Modular Filter Structures Using Current Feedback Operational Amplifiers

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Abstract. *The concept of the wave filtering is followed in the derivation of high-order filter topologies by employing Current Feedback Operational Amplifiers as active blocks. For this purpose, the wave equivalent of an appropriate passive element chosen to be the elementary building block is introduced. As the wave equivalents of the other passive elements are derived by performing appropriate manipulations in the configuration of the wave equivalent of the elementary building block, an attractive characteristic offered by the derived filter topologies is the modularity of their structures. The validity of the proposed method is verified through experimental results in the case of a 3rd-order lowpass filter.*

Keywords

Current feedback operational amplifiers, continuous-time filters, wave active filters, analog signal processing.

1. Introduction

Current Feedback Operational Amplifiers (CFOAs) are important and versatile active building blocks that could be employed for realizing various filter transfer functions. This is originated from the fact that they offer wider signal bandwidth and higher linearity than those of the conventional op-amp configurations. In addition, their terminal properties provide significant design flexibility compared with that offered by the conventional opamps [1]-[17].

High-order active filters could be designed by emulating the operation or the topology of the LC ladder prototype filters. According to the operational emulation method, the voltage/current relationships of the passive prototypes are used for the construction of the corresponding Signal Flow Graph (SFG). The number of the required equations for deriving the corresponding SFG increases according to the order of the filter. In addition, the resulted SFG is realized by employing lossy and loss less integrator configurations [2]. In practice, the realization of lossless integrators is not easy due to the imperfections imposed by the used active and passive elements. According to the topological emulation, the inductors of the passive prototype filters are substituted by appropriate configured active elements [18]. Although the design procedure is quite facilitated by following this method, a drawback of the derived filter topologies is that floating capacitors are generally required. It is known that from the fabrication point of view this type of passive elements is not desired due to the limitations imposed by the parasitics in high-frequency applications.

Another attractive method for designing high-order filters is the wave method [19], [20]. According to this, each element of the passive prototype filter is substituted by its wave equivalent constructed form appropriate configured active elements. Due to the fact that the wave equivalents of the passive elements are manipulated versions of the wave equivalent of a passive element considered as the elementary building block, attractive characteristics offered by the wave method are the following:

- the derived filter structures are modular,
- the design process is quite facilitated due to the availability of a tabular substitution scheme, and
- only lossy integrators realized using grounded only capacitors are required, instead of lossless integrators employed in the operational emulation or floating capacitors employed in the topological emulation [19], [20].

The contribution made by authors is the employment of CFOAs as active elements for realizing wave filters. Thus, due to the availability of appropriate substitution tables, a systematic method for easily deriving high-order filters using CFOAs is introduced. In Section 2 the proposed wave equivalent of an inductor in series branch is given. The substitution scheme for deriving high-order filters is given in Section 3, where some useful signal processing blocks realized using CFOAs are also presented. As a design example, a 3rd-order lowpass wave filter is implemented in Section 4 and its behavior is evaluated through experimental results.

2. Wave Equivalent of Inductor in Series Branch

Following the concept of the wave filtering using the scattering parameters description, the incident (A_i, i=1, 2) and the reflected waves (B_i, i=1, 2) of an inductor in series-branch, considered as a two-port subnetwork, are related according to the equations (1)-(2)

$$B_1 = A_1 - \frac{1}{1+\tau \cdot s}(A_1 - A_2)\,, \tag{1}$$

$$B_2 = A_2 + \frac{1}{1+\tau \cdot s}(A_1 - A_2)\,. \tag{2}$$

In equations (1), (2) the variable τ is a time constant defined as $\tau = L/2R$, where the variable R is a characteristic resistance assigned at each port named port resistance [19], [20]. In order to implement equations (1), (2) the following operations are required: a) lossy integration-subtraction, b) summation, and c) subtraction.

The CFOA shown in Fig. 1 will be used as the active element for performing the aforementioned operations. The relationship that describes its terminal properties is given by:

$$\begin{bmatrix} \upsilon_x \\ i_y \\ i_z \\ \upsilon_o \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix} \cdot \begin{bmatrix} i_x \\ \upsilon_y \\ \upsilon_z \\ i_o \end{bmatrix} \tag{3}$$

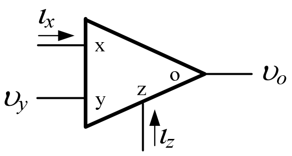


Fig. 1. Used notation for the CFOA.

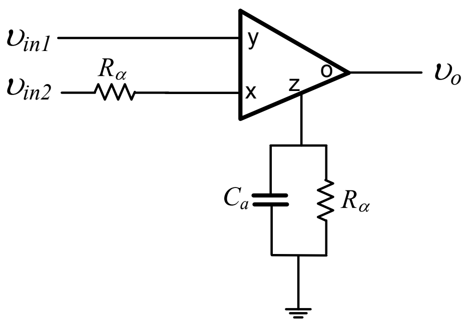


Fig. 2. CFOA based lossy integration-subtraction block.

A lossy integration-subtraction configuration is given in Fig. 2. The input-output relationship is given by the following equation:

$$\upsilon_o = \frac{1}{1+\tau \cdot s}(\upsilon_{in1} - \upsilon_{in2}) \tag{4}$$

where the realized time constant τ is given by $\tau = R_aC_a$. Comparing the transfer function in equation (4) with the corresponding terms of equations (1), (2) it is concluded that the following condition must be fulfilled: $R_aC_a = L/2R$. Considering that $R = R_a$, then the value of capacitor in active realization is given by the formula: $C_a = L/2R^2$.

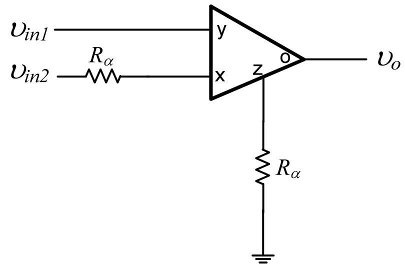


Fig. 3. CFOA based subtraction block.

A CFOA based subtraction block is that depicted in Fig. 3. The input-output relationship is given by

$$\upsilon_o = \upsilon_{in1} - \upsilon_{in2}\,. \tag{5}$$

Thus, the subtraction of the signals A_1 and that derived from the output of the lossy integration-subtraction block will be performed by the topology in Fig. 3 in order to realize equation (1).

A CFOA based summation block is that given in Fig. 4.

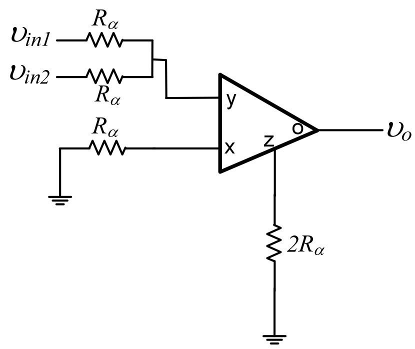


Fig. 4. CFOA based summation block.

The input-output relationship is given by

$$\upsilon_o = \upsilon_{in1} + \upsilon_{in2}\,. \tag{6}$$

Thus, the summation of the signal A_2 and that derived from the output of the lossy integration-subtraction block would be performed by the circuit in Fig. 4 in order to realize equation (2).

Using the blocks in Fig. 2-4 the resulted wave equivalent of an inductor in series-branch is that depicted in Fig. 5a, while its used notation is given in Fig. 5b. The equivalent is constructed from a lossy integration-subtraction block, instead of lossy integrators used in the case of operational emulation. Also, a grounded capacitor is used and this facilitates the implementation of the derived filters configurations in integrated circuit form. This is not the case in the filters derived by following the topological emulation of the passive prototypes.

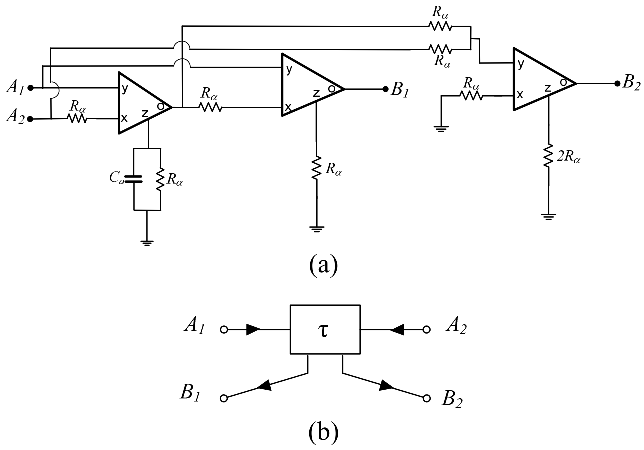


Fig. 5. CFOA based wave equivalent of an inductor in series-branch: (a) Circuit level representation, (b) the used symbol.

The topology in Fig. 5 will be used as the elementary building block for deriving the wave equivalents of the other reactive elements as it will be shown in the next Section.

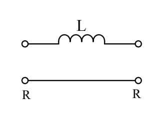
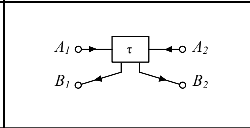
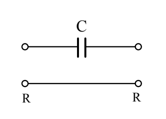
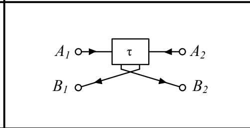
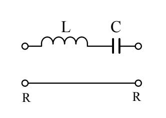
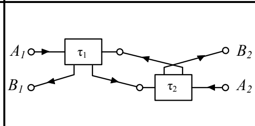
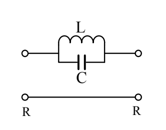
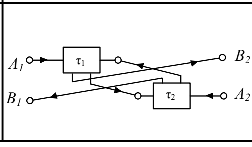
3. Complete Set of Wave Equivalents

According to the wave method, the substitution scheme that could be employed for designing high-order filters is summarized in Tab. 1 and 2 [19], [20]. In addition, the design equations which correspond to the case that CFOAs are employed for performing the required signal processing are given in these tables. The required inversion blocks could be realized by employing the subtraction block in Fig. 2 with the condition that $\upsilon_{in1} = 0$.

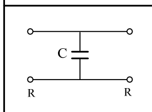
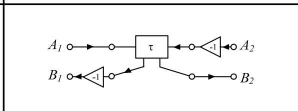
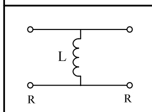
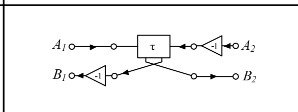
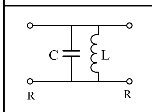
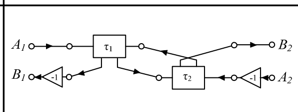
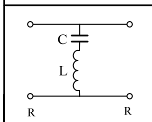
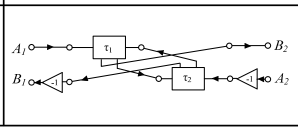
With regards to the construction of the topology of the whole filter an important point is the following: assuming equal port resistances, the construction of the topology of a high-order filter is simply done by a cross-cascade connection of the incident and reflected waves because the incident wave at each port is equal to the reflected wave of the preceding port.

The main conclusions obtained from Tab. 1 and 2 are the following:

- The structures of the resulted high-order filters will be modular, due to the fact that the wave equivalents of the other passive elements are derived by interchanging the outputs of the wave equivalent of an inductor in series-branch and/or using inverters as it is shown in Tab. 2.
- The requirement for only lossy integrators makes the wave filters more realistic from the practical point of view. In addition, the requirement of only grounded capacitors does not impose any restriction concerning the behavior of the filter at high frequencies.

Two-port subnetwork	Wave equivalent	Time-constant	Capacitor in the CFOA integrator
		$\tau = L/2R$	$C_a = L/2R^2$
		$\tau = 2RC$	$C_a = 2C$
		$\tau_1 = L/2R$ $\tau_2 = 2RC$	$C_{1a} = L/2R^2$ $C_{2a} = 2C$
		$\tau_1 = 2RC$ $\tau_2 = L/2R$	$C_{1a} = 2C$ $C_{2a} = L/2R^2$

Tab. 1. Wave equivalents of two-port subnetwokrs in series-branch.

Two-port subnetwork	Wave equivalent	Time-constant	Capacitor in the CFOA integrator
		$\tau = RC/2$	$C_a = C/2$
		$\tau = 2L/R$	$C_a = 2L/R^2$
		$\tau_1 = RC/2$ $\tau_2 = 2L/R$	$C_{1a} = C/2$ $C_{2a} = 2L/R^2$
		$\tau_1 = 2L/R$ $\tau_2 = RC/2$	$C_{1a} = 2L/R^2$ $C_{2a} = C/2$

Tab. 2. Wave equivalents of two-port subnetworks in shunt-branch.

Thus, the design procedure for obtaining high-order filters is quite facilitated, due to the fact that just one step is required for the realization of an arbitrary order filter because of the availability of Tab. 1 and 2. On the other hand, the price paid for the offered benefits is that a more complex circuitry is required for the implementation of wave filters, compared with that of the filters derived according to the operational or the topological emulation of the corresponding passive prototype filters.

4. Experimental Results

The 3rd-order lowpass LC ladder filter shown in Fig. 6 has been chosen to be the prototype filter which will be emulated using the wave equivalents introduced in this manuscript. In order to realize a Chebyshev filter function with 1dB ripple, the normalized element values were $R_S = R_L = 1\ \Omega$, $L_1 = L_3 = 2.024$ H, and $C_2 = 0.9941$ F. The resulted active filter topology is given in block diagram form in Fig. 7. The commercially available AD844 component will be used as a CFOA, with bias voltages equal to ±5 V. The available resistor and capacitor values for implementing the wave equivalents of the inductors of the prototype filter were 2.5 kΩ and 643 pF, respectively. Thus, the corresponding values for the wave equivalent of the capacitor were 2.5 kΩ and 320 pF.

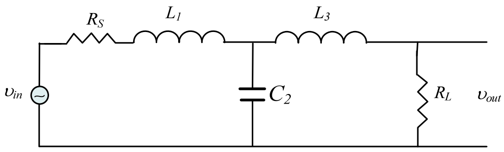


Fig. 6. 3rd-order LC ladder prototype filter.

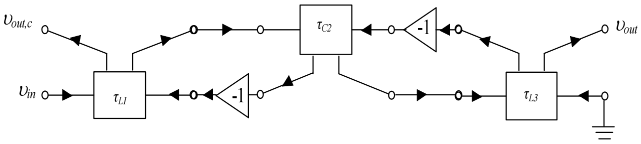


Fig. 7. Block diagram of the corresponding wave active filter.

The frequency behavior of the filter was evaluated using a Network/Spectrum analyzer and the obtained frequency response is given in Fig. 8. The measured cutoff frequency of the filter was about 95.8 kHz instead of 100 kHz, which was the theoretically predicted value. This deviation is mainly caused by the tolerances of the passive components and, also, by the parasitic resistance at the low-impedance input of the AD844.

According to the wave filter theory, the power complementary output (denoted as $\upsilon_{out,c}$ in Fig. 7) is also available by the configuration in Fig. 7 [9], [10] and this is verified through the plot in Fig. 9.

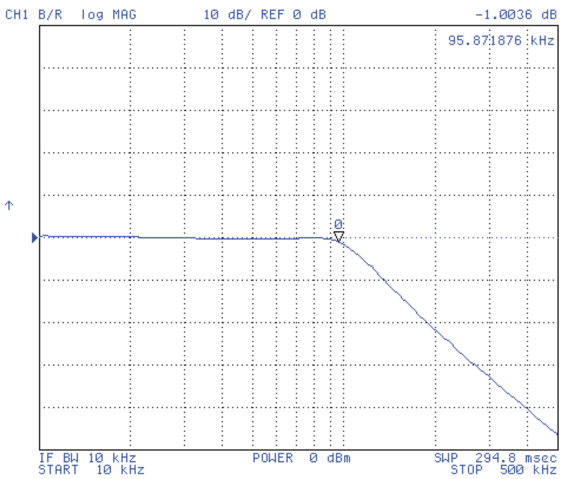


Fig. 8. Measured frequency response of the wave active filter.

The non-linear behavior of the filter was also studied; for this purpose a 10-kHz signal was applied at the input of the filter. The measured output spectrum that corresponds to a 1% THD is given in Fig. 10; the amplitude of the input signal was 1 $V_{p\text{-}p}$.

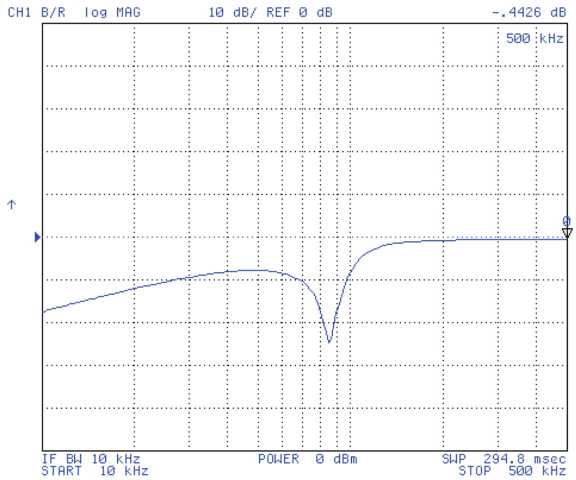


Fig. 9. Measured power complementary frequency response of the wave active filter.

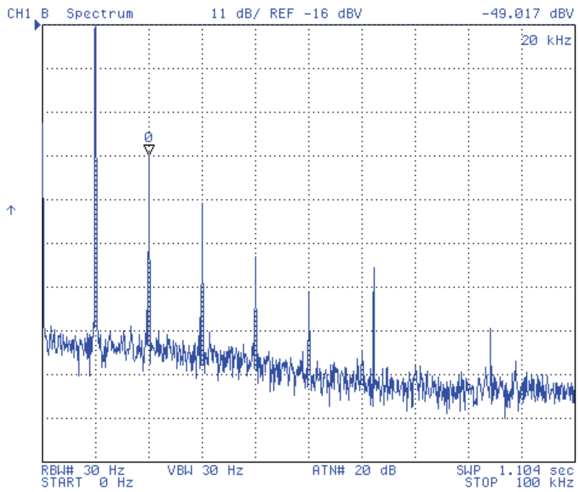


Fig. 10. Linear performance of the wave active filter.

5. Conclusions

The CFOA could be used for realizing high-order wave active filters. For this purpose, lossy integration-subtraction, and simple summation and subtraction blocks are required. Due to the fact that the wave equivalents of the passive elements can be realized as manipulated versions of the wave equivalent of an inductor in series-branch, the derived filter topologies have modular structures. Also, the wave method is a quick design procedure for deriving high-order filters because of the availability of the appropriate substitution tables. Experimental results in the case of a 3rd-order filter confirm the correct operation of the proposed CFOA based wave active equivalents.

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