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Proceedings of the 2020 27th IEEE International Conference on Electronics, Circuits and Systems (ICECS)

eISBN: 978-1-7281-6044-3

DOI: https://doi.org/10.1109/ICECS49266.2020.9294799

Practical Design of Fractional-Order Resonator for Application in the Multiphase Oscillator

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Abstract—**This contribution introduces a new simple electronically adjustable resonator for implementation in design of the fractional-order multiphase oscillator created with parallel connection of this resonator and negative resistor. The circuit may operate in single-ended or differential/pseudo-differential mode using integer and fractional-order capacitor. Design example is provided for generation of signals with ideal phase shifts equal to 22.5, 157.5 and 180 degrees in the operating frequency band of 47 kHz − 275 kHz with simple tuning of a single parameter. The features of the circuit were verified by PSpice simulations using suitable models and building blocks. Results confirmed expected behavior.**

Keywords—Constant phase element, electronic tuning, fractional-order, multiphase oscillator, resonator.

I. INTRODUCTION

Standard synthesis and design of fractional-order oscillators supposes very uncomfortable expression for oscillation condition and oscillation frequency. This type of equation is not very suitable for direct hand calculations [1], [2]. Nevertheless, recent years brought many interesting concepts of fractional-order oscillators that were studied in [1]-[15]. Table 1 provides their brief overview. However, their design is not simple and many features (electronic tunability and relation of phase shifts when oscillation frequency is tuned, etc.) are not analyzed. As we can see, also number of existing multiphase solutions (generating three and more output signals) is not very high [1], [10], [12], [13]. The standard analysis of these circuits targets on the study of parameters of characteristic equation, except [10] and [15]. It seems that tunability of oscillation frequency in these types of oscillators received minimal attention of researchers in recent works. There are only several papers [11]-[13] where variation of the order of fractional-order element (abbreviated as FOE), known also as the constant phase element (CPE), has been studied theoretically for fulfilment of oscillation condition or oscillation frequency tuning. Unfortunately, this is not very practical way when these oscillators should be tuned immediately and electronically. Paper [10] introduces the verification of the tunability by variation of passive element (resistor). Unfortunately, many further beneficial features (phase and amplitude relations between produced waveforms, suitability for usage in differential mode, suitability for multiphase operation, simplified design, way for stabilization of amplitudes, etc.) are not available, except the first partial attempt presented in [15].

Our approach provides a different view on the circuit based on analysis of very complex characteristic equations (complex even in ideal form – without taking parasitic influences into account). Our concept analyses the oscillator as parallel connection of resonator (based on an impedance converter/gyrator) and negative resistor. Of course, we cannot generalize this approach for any topology, but it still provides interesting results. This approach allows us to study features of the resonator independently on the parameters of the rest of the oscillating structure (negative resistor serves only for undamped operation of the resonator). It offers straightforward way for understanding operations in the circuit and logical derivation of all-important design equations in practically applicable form.

TABLE I. COMPARISON OF RECENT OSCILLATOR DESIGNS USING FRACTIONAL-ORDER DEVICES

Reference	Number of passive elements (including CPEs)	Number of active elements	Resonator/gyrator-based approach	Multiphase solution (3 possible outputs and more)	Suitability for usage with differential outputs	Electronic tuning of oscillation frequency	Phase shifts independent on tuning	Straightforward design equations
[1]	3-7	1	No	Yes	No	N/A	N/A	No
[2]	>7	2-3	Yes	No	No	N/A	N/A	No
[3]	3	4	No	No	No	N/A	N/A	No
[4]	3	1*	No	No	No	N/A	N/A	No
[5]	6	1	No	No	No	N/A	N/A	No
[6]	4	6*	No	No	No	N/A	N/A	No
[7]	4	1	No	No	No	N/A	N/A	No
[8]	6	2	No	No	No	N/A	N/A	No
[9]	5-7	1	Yes	No	No	N/A	N/A	No
[10]	4	2	No	Yes	No	Yes	Yes	No
[11]	4-7	1-2	No	No	No	N/A	N/A	No
[12]	8	3	No	Yes	No	N/A	N/A	No
[13]	8	3-4	No	Yes	No	N/A	N/A	No
[14]	5	1	No	N/A	No	N/A	N/A	No
[15]	2	1	Yes	No	No	Yes	Yes	Yes
Fig. 3	5(7)$^{+}$	5(6)$^{+}$	Yes	Yes	Yes	Yes	Yes	Yes

*CMOS cells used (number of functional parts/devices); $^{+}$7 passive and 6 active devices required when additional resistors used in nodes and voltage buffer with differential output considered; N/A – information not available, not tested

II. PROPOSED STRUCTURE OF THE RESONATOR

The proposed structure of the resonator used in [15] includes quite interesting connection of active devices and two grounded CPEs. However, more generalized solution can be proposed and is presented in this paper including possibility of implementation with differential/pseudo-differential [16] outputs (Fig. 1). The ideal resonator includes two passive elements (inductance and capacitance of order between 0 and 1).

This article is based upon work from COST Action CA15225, a network supported by COST (European Cooperation in Science and Technology). Research described in this paper was financed by the Ministry of Education, Youth and Sports under grant LTC18022 of INTER-COST program.

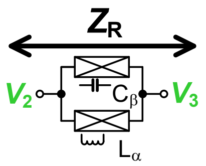


Fig. 1. Floating impedance resonator using CPEs.

The solution is highlighted in right part of Fig. 2. The functionality of active devices is very simple. The electronically controllable current conveyor of second generation (ECCII−) [17], [18] performs the following operations: $V_X = V_Y$, $I_Y = 0$, $I_Z = -B \cdot I_X$, and voltage differencing differential difference amplifier (VDDDA) [19], [20] used with full negative feedback brings simple summation/subtracting operation in form: $V_{out} = (V_+ + V_+ - V_-)$.

The overall impedance of the resonator can be expressed as:

$$Z_R(s) = \frac{V_{in}}{I_{in}} = \frac{s^{\alpha} L_{\alpha}}{s^{\alpha+\beta} L_{\alpha} C_{\beta} + 1} = \frac{s^{\alpha} C_{\alpha} R_1 \dfrac{R_2}{B_1}}{s^{\alpha+\beta} C_{\alpha} C_{\beta} R_1 \dfrac{R_2}{B_1} + 1} . \quad (1)$$

The equivalent inductance has its value adjustable by current gain B_1 of the ECCII [17], [18] in the form of $L_\alpha = C_\alpha R_1 R_2 / B_1$. It means that L_α is transformed from C_α (fractional-order capacity – indicated as Z_{CPE1} in Fig. 2) by simple impedance converter core of the resonator (all active and passive parts except Z_{CPE2}). Note that obtainment of the following expressions requires support of some mathematical tool for solution and simplification of symbolical expressions. Connection with floating Z_{CPE2} (fractional-order capacity) forms ideal behavior described by (1). The impedance $Z_R(s)$ can be expressed also as:

$$Z_R(j\omega) = \frac{\omega^{\alpha}\left[\cos\left(\alpha\frac{\pi}{2}\right) + j\sin\left(\alpha\frac{\pi}{2}\right)\right] C_{\alpha} R_1 \frac{R_2}{B_1}}{\omega^{\alpha+\beta}\left[\cos\left(\frac{(\alpha+\beta)\pi}{2}\right) + j\sin\left(\frac{(\alpha+\beta)\pi}{2}\right)\right] C_{\alpha} C_{\beta} R_1 \frac{R_2}{B_1} + 1} . \quad (2)$$

All oscillators operate when their closed-loop transfer reaches sufficiently high gain (0 dB) as well as the phase response crosses 0° [21]. The resonant frequency of the resonator ω_0 can be found easily from: $\varphi(\omega_0) = \tan^{-1}[\mathrm{num}(Z_R(j\omega_0))] - \tan^{-1}[\mathrm{den}(Z_R(j\omega_0))]$, because the phase response crosses (equals) 0° when this value is reached, i.e.: $\tan^{-1}[\mathrm{num}(Z_R(s))] = \tan^{-1}[\mathrm{den}(Z_R(s))]$, that can be substituted by:

$$\tan^{-1}\left[\frac{\sin\left(\alpha\frac{\pi}{2}\right)}{\cos\left(\alpha\frac{\pi}{2}\right)}\right] = \tan^{-1}\left[\frac{\omega^{\alpha+\beta}\sin\left((\alpha+\beta)\frac{\pi}{2}\right) C_{\alpha} C_{\beta} R_1 \frac{R_2}{B_1}}{\omega^{\alpha+\beta}\cos\left((\alpha+\beta)\frac{\pi}{2}\right) C_{\alpha} C_{\beta} R_1 \frac{R_2}{B_1} + 1}\right], \quad (3)$$

and the frequency while crossing 0° is in the form of:

$$\omega_0 = \left[\frac{\frac{B_1}{C_{\alpha} C_{\beta} R_1 R_2}\sin\left(\alpha\frac{\pi}{2}\right)}{\cos\left(\alpha\frac{\pi}{2}\right)\cdot\sin\left((\alpha+\beta)\frac{\pi}{2}\right) - \sin\left(\alpha\frac{\pi}{2}\right)\cdot\cos\left((\alpha+\beta)\frac{\pi}{2}\right)}\right]^{\frac{1}{\alpha+\beta}} . \quad (4)$$

The magnitude of the impedance at the frequency ω_0 is found as:

$$\left|Z_R(\omega = \omega_0)\right| = \frac{C_{\alpha} R_1 \frac{R_2}{B_1}\left(\frac{B_1 \sin(\alpha\frac{\pi}{2})}{C_{\alpha} C_{\beta} R_1 R_2 \sin(\beta\frac{\pi}{2})}\right)^{\frac{\alpha}{\alpha+\beta}}}{\sqrt{\left(\frac{\sin(\alpha\frac{\pi}{2})}{\sin(\beta\frac{\pi}{2})}\right)^2 + 2\cos\left((\alpha+\beta)\frac{\pi}{2}\right)\left(\frac{\sin(\alpha\frac{\pi}{2})}{\sin(\beta\frac{\pi}{2})}\right) + 1}} . \quad (5)$$

III. APPLICATION PROPOSAL FOR MULTIPHASE OSCILLATOR

Simple completion of the topology in Fig. 1 by controlled negative resistance fulfills all requirements for signal generation within the structure, because negative resistance eliminates losses in the structure when properly set, see Fig. 2. This in fact supports beneficial features discussed in further text. The circuit in Fig. 2 is suitable for differential/pseudo-differential generation ($V_2 - V_3$ and $V_1 - V_1'$) after simple modification (additional special voltage buffer producing signals of both polarities – dashed lines).

The oscillation frequency of this oscillator is given by (4) and amplitude condition fulfillment bases on: $R_{neg} \cong |Z_R(\omega_0)| \cong R_3/B_2 \cong R_3/V_{SETB2}$. It means that design and setting of the oscillator by presented approach is much more simpler than approaches requiring comprehensive steps and complex mathematical background shown in [1]-[14], where full oscillation condition is analyzed and clear dependences of oscillation frequency as well as oscillation condition on circuit parameters are unsuitable for fast and simple design and easy electronic controllability. The voltage transfer between nodes V_1 and V_2 in green color yields:

$$\left.\frac{V_1}{V_2}\right|_{\omega=\omega_0} = \frac{-1}{s^{\alpha} C_{\alpha} R_1} = \frac{-e^{j\cdot\tan^{-1}\left[\frac{\sin\left(\alpha\frac{\pi}{2}\right)}{\cos\left(\alpha\frac{\pi}{2}\right)}\right]}}{C_{\alpha} R_1\left[\frac{\sin\left(\alpha\frac{\pi}{2}\right)}{C_{\alpha} C_{\beta} R_1 \frac{R_2}{B_1}\sin\left(\beta\frac{\pi}{2}\right)}\right]^{\frac{\alpha}{\alpha+\beta}}} . \quad (6)$$

The equation (6) gives relation between voltage ratio and phase shift of generated signals that is equal to:

$$\varphi_{1-2} = 180 - \tan^{-1}\left[\frac{\sin\left(\alpha\frac{\pi}{2}\right)}{\cos\left(\alpha\frac{\pi}{2}\right)}\right] \Rightarrow \varphi_{1-2} = 180 - \alpha\frac{\pi}{2} . \quad (7)$$

Independence of the phase shift on β (clear from (7)) is the most interesting finding of this analysis. The similar relation for the phase shift as (6) is also valid for nodes V_1 and V_3: $\varphi_{1-3} = -\alpha\cdot\pi/2$ (the amplitude ratio has the same form). Phase and voltage relation of voltages in nodes V_2 and V_3 is simple – inversion (180° phase shift). However, the implementation of both capacitors in fractional form (CPEs) is useful for obtainment of various dependences of oscillation frequency on time constants (parameters influencing time constants) because both orders impact power of expression for frequency.

IV. DESIGN AND ANALYSIS OF THE RESONATOR

We selected the following parameters: $\alpha = 0.25$, $C_\alpha = 220\ \mu F/sec^{3/4}$, $\Delta\varphi_\alpha = \pm 2°$ designed for the frequency range of 30 Hz and 10 MHz; $\beta = 1$, $C_\beta = 1$ nF, $R_1 = R_2 = 220\ \Omega$, $B_1 = 1$ (obtained by $V_{SETB1} = 1$ V, see datasheet of EL2082). Figure 3 shows impedance plots of the CPE. The resonator impedance characteristic is shown for variation of B parameter (0.2, 0.5, 1, 2) in Fig. 4. The tunability expects range between 10 kHz and 1 MHz (respecting active devices). Passive RC CPE solution including designed values (based on approaches presented in [22], [23]) is given in Fig. 5. Practical examples of the design and Matlab algorithm are available in [24], [25], for instance.

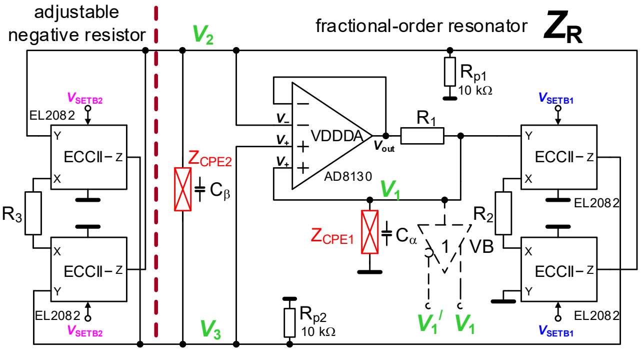


Fig. 2. Proposed application – multiphase oscillator based on resonator and negative resistor.

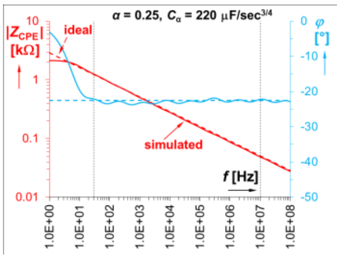
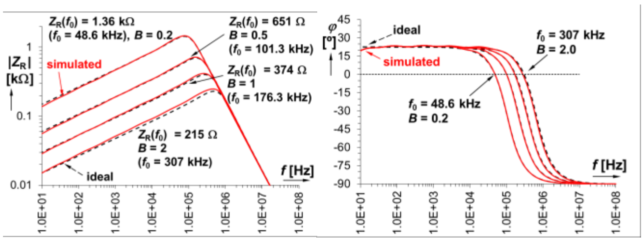


Fig. 3. Impedance plot of CPE used in further design.



a) b)

Fig. 4. Impedance plots of the resonator for selected values of B (0.2, 0.5, 1, 2) – simulation results: a) magnitudes, b) phase responses.

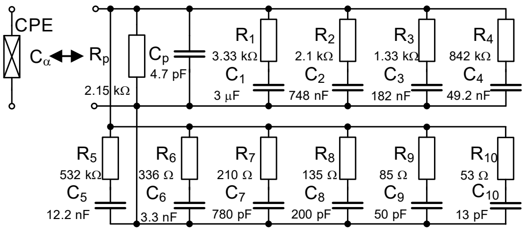
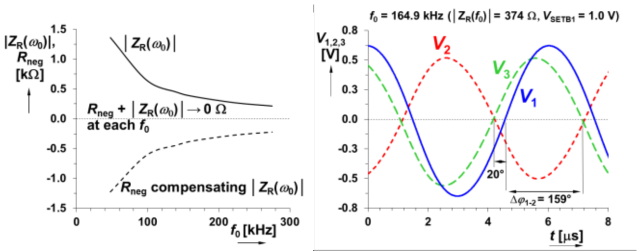
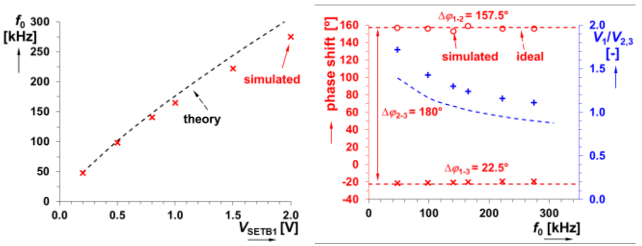


Fig. 5. The RC realization of CPE ($\alpha = 0.25$, $C_\alpha = 220\ \mu F/sec^{3/4}$) used in resonator structure as C_α.



a) b)

Fig. 6. Exemplary results: a) magnitude impedance plots of resonator and negative resistor when f_0 varied, b) selected example of output waveforms of the oscillator.



a) b)

Fig. 7. Dependence of: a) oscillation frequency on driving parameter V_{SETB1}, b) phase shifts between nodes $V_{1\text{-}3}$ and amplitude ratios on tuning procedure.

V. VERIFICATION OF THE OSCILLATOR

We used previously noted features of the resonator for simple design of the multiphase oscillator generating output voltages in three independent nodes of the structure. The passive elements and other parameters remain identical to resonator design. Resistors values (10 kΩ) sufficiently higher than rest of resistors in the circuit in Fig. 2 were selected for $R_{p1,2}$ (avoidance of impact of DC offset, reference to analog ground, with insignificant impact on other features). We studied behavior of the circuit for process of electronic tuning by variation of V_{SETB1} between 0.2 and 2.0 V. As we know, the magnitude $|Z_R(\omega_0)|$ decreases with oscillation frequency f_0. Therefore, the negative resistor (R_{neg}) must compensate these changes as shown in Fig. 6(a). The value of R_{neg} can be driven from specific circuit for amplitude stabilization in practice (as shown in [15]). The tested theoretical range of f_0 was between 48.6 kHz and 307 kHz (Fig. 6 and Fig. 7). The PSpice simulations yield tunability between 47.6 kHz and 275 kHz. The obtained phase shifts are studied in Fig. 7(a). Based on equation (6), we expect impact of f_0 tuning on ratio between generated amplitudes ($V_1/V_{2,3}$). However, the phase shift remains unchanged during the tuning process. The example of time domain responses for $f_0 = 164.5$ kHz ($V_{SETB1} = 1$ V) is shown in Fig. 6(b).

Many other simulations and analyses were performed, however cannot be presented in graphical form in this paper because of limited space. Therefore, at least some numerical results are presented in this paragraph. Output amplitudes reach levels between 740 and 1020 mV$_{P\text{-}P}$ (V_2), between 780 and 1080 mV$_{P\text{-}P}$ (V_3) and between 940 and 1420 mV$_{P\text{-}P}$ (V_1) in observed range of f_0 tuning (47.6 kHz → 275 kHz). The total harmonic distortion was found between 2-3 %. The error between theoretical and simulated phase shift ($\varphi_{1\text{-}2}$) was found between 4 and 15% and between 0.3 and 3% for $\varphi_{1\text{-}3}$. The error of value f_0 reaches values between 2 and 10% in observed range. The error of amplitude ratio has systematical character about 23 – 26% against theoretical dependence.

These errors are acceptable when considering all inaccuracies, operation in hundreds of kHz and complexity of the circuitry. Of course, some of these errors could be compensated, if necessary.

VI. CONCLUSION

It seems that combination of integer- and fractional-order capacitors in specific structure of the oscillator offer different features than oscillators using two identical CPEs [15]. However, the phase shift between generated signals seems to be given by fractional-order device only. We tested designed electronically tunable multiphase oscillator employing special resonator circuit and negative resistor in f_0 range 47.6 → 275 kHz and preserving phase shifts between generated amplitudes for combination elements having integer- and fractional-order character. Moreover, this circuit can be easily used as differential/pseudo-differential source of signal. There are still many unanswered questions. Future research will target on study of structure using accumulating elements of different fractional order (α, β) and practical features of the circuit in tuning operation (phase shift, ratio of generated amplitudes as well as proposal of suitable systems for amplitude stabilization). Some modifications of the concept should be considered and studied for obtainment of more output phases as available in [26] for example. However, these multiphase solutions use different concepts (topologies using arbitrary number of lossy sections in closed loop) offering more than two output phases.

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