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Independently tunable mixed-mode universal biquad filter with versatile input/output functions

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ABSTRACT

This paper presents an independently tunable mixed-mode (including voltage, current, transadmittance, and transimpedance modes, i.e. four modes) universal biquad filter using one fully differential current conveyor (FDCCII), one differential difference current conveyor (DDCC), two grounded capacitors, four grounded resistors, and two floating resistors, which can realize all four modes five universal filtering responses (lowpass, highpass, bandpass, notch, and allpass). The proposed biquad filter has versatile input/output functions which not only realize all four modes five universal filtering functions in single-input multiple-voltage/current-output (SIMO) type but also provide all of them in multiple-input single-voltage/current-output (MISO) type without changing the filter topology. The proposed circuit permits both independent tunability (for ω_0 and ω_0/Q) and orthogonal controllability (for ω_0 and Q) by adjusting grounded resistors without control factors matching conditions. No floating capacitors are used, and all the active and passive sensitivities are low. Moreover, in some modes, the proposed circuit still maintains the following advantages for five universal filtering responses: (i) cascadable feature, (ii) no component-value constraints, and (iii) no need of extra inverting or non-inverting amplifiers. H-spice simulations with TSMC 0.18 μm 1P6 M CMOS process technology and experimental results validate theoretical predictions.

1. Introduction

In recent years, the applications and advantages in the designing mixed-mode active filters have received considerable attentions [1–27]. Moreover, there is a growing interest in designing active filters or analog circuits using current conveyors [1–3,7–9,11,12,16–18,20,22,23,26–39,41–43]. For example, because the addition and subtraction operations of voltage-mode or mixed-mode signals needs the realization of addition and subtraction circuits, unlike in the case of current-mode signals, two introduced current conveyors, namely, fully differential current conveyor (FDCCII) [2] and differential difference current conveyor (DDCC) [35,36], with the intrinsic voltage addition and subtraction ability, are very important for the design of voltage-mode [37,38] or mixed-mode filters. In this paper, the proposed circuit uses the active elements FDCCII and DDCC with their ability to perform operations of voltage addition and subtraction in the realization of mixed-mode universal biquadratic filter.

Many mixed-mode filters [1–27] have been presented. The filter structures [1,2,15–17,23–25] are only operated in single-mode or dual-mode. The filters consist of more modes and filtering functions, meaning more applications for which they can be used. Therefore, many mixed-mode filter structures which can be operated in voltage-mode (VM), current-mode (CM), transimpedance-mode (TIM) and transadmittance-mode (TAM) (i.e. four modes) were proposed [3–14,18–22,26,27]. However, only several structures can realize all five universal filtering functions in all the four possible modes [3–5,7,8,10,13,20–22,26]. Each of these universal mixed-mode (four modes) structures [3–5,7,8,10,13,20–22,26] employs at least three active elements. Moreover, only one universal mixed-mode structure [5] can offer the following important advantage: independent tunability of the parameters ω_0 and ω_0/Q by adjusting bias currents or grounded resistors (for electronic tunability [39,40]) without control factors matching conditions. However, the filter in [5] needs to employ seven operational transconductance amplifiers (OTAs), in addition to two grounded capacitors and it only has one voltage/current output. The biquad [9] using three differential voltage current conveyors (DVCCs), two grounded capacitors and three grounded resistors also has the above important advantage, but the biquad [9] is not universal

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filter in all the four modes. Although the universal mixed-mode biquad filter structure [3] has independent tunability of the parameters ω_0 and ω_0/Q, the resistors used in independent tunability are not grounded. The use of grounded resistors can be replaced by electronic resistors to obtain electronic tunability [39,40]. Moreover, the structure [3] needs to use seven current conveyors in addition to ten passive elements, and it only has one voltage/current output. Most of the mixed-mode filter structures are multiple-input single-voltage/current-output type (MISO type), which only can realize one standard filter function in each filter realization. In some applications, however, simultaneous outputs of many different filter functions may be needed and few works have been done in the domain of single-input multiple-voltage/current-output type (SIMO type) mixed-mode (four-mode) filters [4,6,9,11,12,19,20]. Only two SIMO type mixed-mode (four-mode) filters [4,20] can realize all five universal filtering functions in all the four possible modes. In [4], it has shown that the mixed-mode universal biquad filter with multiple-outputs needs to use four current feedback operational amplifiers (CFOAs), eleven passive elements and a switch. However, only one current output and four voltage outputs can be simultaneously obtained in each filtering realization. Moreover, the circuit [4] does not permit independent tunability of the parameters ω_0 and ω_0/Q, and orthogonal controllability of the parameters ω_0 and Q. In 2011, the reported SIMO type universal mixed-mode biquad filter [20] with five voltage outputs and three current outputs using three DDCCs, four resistors, and two grounded capacitors can permit orthogonal controllability of the parameters ω_0 and Q, but the resistor used in orthogonal control is not grounded. Moreover, it should be noted that although the denominator of the filtering transfer functions in [20] permits orthogonal controllability of the parameters ω_0 and Q, it does not permit independent tunability of the parameters ω_0 and ω_0/Q. In 2009, a single FDCCII-based mixed-mode biquad filter [11] was proposed by Lee and Chang. The biquad filter [11] based on one active element, namely FDCCII, can realize many filter functions simultaneously. It is a pity that the biquad [11] is not universal filter in all the four modes. Moreover, the biquad [11] has neither independently tunability nor the grounded resistor used in tunability. In 2011, the reported SIMO type mixed-mode biquad [19] using three current controlled current conveyor transconductance amplifiers (CCCCTAs) and two grounded capacitors can realize many filtering functions in all the four possible modes. However, it cannot realize VM/TIM notch and allpass responses. In 2013, the recent publication [22] reported that mixed-mode (four-mode) biquad using four multiple-output current controlled current conveyors (MOCCCIIs) and two grounded capacitors can offer five universal filtering functions in all the four possible modes by the exploitation of multiple-input multiple-output type (MIMO type) and changing filter topology, but it is not universal filter in MISO type or SIMO type. Note that the filters in [19,22] have electronically tunable feature, but the denominators of the filtering transfer functions in [19,22] show that the parameters ω_0 and Q are interactive. Hence, the filters [19,22] need some matching conditions of bias currents (i.e. control factors) to obtain the non-interactive filter parameter controls and then achieve independent tunability or orthogonal control. However, this may not be convenient for the users.

There are two main types of mixed-mode universal biquad filters which can respectively achieve one of the following two main features: (i) the filters do not need to change the output terminal for realizing any filtering responses [3,5,7,8,10,13,18,21,26], and (ii) the filters can be driven by only one input and simultaneously realize five universal filtering responses [20]. The filters in [4,6,9,11,12,19] can simultaneously realize many (no five universal) filtering responses, and therefore, partly achieve feature (ii). The first type (i.e. the MISO-type universal filter) has many inputs and one voltage-output terminal/one current-output terminal which can realize all five universal filtering responses by selecting different input signals [3,5,7,8,10,13,18,21,26]. Although this type cannot realize all five universal filtering responses simultaneously (due to only a single output), it has one universal output terminal (i.e. the feature (i)). The second type (i.e. the SIMO-type universal filter) has one input, multiple-outputs [20], and meets the feature (ii), but each voltage/current output terminal only offers a specific filtering function. In 2013 and 2014, the very recently reported two mixed-mode [24,25] (only including TAM in [25] and only including VM/TAM in [24]) biquads using two voltage differencing transconductance amplifiers (VDTAs) in [24]/three OTAs in [25] and two grounded capacitors in [24,25] can realize five universal filtering functions for TAM in [25] and VM/TAM in [24]. Only in TAM, the biquads [24,25] can achieve the features (i) and (ii). Therefore, it should be noted that, up until now, no previous papers have reported mixed-mode (including four modes) universal biquad filters which can achieve the features (i) and (ii) in all four modes. The aim of this paper is to present a new mixed-mode (including four modes) universal filter with versatile input/output functions (the functions mean that the proposed mixed-mode biquad filter not only realizes all four modes five universal filtering functions in the SIMO type but also provides all of them in the MISO type without changing the filter topology) which can achieve the features (i) and (ii) in all four modes, and still enjoys two very attractive advantages: (i) independent tunability of the parameters ω_0 and ω_0/Q by adjusting only

Table 1
Comparison of the previous reported mixed-mode universal filters which can realize TAM, TIM, VM, and CM all five universal filtering responses.

Previous reported mixed-mode universal filters	Advantages									
	(i)	(ii)	(iii)	(iv)	(v)	(vi)	(vii)	(viii)	(ix)	(x)
Ref. [26] in 2014	CCII = 3 for 2nd order	No	No	No	No	Yes	No	No	Yes	Yes
Ref. [22] in 2013	MOCCCII = 4	No	No	No	No	No	No	Yes	Yes	Yes
Ref. [21] in 2012	OTA = 5 for 2nd order	No	No	No	No	Yes	No	No	Yes	Yes
Ref. [20] in 2011	DDCC = 3	No	No	No	Yes	No	No	No	Yes	No
Ref. [13[1st structure]] in 2010	OTA = 4	No	No	No	No	Yes	No	No	Yes	Yes
Ref. [13[2nd structure]] in 2010	OTA = 5	No	No	No	No	Yes	No	No	Yes	Yes
Ref. [10] in 2009	OTA = 4 for 2nd order	No	No	No	No	Yes	No	No	Yes	Yes
Ref. [8] in 2006	CCII = 3	No	No	No	No	Yes	No	No	No	Yes
Ref. [7] in 2006	DDCC = 3 for 2nd order	No	No	No	No	Yes	No	No	Yes	Yes
Ref. [5] in 2005	OTA = 7	No	Yes	Yes	No	Yes	No	No	Yes	Yes
Ref. [4] in 2005	CFOA = 4	No	No	No	Yes	No	No	No	Yes	Yes
Ref. [3] in 2004	CCII = 7	No	No	No	No	Yes	No	No	Yes	Yes
Proposed circuit	FDCCII = 1 and DDCC = 1	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes