MISO Universal Frequency Filter with Dual-Parameter Control of the Pole Frequency

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Abstract

This contribution presents a universal multiple-input single-output (MISO) filter with the dual-parameter control of the pole frequency. The current-mode filter is of the second order and the required type of the response (low pass, inverting band pass, high pass, band reject and all pass) is obtained by proper selection/combination of input(s). The filter employs two capacitors, two modified current differencing units (MCDUs), each of them with four controllable parameters, and one multiple-output current follower (MO-CF). Pole frequency of the filter is directly influenced by two adjustable parameters in frame of MCDU active elements.

1. Introduction

Possibility of change or adjusting of an analog circuit (filter, oscillator and generator) is always very important requirement in the signal processing area. Filtering of a part of the frequency spectrum of the signal is a basic operation of suppressing or amplifying of some spectral components or parts of processed bandwidth [1]. Many scientific works [2-7] focus on filters referred as multifunction or universal. These filters have several transfer functions available between different nodes of the network. These circuits are referred as a triple input – single output (TISO) or single input – triple output (SITO), or more generally as a single input – multiple output (SIMO) [8] or a multiple input – single output (MISO) [9]. The most general form is multiple input multiple output (MIMO) [10] type, usually with many input or output terminals. When a filter is universal [11-12], each of five standard transfer functions (low pass, high pass, band pass, band reject and all pass) are available from the same topology by proper selection of input, output or by reconfiguration in case of reconfigurable filters [13-14]. A filter is adjustable or tunable if one or more of its parameters (angular frequency, quality factor, bandwidth, pass-band or stop-band gain) are controllable and their control must be mutually independent [15-17]. Controllability of the filter can be achieved by driving of one or more parameters of active element (transconductance g_m [18, 19], intrinsic resistance R_X [20], current gain [21-22] or voltage gain [23]), controlled by DC voltage or current most frequently. Table 1 summarizes some of the previous works that focus on current-mode universal 2nd-order filters providing some type of electronic control.

As is obvious from Table 1, the previous filtering solutions vary in the type of filter topology and the number of active elements being used, in necessity of discrete resistors in the structure and in controllability testing. Of course, presented solution vary also in type of active elements being used, however their comparison is out of scope of this contribution. Our solution has the dual-parameter (extended) type of control because pole frequency (f_P) is controlled by both the current gain and intrinsic resistance. Moreover, several transfer functions of our filtering circuit have independently controllable pass-band gain. Note that this feature is not available in any of listed solutions.

Table 1. Several examples of current-mode universal 2nd-order filters with electronic control

Reference	Type of filter topology	Number of active elements	Passive components (type, number)	Electronic control possible / used	Dual-parameter type of control
[8]	SITO	3	C (2), R (2)	yes / no	no
[24]	TITO	3	C (2)	yes / no	no
[25]	SIMO	3	C (2)	yes / yes	yes
[26]	SIMO	2	C (2), R (1)	yes / no	no
Fig. 1	MISO	2 + 1	C (2)	yes / yes	yes

2. Designed Universal Filter

Designed filter contains two Modified Current Differencing Units (MCDUs) [27] and one simple Multiple-Output Current Follower [16].

MCDU element is described by the following equations:

$$I_{+x} = I_p B_1 - I_n B_2, \quad (1)$$

$$V_p = V_{Y1} + R_p I_p, \quad (2)$$

$$V_n = V_{Y2} + R_n I_n. \quad (3)$$

where I_{+x} represents output current, I_p represents current flowing into positive input, I_n represents current flowing into negative input, B_1 is voltage-controlled current gain in positive path, B_2 is voltage-controlled current gain in negative path, Y_1 and Y_2 are auxiliary voltage terminals, R_p is voltage-controlled intrinsic resistance of p input and R_n is voltage-controlled intrinsic resistance of n input.

MO-CF element is very simple and input current is only mirrored or inverted to respective output according to the symbol used on output side of the circuit.

Whole filtering structure including four input nodes and one output terminal is shown in Fig. 1.

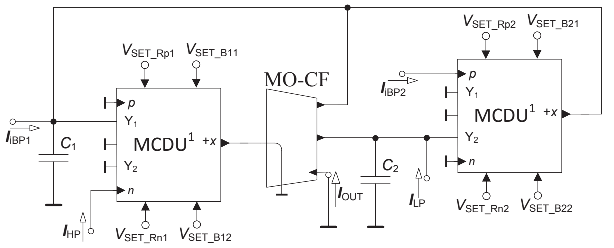

Fig. 1. Designed current-mode universal filter with the dual-parameter control of the f_P

All transfer functions of this filter are (LP = low pass, iBP = inverted band pass, HP = high pass):

$$K(\boldsymbol{s}) = \frac{\boldsymbol{I}_{OUT}}{\boldsymbol{I}_{HP}} = \frac{\boldsymbol{s}^2 C_1 C_2 B_{12}}{D(\boldsymbol{s})} \quad , \tag{4}$$

$$K(\boldsymbol{s}) = \frac{\boldsymbol{I}_{OUT}}{\boldsymbol{I}_{iBP1}} = \frac{\boldsymbol{s} C_2 G_{p1} B_{11}}{D(\boldsymbol{s})} \quad , \tag{5}$$

$$K(\boldsymbol{s}) = \frac{\boldsymbol{I}_{OUT}}{\boldsymbol{I}_{iBP2}} = \frac{\boldsymbol{s} C_2 G_{p1} B_{11} B_{21}}{D(\boldsymbol{s})} \quad , \tag{6}$$

$$K(\boldsymbol{s}) = \frac{\boldsymbol{I}_{OUT}}{\boldsymbol{I}_{LP}} = \frac{G_{p1} G_{n2} B_{11} B_{22}}{D(\boldsymbol{s})} \quad , \tag{7}$$

where denominator is the same for all of the transfer functions:

$$D(\boldsymbol{s}) = \boldsymbol{s}^2 C_1 C_2 + \boldsymbol{s} C_2 G_{p1} B_{11} + G_{p1} G_{n2} B_{11} B_{22} \ . \tag{8}$$

The meaning of symbols is obvious from the Fig. 1 and previous text, $G_{p1} = 1 / R_{p1}$, $G_{n2} = 1 / R_{n2}$. When I_{HP} and I_{LP} currents are available simultaneously, band reject (BR) function is obtained. If also I_{iBP1} is available, all-pass (AP) response with unity gain is obtained on the output terminal. Note that iBP1 and iBP2 transfer function require inversion of input current in order to provide inverting version of BP function, however it is important only for AP response. Therefore, if AP response is not necessary, inversion of input current is also not necessary in particular application.

Angular frequency (ω_0) and quality factor (Q) are equal to:

$$\omega_0 = \sqrt{\frac{G_{p1} G_{n2} B_{11} B_{22}}{C_1 C_2}} \quad , \tag{9}$$

$$Q = \sqrt{\frac{C_1 G_{n2} B_{22}}{C_2 G_{p1} B_{11}}} \quad . \tag{10}$$

From eqs. (9) and (10) can be derived that if $G_{p1} = G_{n2} = G = 1 / R$ is controlled, ω_0 is adjusted without disturbing Q. Let us assume that this is the first tuning parameter in the following text. Same is valid for $B_{11} = B_{22} = B$ (second tuning parameter in the following text). Therefore, there are two ways how to control ω_0 that can be used mutually independently or even better can be combined in order to obtain extended control range as will be shown later in this paper. Note that B_{12} can be used to adjust independently the pass-band gain of HP response and B_{21} can independently control the pass-band gain of iBP2 transfer function.

3. Tuning Suitability Analyses

Because no on-chip implementation of MCDU is currently available, one MCDU elements have to be behaviorally emulated by structure consisting of commercially available ICs [28], 6 pieces of EL2082 [27, 28] and one OPA860 [27, 28] and several passive components. MO-CF can be emulated by UCC-N1B_0520 model [8]. Of course this type of behavioral modeling has several drawbacks (usually limited bandwidth or dynamic range, or both) but it is very useful in preliminary phase of testing of application possibilities of new circuits. This particular solution limits theoretically the first and second control voltages (V_{SET_R}, V_{SET_B}) approximately from 0.05 V up to approximately 2.8 V and therefore also the tuning range of R and B is limited from the start. Usually, when tuning range is too wide (more than two decades, for instance), problems with linearity, accuracy, bandwidth or transfer function shape occur in lower and/or upper corner of tuning range. Therefore we conducted several tuning suitability analyses of the first and second adjustable parameter (R and B) in order to find out applicable parameter range in order to obtain the widest possible tuning range of the f_P of the whole filter in our particular case. Initial parameters of the filter were chosen as follows: R = {9240; 188} Ω obtained by V_{SET_R} = {0.048; 2.75} V, B = {0.05; 2.5} obtained by V_{SET_B} = {0.048; 2.75} V, capacitors C_1 = 120 pF and C_2 = 240 pF, Q = 0.707 (Butterworth approximation), B_{12} = 1, B_{21} = 1, leading theoretically to f_{P_THEOR} = {0.005; 12.5} MHz. This means that ratio between the highest and the lowest f_P is calculated as 2500.

Series of graphs introduced below include theoretical f_P, simulated f_P, (if filter worked in simulation in PSpice) and relative error (%) between these two values vs tuning of first or second tuning parameters in several scenarios. Because one of tuning parameters was fixed in these cases, it represents single-parameter tuning procedure.

First graph (Fig. 2) shows that if one tuning voltage has relatively low value (V_{SET_R} = 0.147 V), filter will work only if second tuning voltage is not relative low (in this particular case works up from V_{SET_B} = 0.147 V). Second graph (Fig. 3) presents inverse situation, when V_{SET_R} = 1.55 V, filter was working only up to V_{SET_B} = 1.55 V. Figure 4 and Fig. 5 show reciprocal situation – V_{SET_R} is tuned while V_{SET_B} is kept constant. Note that these results prove the same trend – if one control voltage is low, second cannot be relatively low and vice versa in order to keep the filter working in simulations.

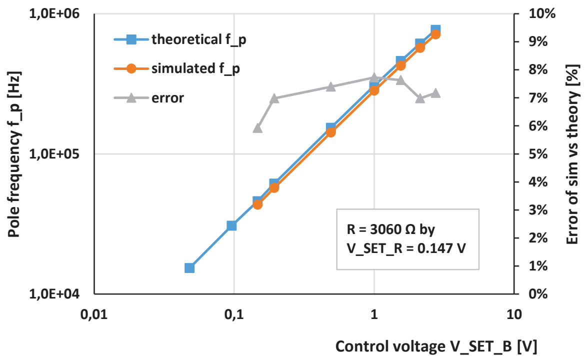

Fig. 2. Tuning suitability analysis under first set of conditions showing the possible workability of the filter (tuning of $V_{\mathrm{SET\_B}}$ while $V_{\mathrm{SET\_R}}$ is fixed to low value)

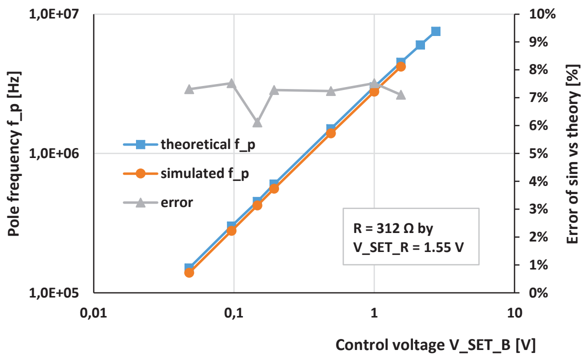

Fig. 3. Tuning suitability analysis under second set of conditions showing the possible workability of the filter (tuning of $V_{\mathrm{SET\_B}}$ while $V_{\mathrm{SET\_R}}$ is fixed to high value)

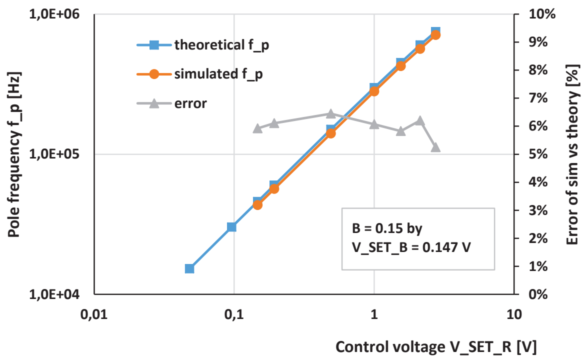

Fig. 4. Tuning suitability analysis under third set of conditions showing the possible workability of the filter (tuning of $V_{\mathrm{SET\_R}}$ while $V_{\mathrm{SET\_B}}$ is fixed to low value)

In this case the ratio between the highest and the lowest f_{P} is only 50 in theory, $f_{\mathrm{P\_THEOR}}$ = {0.15; 7.5} MHz, however is not better than 30 in simulations, tuning range $f_{\mathrm{P\_SIM}}$ = {0.14; 4.2} MHz for instance (the best case). Therefore it is obvious that single-parameter control actually limits the tuning range in this particular case.

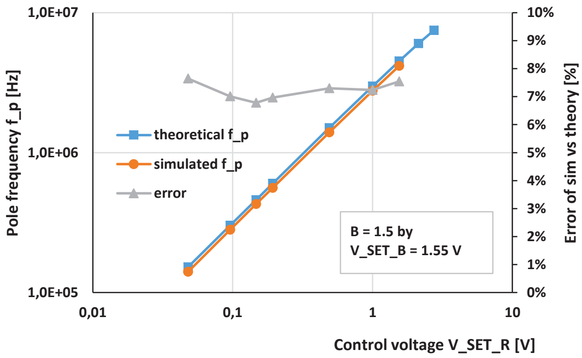

Fig. 5. Tuning suitability analysis under fourth set of conditions showing the possible workability of the filter (tuning of $V_{\mathrm{SET\_R}}$ while $V_{\mathrm{SET\_B}}$ is fixed to high value)

These results lead us to decision that our filter based on above mentioned models will work properly with the following tuning ranges: R = {3060; 322} Ω obtained by $V_{\mathrm{SET\_R}}$ = {0.147; 1.55} V and B = {0.15; 1.5} obtained by $V_{\mathrm{SET\_B}}$ = {0.147; 1.55} V. Figure 6 presents results of tuning suitability analysis for dual-parameter control, when above mentioned parameter limits were applied. In order to make the graph better comparable with previous graphs, X axis represents the product of $V_{\mathrm{SET\_R}}$ and $V_{\mathrm{SET\_B}}$.

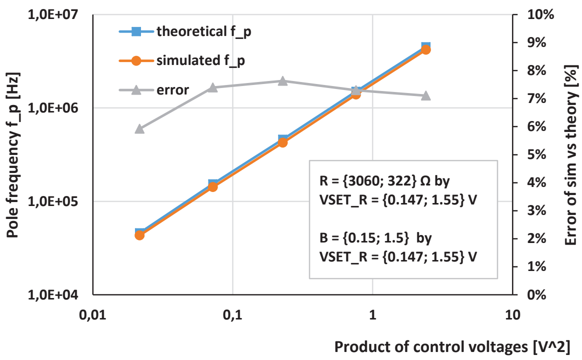

Fig. 6. Dual-parameter tuning suitability analysis showing the possible workability of the filter (tuning of both $V_{\mathrm{SET\_R}}$ and $V_{\mathrm{SET\_B}}$)

In this dual-parameter control scenario, the ratio between the highest and the lowest f_{P} is 98 in theory, $f_{\mathrm{P\_THEOR}}$ = {0.046; 4.5} MHz, and it is almost the same in case of simulation results: it reaches 97, because tuning range is approximately $f_{\mathrm{P\_SIM}}$ = {0.043; 4.19} MHz. Therefore it is obvious that dual-parameter control actually extends the tuning range significantly in this particular case (more than 3 times).

Also note that error of simulated f_{P} against theoretical f_{P} is not effected by dual-parameter control (it is around 7 % in both the cases).

4. Examples of the Simulation Results

Overall simulation results (prepared in PSpice) of the filter's transfer functions (LP, iBP1, HP, BR) vs theory are depicted in Fig. 7 for these fixed tuning parameters: B = 0.5 (V_{SET_B} = 0.49 V) and R = 471 Ω (V_{SET_R} = 1 V). Simulation results match the theory very well except high-frequency band, where used behavioral model is far beyond its bandwidth [29].

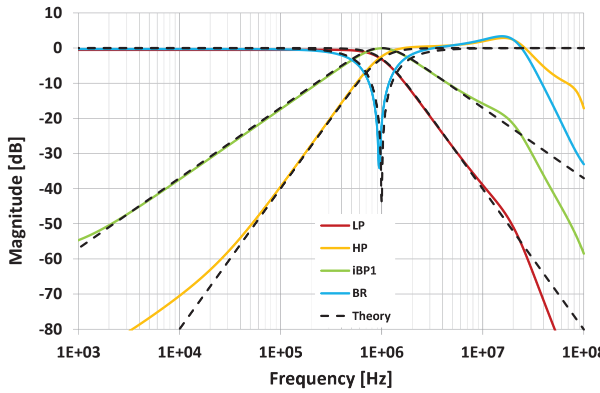

Fig. 7. Overall simulation results of the filter vs theory for B = 0.5 (V_{SET_B} = 0.49 V) and R = 471 Ω (V_{SET_R} = 1 V)

Dual-parameter control of f_P in the case of LP and AP transfer function is shown in Fig. 8 and Fig. 9. First figure shows the magnitude response of LP, second phase response of AP, as an example. From both graphs it is obvious that ratio between the highest and the lowest f_P in simulation and theory is similar and around 100 and both tuning parameters respect above derived limits (Fig. 6 and related text).

Last graph (Fig. 10) shows the possibility of tuning the pass-band gain in the case of iBP2 function (by B_{21} controlled by V_{SET_B21}) while first and second tuning parameters were fixed to: B = 0.5 (V_{SET_B} = 0.49 V) and R = 471 Ω (V_{SET_R} = 1 V). Control voltage V_{SET_B21} was tuned from 0.1 V up to 4 V in this particular case in order to prove both the attenuation and amplification in the pass band of the iBP2 function.

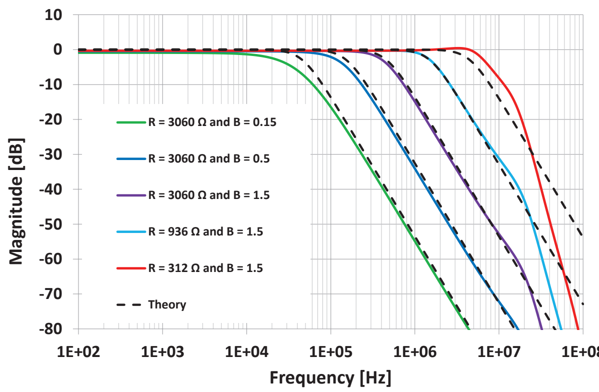

Fig. 8. Dual-parameter tuning of f_P of the LP function (magnitude response)

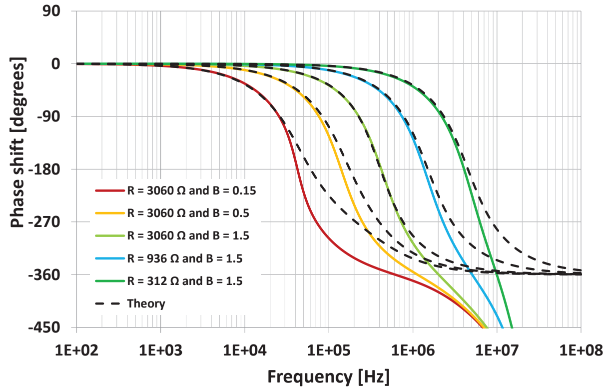

Fig.9. Dual-parameter tuning of f_P of the AP function (phase response)

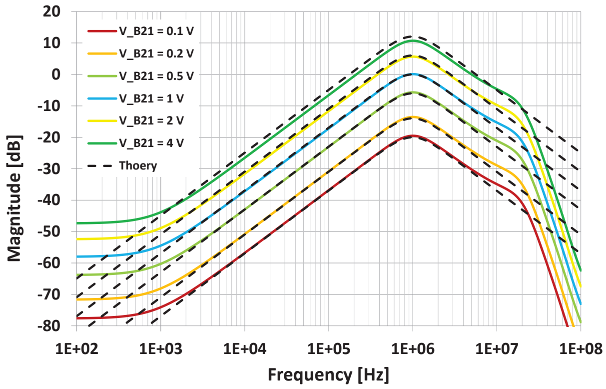

Fig.10. Control of pass-band gain of the iBP2 function (magnitude response) by V_{SET_B21}

5. Conclusions

This paper presented dual-parameter control of universal current-mode filter. Tuning suitability analyses help us to determine optimal tuning range of individual parameters. Simulation results prove that dual-parameter type of control of the filter's parameters is very useful and extends the tuning range. In our case the ratio between the highest and the lowest f_P was around 100 (two decades) both in simulation and theory. It is 3 times wider range than in the case of single-parameter control.

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