DESIGN OF RC-ACTIVE OSCILLATORS USING COMPOSITE AMPLIFIERS

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Abstract

The design of composite opamp Wien-Bridge oscillators is systematically approached by using a general model including amplitude control issues. Two different design criteria are presented and their main features summarized. A general composite opamp topology is presented from where a catalog of structures can be obtained in a systematic way. Experimental data are included illustrating the performance of the proposed design criteria.

Introduction

It is well known that the finite gain-bandwidth (GB) product of operational amplifiers (opamp) degrades the high-frequency behavior of active RC circuits. One of the solutions proposed in the literature is the use of active compensation techniques. Many papers have dealt with the topic of proposing active-compensated amplifiers (henceforth called *composite amplifiers*), see for instance [1,2], and a systematic study have been reported recently [3].

Composite amplifier techniques are not directly applicable to the design of sinusoidal oscillators. Although some circuit structures have been just proposed [4-8], there is a lack of systematic, this lack preventing from a meaningful comparison among the reported solutions, and among them and non-compensated oscillators. Besides some approaches are based on oversimplified linear models, which are not able to correctly explain data measured on actual prototypes.

In this communication we will undertake a systematic study of the use of composite amplifiers for the Wien-Bridge family of oscillators. Models including issues related to the control and stabilization of the amplitude are used to this purpose.

Single-opamp Wien-Bridge Family

Fig.1 is the block diagram for the Wien-Bridge family of opamp based RC-active oscillators. Fig.2 shows a complete set of canonical RC structures for the passive block (see references in [9]). The function of this block is to make the *phase* around the loop *to be zero* at a frequency $\omega_o = \omega_i$ being nonzero at any other frequency. The function of the amplifier is, on the other hand, twofold. First, it has to provide *signal gain* to make the loop transfer function magnitude to be 1 at ω_o. Second, it has to include an *adaptive mechanism* making the amplifier gain to depend on the signal amplitude A in such a way that the critical gain value is obtained just for a single amplitude value A_o. For $A > A_o$ the amplifier gain must be smaller than the critical value being larger otherwise. Whether the amplifier fulfills previous requirements, Fig.1 would generate a *quasi-sinusoidal* signal of amplitude A_o and frequency ω_o.

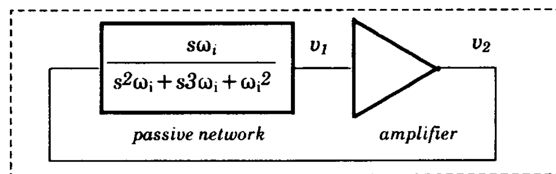

Fig. 1: Block diagram for the Wien-Bridge family of oscillators.

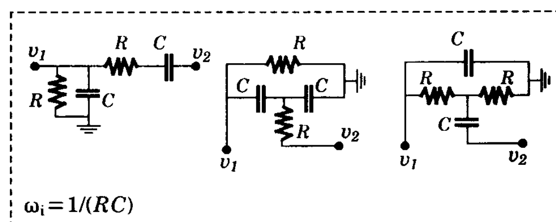

Fig. 2: Canonical RC structures for the Wien-Bridge family.

Fig.3(a) shows a conventional one-opamp implementation for the amplifier of Fig.1. Opamp nonlinearities can be exploited to get an adaptive gain and hence to stabilize the amplitude. For lower distortion, it may be however more convenient to use an AGC circuit controlling the value of resistor R as a function of the opamp signal amplitude. No matter how the amplitude control is made, if ideal opamps were available Fig.3(a) would allow us get $\omega_o = \omega_i$, for any value of ω_i, by just making $k = 3 + \varepsilon\ (0 < \varepsilon << 1)$.

Let us now consider a real opamp and use the model of Fig.3(b) to describe its corresponding *small-signal* behavior. After some calculations the following result for the *oscillation frequency* and the *oscillation condition*, respectively:

$$\omega_0^2 = \omega_i^2 \frac{1}{1 + 3k\omega_i\tau} \tag{1}$$

$$b = (3 - k)(1 + \omega_i\tau 9k) + (\omega_i\tau)^2 3k^2 = 0 \tag{2a}$$

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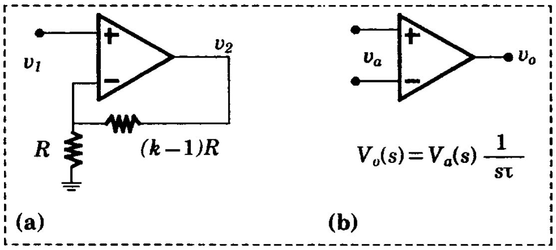

Fig. 3: (a)One-opamp amplifier, (b)First-order opamp small-signal model.

These equations provide a *linear* view on the operation of the oscillator. They have to be slightly modified to account for the *amplitude stabilization* mechanism. Let us assume to this purpose that parameter b above is controlled by an amplitude-dependent *adaptation parameter* $\xi(A)$ which we define to be a function of the signal amplitude as follows:

$$\xi(A)=1 \quad for \quad A<A_0 \quad ; \quad \left.\frac{d\xi}{dA}\right|_{A_0}<0 \tag{2b}$$

where A_o is the critical amplitude value (i.e., the stable oscillation amplitude).

For *stable self-starting* oscillations to exist parameter b must fulfill the following set of conditions:

$$\begin{aligned} &b(\xi)<0 \quad for \quad A<A_o \\ &b(\xi)=0 \quad for \quad A=A_o \\ &\left.\frac{db}{d\xi}\right|_{A_o}<0 \end{aligned} \tag{2c}$$

First one guarantees that for low amplitude there will be a pair of imaginary roots on the right-half of the complex frequency plane and hence that oscillations will self-start. Second one allows to calculate the amplitude value for which the roots are on the imaginary axis. Finally, the third one ensures the roots will cross the imaginary axis from right to left for the amplitude increasing, as it is required for the oscillations to be stable. In summary, (2c) is a much more realistic *oscillator condition* than (2a).

Equations (1) and (2) are the *basic design equations* for the one-opamp Wien-Bridge oscillators. In actual circuits there are two ways to achieve b to depend on ξ. One possibility is to control the amplifier DC gain k by making $k \propto \xi$. Other possibility is to control the opamp time constant τ by making $\tau \propto 1/\xi$. In both cases nonlinear limitation (for instance the slew-rate for the time constant or diodes for k) as well as AGC circuits can be used. However no matter which technique is used circuit operation is described with reasonable accuracy by (1) and (2) for frequencies up to about. $0.2/\tau$ [9].

From (1) it can be seen that the actual oscillation frequency deviates with respect to the ideal one, the deviation increasing as $(\omega_i\tau)$ increases. This drawback can be however partially overcome in case amplitude control is made via τ, parameter k remaining fixed. From (2) it can be seen that the critical $\omega_i\tau$ value (the one making $b=0$) for this case does not depend on ω_i.

Hence the actual and the ideal frequency are related in a linear way ($\omega_o=\beta\omega_i$), the ratio β depending only on k and hence being independent on the amplifier characteristics. This is a very interesting feature of single opamp whose only drawback comes from the fact that parameter b determining the oscillator condition is strongly dependent on $\omega_i\tau$. Hence, in case k is selected to ensure $b>0$ (self-starting operation) in wide frequency ranges, ξ_o can be shown to exhibit large variations from one extreme to the other of the range. This is not convenient in practice as it can be understood from Table 1. Data on this table have been measured from oscillators using the slew-rate as the controlling mechanism. The two rightmost columns correspond the single-opamp case. Parameter *dist.* refers to the ratio between the first and the third harmonics. k was selected to ensure self-starting operation in the range shown, which resulted in ξ_o being very close to unity for the higher frequency and increasing as the frequency decreases. Since changes in ξ_o have to be absorbed by the nonlinearity, large distortion may be expected for low frequencies, as it is confirmed from the measured data.

Table 1

composite opamp		single opamp	
f_o, hz	dist.	f_o hz	dist.
103848	−40dB	94930	−38dB
68030	−40dB	55460	−25dB
20800	−43dB	14820	−20dB

Composite Opamp Oscillators

Let us assume the amplifier in Fig.1 is made by using two opamps and some linear resistors (see Fig.4). In the more general case and using the opamp model of Fig.3(b) the following transfer function can be obtained for the amplifier:

$$\frac{V_2(s)}{V_1(s)} = k\frac{1+p_1\alpha(\tau_1,\tau_2)}{1+s\tau_2p_2+s^2\tau_1\tau_2p_3} \tag{3}$$

where k, p_1, p_2 and p_3 are controlled by resistor ratios (they are not typically separately controllable) and $\alpha(\tau_1, \tau_2)$ can be either τ_1 or τ_2 depending on the actual composite opamp structure.

After some analysis, the following can be obtained for parameters w_o and b of the composite opamp oscillator:

$$w_0^2 = w_i^2\frac{1+\dfrac{3-k}{w_i\tau_2p_2}}{1+\dfrac{3w_i\tau_1p_3}{p_2}} \tag{4a}$$

$$b = \omega_o^4 \tau_1 \tau_2 p_3 - \omega_o^2 \left[\omega_i^2 \tau_1 \tau_2 p_3 + \omega_i \tau_2 (3p_2 - kp_1 \frac{\alpha}{\tau_2}) + 1 \right] + + \omega_i^2 \quad \text{(4b)}$$

As for the one-opamp case, an adaptation parameter ξ fulfilling (2b) is assumed to be the vehicle for amplitude control via either one of the opamp time constants or the amplifier parameters k and p_i. Equations (2b-c) hence also holds as the oscillator condition, parameter b for this case being that in (4b).

Ideal gain design criterion. Different design design criteria for composite opamp Wien-Bridge can be devised by carefully analyzing (4). Since the purpose of composite opamp is to approach the performance of ideal amplifiers, one possible criterion is to try to fix k to the ideal value 3. As it can be seen from (4a) this yields frequency deviations which are very similar to the ones for the single-opamp case. The advantage of the composite-opamp case comes from the oscillator condition. After some analysis, we get,

$$b \simeq \omega_i^2 \tau_2^2 \left[3p_2^2 (p_2 - p_1 \frac{\alpha}{\tau_2}) - \frac{\tau_1}{\tau_2} 3p_2 p_3 \right] \quad \text{(5)}$$

where it can be seen that parameter b does not depend, to a first-order, on ω_i. Hence and no matter the amplitude control be made via τ, k or any of the p_i parameters, the critical value of the adaptation parameter will change only slightly over wide frequency ranges. This is advantageous in comparison to the one-opamp case as it can be confirmed from Table 1. In the two leftmost columns measured data have been collected for a composite amplifier structure with $p_1 = 1.55$, $p_2 = k = 3$ and $p_3 = kp_1$ and for the slew-rate of amplifier #2 being the amplitude control mechanism. LM747 dual opamps were used. As it can be seen, the distortion remains practically unchanged in the whole oscillation frequency range.

There are several observations to be made concerning the use of this ideal gain design criterion:

1) According to the first-order expression of b, it is not possible to get stable oscillations by controlling via the slew-rate of opamp #1 ($\tau_1 \propto \tau_1'/\xi$). For slew-rate based stable oscillations the opamp #2 should be the controlling device.
2) It is possible to make $p_1 = 0$ (no phase compensation allowed) without degrading the criterion features.
3) Controlling via p_3 ($p_3 \propto \xi$) yields the oscillator frequency to be insensitive to simultaneous proportional changes in the opamp time constants. Random changes in τ_2 cannot however be absorbed by the adaptation mechanism and will hence influence the oscillation frequency.

Notice finally that, since ω_i does not influence the sign of b, it is not possible to get a linear relationship between ω_o and ω_i, in opposition to what can be achieved for the one-opamp case.

Ideal frequency design criterion. Some interesting properties can be observed in case k is not fixed to the ideal value. As a matter of fact, in [7] the authors proposed a composite amplifier structure were by properly selecting k it was possible to get $\omega_o = \omega_i$ for frequencies up to about $1.5/\tau$. It means that the oscillation frequency can be made to be completely independent of the opamp time constants, which is a very appealing feature deserving further attention.

From (4b) it can be shown that by making,

$$3p_2 - kp_1 \frac{\alpha}{\tau_2} = 0 \quad \text{(6)}$$

the oscillation frequency exactly coincides to ω_i providing the following is fulfilled for the critical value of the adaptation parameter,

$$k - 3(1 - p_3 \omega_i^2 \tau_1 \tau_2) \Big|_{\xi_o} = 0 \quad \text{(7)}$$

Regarding the parameter determining the oscillation condition, it is convenient to separately consider two different cases. One where p_1, p_2, and the time constants are fixed according to (6) and the control is made either via k or p_3. For this case it results,

$$b \simeq -p_2 \left[k - 3(1 - p_3 \omega_i^2 \tau_1 \tau_2) \right] \quad \text{(8a)}$$

On the other hand if k and p_3 are fixed using (7) and the control is made via any of the other parameters, the following can be obtained:

$$b \simeq \omega_i^2 \tau_2^2 p_2^2 \left[3p_2 - kp_1 \frac{\alpha}{\tau_2} \right] \quad \text{(8b)}$$

There are some observations applying to this design criterion:

1) Stable operation controlling via the slew-rate is only possible for those structures where $\alpha = \tau_1$, and for the controlling device being the opamp #2 ($\tau_2 \propto \tau_2'/\xi$). Besides, the oscillation condition for this case is insensitive to proportional changes in the opamp time constants.
2) Amplitude control via τ_2, p_1 or p_2 (based on (8b)) requires k to be selected to fulfill (7) which depends on frequency. Hence this approach is only appropriate for fixed frequency applications.
3) For amplitude control via k ($k \propto k'\xi$), the oscillation condition can be made insensitive to both random and simultaneous changes in the opamp time constants by resorting to structures having $\alpha = \tau_2$. Otherwise, this condition will only be insensitive to simultaneous proportional changes.
4) Observe for amplitude control via k, the oscillation condition (8a) depends on frequency. As a consequence, large variations of the critical ξ values result in case $k'(k \propto k'\xi)$ is selected to ensure self-starting operation in a wide frequency range. In case the the adaptation process is implemented by resorting to nonlinear limitation, large distortions are thus expected for the high-frequency edge of the range.

Performance of the ideal frequency criterion is illustrated in Table 2 where we show experimental results for a composite opamp structure with $p_1 = 3.105$, $p_2 = k$ and $p_3 = kp_1$. LM747 dual opamps were used, the controlling device being the slew-rate of the opamp #2. As it can be seen, deviations in frequency are lower than 2% for frequencies up to 100Khz.

Table 2

Ideal frequency, *kHz*	Real frequency, *kHz*
22.7	*22.5*
49.1	*49.2*
88.4	*88.3*
107.8	*105.5*
154.8	*147.7*

Discussion on Composite opamp structures

Fig.4(a) shows a general block diagram for a two opamps composite amplifier. Triangular blocks correspond to opamps while rectangular blocks represent weighting by resistors as it is illustrated in Fig.4(b). Switches S_1 and S_2 have not be actually implemented but have been used to indicate that two different points are available to be used as the actual amplifier output.

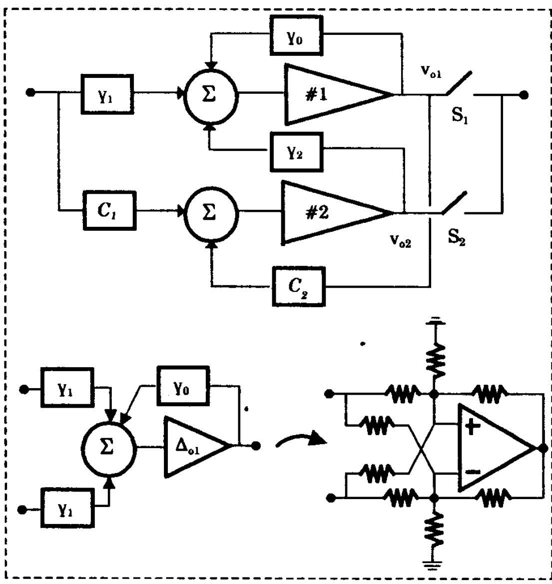

Fig. 4: General block diagram for a two opamps composite amplifier.

Table 3 shows expressions for k, p_1, p_2, p_3 and α as functions of C_i and γ_i for the two possible amplifier outputs. For proper operation of the composite amplifier Wien-Bridge, actual structures derived from Fig.4 would fulfill the following constraints,

$$p_1>0 \; ; \; p_2>0 \; ; \; p_3>0 \qquad |C_1|=|\gamma_1|=1 \qquad (9)$$

first one ensure no parasitic poles will be allocated in the right half of the complex frequency plane (according to the one pole opamp model). Second one ensures input to the composite opamp will be via high impedance nodes.

Table 3

output	p_1	p_2	p_3	k	α
V_{o1}	$\frac{\gamma_1}{C_1\gamma_2}$	$\frac{\gamma_o}{C_2\gamma_2}$	$\frac{1}{-C_2\gamma_2}$	$\frac{-C_1}{C_2}$	τ_2
V_{o2}	$\frac{C_1}{C_2\gamma_1 - C_1\gamma_o}$	$\frac{\gamma_o}{C_2\gamma_2}$	$\frac{1}{-C_2\gamma_2}$	$\frac{C_2\gamma_1 - C_1\gamma_o}{-C_2\gamma_2}$	τ_1

Starting from Fig.4 with (9) and taking into account Table 3 it is not a complicated task to derive composite amplifier structures for two composite amplifier design criteria presented in the paper. As it is demonstrated by the experimental results included in the communication, structures can be found fulfilling the criteria for frequencies up to about $0.2/\tau$.

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