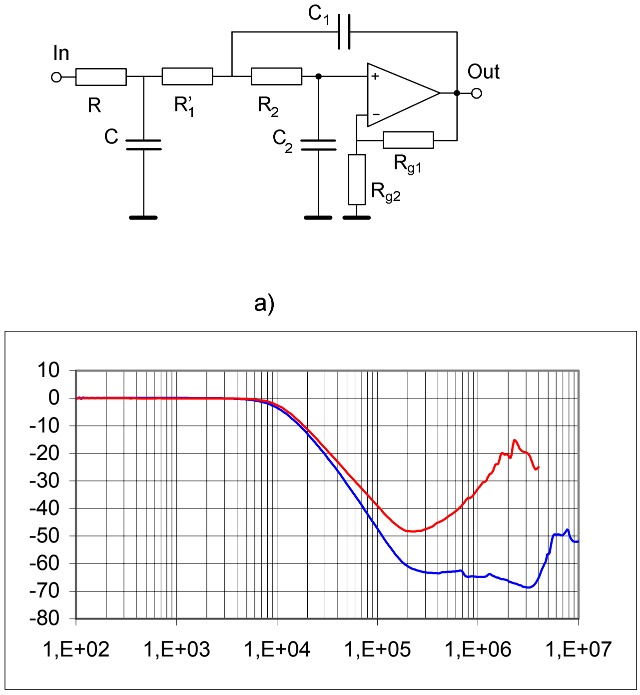


Fig.6 . The comparison of simulated and measured transfer response of FDNR network

These conclusions have been confirmed by measurement of realised low – pass filter networks (see Fig.5, Fig.6.

Further part of our work was focussed to improving of investigated network using idea of compensation of above described effect. Using derived formula (4) thus have been derived compensated Sallen – Key circuit (Fig.7a). By adding two elements (R,C) which form supplementary pole, can be essentially improved transfer function of network, how it is seen from Fig.7b.



a)

b)

Fig.1. a) Compensated Sallen – Key network, b) response of compensated network

Knowledge of parasitic transfer zero frequency enable to calculate the suppression factor of compensated Sallen – Key circuit according next formula:

$$A_{\max} \cong -40 \cdot \log\left(\frac{f_0}{f_N}\right) \quad , \qquad (5)$$

where $f_0$ is cut – off frequency of supplementary RC network and $f_n$ is frequency of parasitic transfer zero. The formula (5) can be to optimization process during filter synthesis used, it is also useful to selection of proper type operational amplifier. However the prescribed method cannot be applied to compensation of above discussed FDNR network from Fig.1b, because the node, where the voltage transfer is going to zero is common for the input as well to output of network.

## 3. CONCLUSION

The results of previously prescribed low – pass network analysis express that the real characteristics of one-OA Sallen-Key and FDNR biquads show significant imperfections of transfer response in the stop band area, due to real operational amplifier properties. It was discussed some property causing this effect and derived the relations between the filter component values, real OA characteristics and between the parasitic zero-transfer frequency. The knowledge of the location of parasitic zero frequency allows to optimize filter design from point of view of required OA parameters and proper network structure selection. An insertion of one supplementary pole to the network enables to compensate the above described effect and thus to improve the final characteristics of the filter in stop – band.

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