DESIGN OF ACTIVE FILTERS INDEPENDENT OF FIRST- AND SECOND- ORDER OPERATIONAL AMPLIFIER TIME CONSTANTS EFFECTS

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ABSTRACT

A PRACTICAL METHOD OF DESIGNING ACTIVE FILTERS IN WHICH THE TRANSFER FUNCTION IS INDEPENDENT OF BOTH FIRST- AND SECOND-ORDER OPERATIONAL AMPLIFIER TIME CONSTANT EFFECTS IS PRESENTED. NEITHER MATCHED OPERATIONAL AMPLIFIERS NOR A TUNING PROCEDURE DEPENDENT ON AN ACTIVE PARAMETER IS REQUIRED. THE ACTIVE PORTION OF THESE FILTERS IS UNIVERSAL AND READILY INTEGRABLE SINCE IT IS COMPRISED OF CONVENTIONAL OPERATIONAL AMPLIFIERS AND RESISTORS. THE METHOD CAN BE USED TO DESIGN A FILTER WITH ANY REALIZABLE TRANSFER FUNCTION OF ANY ORDER.

A NEW FILTER OBTAINED FROM THIS METHOD IS INTRODUCED AND EVALUATED BOTH THEORETICALLY AND EXPERIMENTALLY. THE SIGNIFICANT IMPROVEMENTS IN FILTER PERFORMANCE OF THIS NEW FILTER IS DEMONSTRATED IN THIS EVALUATION.

INTRODUCTION

The response of most active filters employing operational amplifiers (OP AMPs) that are designed to operate at high frequencies and/or high Qs changes significantly if the OP AMPs used in the design are replaced with devices of the same type but with slightly different characteristics. These changes in the response of the active filter are a result of the departure of the magnitude and phase characteristics of the OP AMPs themselves from the ideal values.

During the last few years, research efforts in active filter design have been directed towards topological configurations that are less dependent upon the parameters of the OP AMPs than were previous designs. A host of active filters have appeared in the literature [1] - [7], many of which perform better than the designs of ten years earlier.

Recently several configurations have appeared in the literature [1], [3], [7] - [9], in which first-order OP AMP time constant effects have been eliminated. Some of these circuits [8], [9] however, require either matched OP AMPs or a cumbersome active-parameter-dependent tuning procedure to remove these first-order effects.

It was recently shown by Geiger and Budak [1] that the active sensitivity function (sensitivity with respect to the OP AMP time constant) is a figure of merit for comparing the OP AMP related performance of active filters. Several filters [1], [3], [7], in which the active sensitivities of the poles and zeros vanish have been introduced. The poles and zeros of these zero active sensitivity designs are independent of first-order OP AMP time constant effects. In addition, the transfer function itself is independent of the first-order time constant effects for the circuits presented in [3] and [7]. The active sensitivity filters do not require either matched OP AMPs or an active parameter-dependent tuning procedure to eliminate the first-order effects.

Geiger and Budak [1] also presented criteria necessary to eliminate second-order as well as first-order time constant effects without requiring matched OP AMPs. No filters presented in the literature to date are independent of both first-order and second-order time constant effects.

In this paper a method of designing active filters is introduced in which both the first and second derivatives of the transfer function with respect to the OP AMP time constants vanish. This is achieved by imposing constraints on the gain of the amplifiers to eliminate both first- and second-order time constant effects in any filter employing these amplifiers. Using these constraints a new amplifier is synthesized. The ensuing filters require neither matched OP AMPs nor an active-parameter-dependent tuning procedure.

A bandpass configuration employing the proposed amplifier is introduced. A performance evaluation of this filter confirms the reduced OP AMP dependence of the new design over that of existing state of the art filters. Experimental results presented agree favorably with the theoretical development of the new filter.

The proposed amplifier can be used to design active filters with any realizable pole-zero assignment. The results presented for the bandpass situation are representative of the general case.

ACTIVE FILTERS WITH ZERO FIRST & SECOND DERIVATIVES

A general active filter employing a single amplifier with gain A(s) is shown in Fig. 1.

Assume the A(s) amplifier is constructed from resistors and three internally compensated OP AMPs which are ideal except for a frequency dependent gain given by the expression [11]

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$$A_i(s) = \frac{1}{\tau_i s} \tag{1}$$

where the OP AMP time constant τ_i is the reciprocal of the gainbandwidth product of the i^{th} OP AMP and is ideally zero. The OP AMP time constants are not assumed to be identical. If T(s) is the transfer function of any filter employing A(s) it can be shown that all first-and second-order derivatives of T(s) with respect to all OP AMP time constants will vanish provided A(s) is expressable in the form

$$A(s) = \frac{[a_o + s\tau_2 a_2 + s\tau_3 a_3 + s^2\tau_2\tau_3 a_{23}]}{\pm\frac{1}{K_0}[a_o + s\tau_2 a_2 + s\tau_3 a_3 + s^2\tau_2\tau_3 a_{23}] + s^3\tau_1\tau_2\tau_3} \tag{2}$$

where the a's are real constants with magnitudes less than or equal to unity and $\pm K_0$ is the dc gain of the A(s) amplifier and may be either finite or infinite.

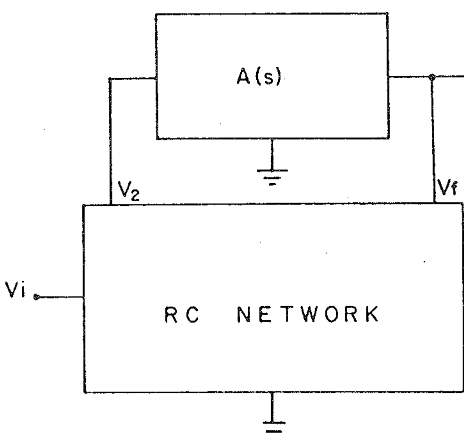
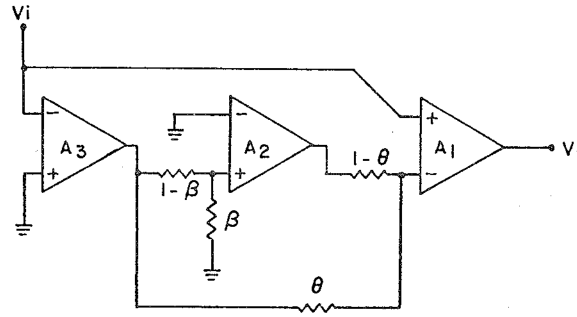


Fig. 1 General Active Filter

ZERO FIRST AND SECOND DERIVATIVE AMPLIFIERS

A new amplifier along with the corresponding gain A(s) is shown in Fig. 2. Note that the gain expression agrees with the functional form required by (2) to eliminate first- and second-order time constant effects in the transfer function of any filter employing this amplifier as the active device. As can be seen, the amplifier of Fig. 2 has ideally infinite gain. The infinite gain amplifier of Fig. 2 is readily integrable and universal in the sense that it may replace conventional OP AMPs in many existing filter configurations. The zero sensitivity property if unaffected in the input leads of any of the OP AMPs are interchanged. For example, reversing the + and - inputs on A_1 results only in a sign change in front of the transfer function.

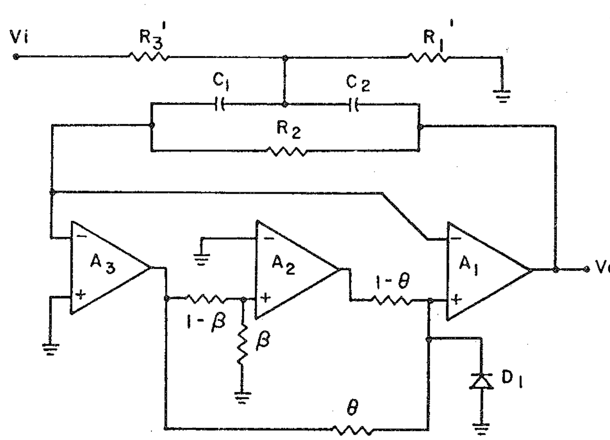


$$\frac{Vo}{Vi} = \frac{\theta\beta + s\tau_2(1-\theta) + s^2\tau_2\tau_3}{s^3\tau_1\tau_2\tau_3}$$

Fig. 2 Zero Second Derivative Amplifier

SOME NEW FILTERS WITH ZERO TRANSFER FUNCTION SECOND DERIVATIVES

For the purpose of easy comparison with existing designs the new filter presented in this paper ideally realizes a second-order bandpass transfer function. It should be emphasized, however, that any realizable transfer function of any



$A_i = \frac{1}{s\tau_i}$ $\quad i = 1,2,3$

$C_1 = C_2 = C$

$R_1 = R_1' // R_3'$

Fig. 3 Zero Second Derivative Bandpass Filter order can be synthesized with the amplifier of Fig. 2. The results given here are to be interpreted as being representative of the general case.

The circuit shown in Fig. 3 is a second-order bandpass configuration in which both the first and second derivatives of $T(s) = \frac{V_o}{V_i}$ with respect to the τs of the OP AMPs vanish. This configuration has been chosen for this presentation because its topological structure is similar to that of some well known configurations and the passive sensitivity expressions are identical to their well known counterparts.

The circuit of Fig. 3 uses the amplifier of Fig. 2 with the + and - leads of A_1 reversed.

Diode D_1 is necessary for stability with some OP AMPs. The parameters θ and β must be picked so that the parasitic filter poles are in the left half-plane [18].

The transfer function of this configuration is

$$T(s) = \frac{V_o}{V_i} = -\frac{s\omega_o\left[\frac{2\,QR_1}{R_3'}\right]\left[1 + s\tau_2\frac{(1-\theta)}{\beta\theta} + s^2\tau_2\tau_3\frac{1}{\beta\theta}\right]}{\left(s+s\frac{\omega_o}{Q}+\omega_o^2\right)\left[1 + s\tau_2\frac{(1-\theta)}{\beta\theta} + s^2\tau_2\tau_3\frac{1}{\beta\theta}\right] + s^3\tau_1\tau_2\tau_3\frac{1}{\beta\theta}\left[s^2 + s\omega_o\left(2Q+\frac{1}{Q}\right) + \omega_o^2\right]} \quad (3)$$

where

$$\omega_o = \frac{1}{\sqrt{R_1R_2C_1C_2}}$$

and

$$Q = \frac{1}{2}\sqrt{\frac{R_2}{R_1}}\,.$$

FILTER EVALUATION

A plot of the transfer function magnitude of this filter appears in Fig. 4 for values of $\tau_n = \tau\omega_o$ of .025 and .05.

In this evaluation all OP AMPs are assumed identical. This assumption is not essential but rather used for convenience.

The merit of the new filter is best established by a comparison with previous state of the art designs. A discussion of the performance of existing designs was presented by Geiger and Budak [1].

EXPERIMENTAL RESULTS

The circuit of Fig. 3 with θ = .2 and β = 1 was used to realize a filter with Q = 10 and ω_o= 27 KHz when the OP AMPs are ideal. The resulting filter was evaluated experimentally using both 741 (measured GB = 1.0 MHz ± 1%) and 356 (measured GB - 4.15 MHz ± 10%) type of OP AMPs. A summary

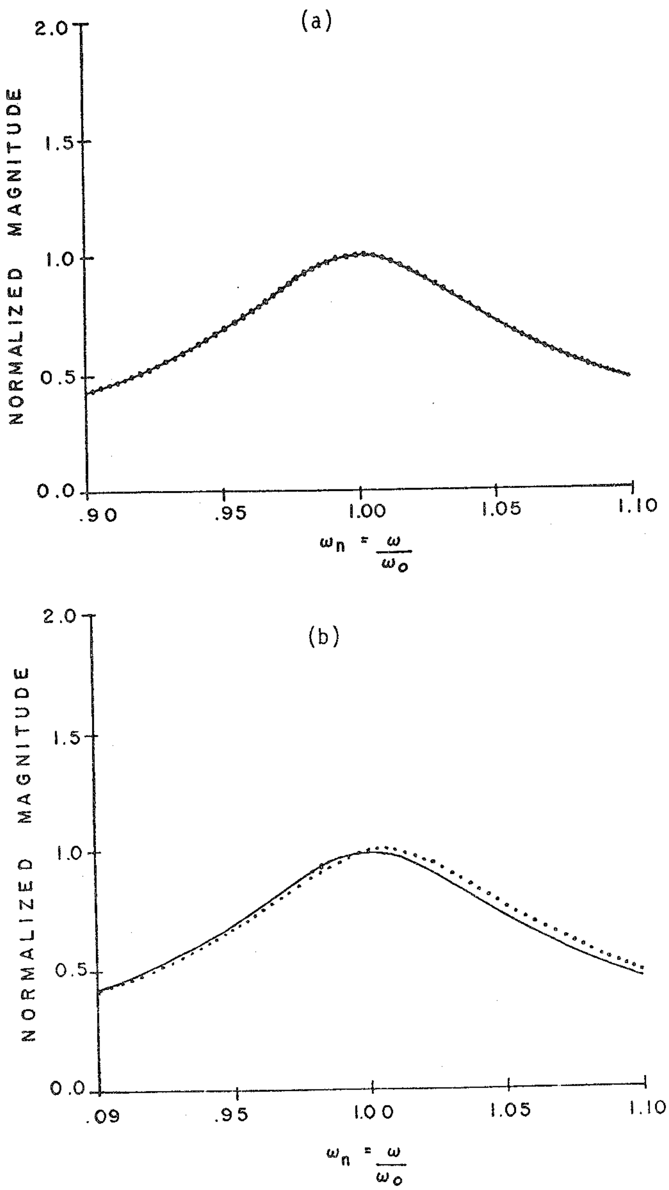


Fig. 4 Magnitude Response
a) τ_n = .025
b) τ_n = .05

of the experimental results is included in Table 1.

The close agreement between theoretical and experimental results is obvious from this comparison. The performance of the filter using 741's designed for a center frequency of 27 KHz (τ_n = 0.27) emphasizes the usefulness of these filters. Notice also that changing GB by more than 400% (i.e. using a 356 rathen than a 741) does not significantly affect the filter performance and may well be a better indication of performance than the comparison to the theoretical characteristics which rely on the absolute accuracy of the measured component values as well as the absolute accuracy of the frequency counter used in the experimental evaluation.

	Theoretical	Experimental		% Error	
		741	356	741	356
fo	26.963KHz	26.88KHz	26.949KHz	-.3%	-.05%
Q	9.41	7.64	7.86	-18.8%	-16%

Table 1

CONCLUSIONS

It has been shown that it is possible to design active filters with zero first and second transfer function derivatives with respect to the parameters of the OP AMPs. This was attained by first establishing the constraints on the gain of amplifiers necessary to obtain these properties and then synthesizing an amplifier which satisfied the constraints. This new amplifier is both universal and readily integrable.

A novel second-order bandpass circuit possessing these zero first and second transfer function derivative properties has been introduced. This circuit is less dependent upon the parameters of the OP AMPs at low frequencies than previously existing designs. In addition, in the 100 KHz range this circuit performs well using low-cost conventional OP AMPs whereas the performance of most previously existing active filters employing the same operational amplifiers is generally considered inadequate. These improvements in performance are attained without requiring either matched OP AMPs or an active parameter dependent tuning procedure. Experimental results confirmed the predicted performance of the new filter.

The new amplifier can be used to synthesize a filter with any prescribed realizable pole-zero assignment. These filters have the zero first and second transfer function derivative property and offer performance improvements similar to those of the bandpass configuration presented.

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