VCO Controlled by One Variable Resistor

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Abstract—A multiloop active filter circuit of Kerwin is shown to yield a VCO whose oscillation frequency is conveniently controlled with one variable resistor. Using an FET to obtain the voltage variable resistor, experimental results are shown to agree with the theory developed.

I. INTRODUCTION

The voltage controlled oscillator (VCO) has a number of important applications [1], [2], [3, p. 567] among which is its use as the critical feedback element in phase-locked loops [4], [5]. And various means of realization of a VCO have been given [6] among which are some using varactor diode capacitance control of a Clapp oscillator [2, p. 115], variable capacitance control in a Wien bridge [7], variable diode resistance in an RC-phase-shift oscillator [8, p. 844, 856], voltage controlled current sources in integrator-Schmitt-trigger or emitter-coupled multivibrator circuits [4, p. 44], and resistor control in an op-amp RC-Wien bridge oscillator [9], [10]. Indeed a classification of RC active VCO's containing two charge-controlled devices has been presented in [11] where an integrated VCO controlled by the gate voltage of an FET is given.

Here we show that by using the latter concept of FET gate control within the multiloop feedback structures of Kerwin [12] an alternate means of obtaining VCO's results.

II. BASIC CIRCUITS

Two of the multiloop feedback circuits of Kerwin [12, p. 35, 38], those using a minimum number of capacitors, are shown in Fig. 1. Fig. 1(a) is a low-pass filter of transfer function connecting the input resistor to ground. And in both cases these natural frequencies, $\omega_0$, being the square roots of the denominator constant terms, are independently controllable through $K_1$, which in Kerwin's case was taken negative [12, p. 33].

The conditions for oscillation and the oscillation frequencies are then seen to be:

$$K_1 = 1 + a_3a_4 \left[ 1 + \frac{1}{a_1} + \frac{1}{a_3} \right]$$

$$f_0 = \frac{\omega_0}{2\pi} = \frac{1}{2\pi RC} \left[ \frac{a_1 + (1 - K_1 K_2)}{a_1 a_2 a_3} \right]^{1/2}$$

Fig. 2 gives plots of normalized frequency, $\omega_0/RC$, versus the second stage gain for various values of the parameters $a_1, a_2, a_3, a_4$.

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III. VCO

As $K_2$ can be realized to depend only upon a single variable resistor, the oscillation frequency can be varied by the single resistor. And since the single resistor can be realized by an FET working in the range below pinchoff, both of the circuits of Fig. 1 are seen to conveniently yield VCO's. Typical realizations are shown in Fig. 3 for the choice $a_2 = a_3 = a_4 = 1$ for which $K_I = 4$.

For the circuits shown the dependence of $K_2$ upon the FET drain to source resistance $R_{DS}$ is given by

$$K_2 = -\frac{1}{R_2R_4} \frac{R_3R_{DS}}{R_3 + R_{DS}}. \quad (4)$$

In turn, the drain to source resistance, at zero drain to source voltage, is given by [13, pp. 144-148], [14, p. 54]

$$R_{DS} = \frac{1}{\beta(V_{GS} + V_0)} \quad (5)$$

where $V_0$ is the pinchoff voltage for depletion devices and the negative of the threshold voltage for enhancement mode devices; $\beta$ is a constant dependent on the properties of the channel.

Substituting (5) into (4) then into (2) and (3) yields the dependence of the VCO oscillation frequency $\omega_0$ upon the controlling voltage $V_{GS}$. For example, for the circuits of Fig. 3 we find

low-pass circuit:

$$\omega_0RC = \sqrt{2} \left(1 + 2 \frac{\beta R_3R_4(V_{GS} + V_0) - R_3}{\beta R_2R_3(V_{GS} + V_0) + R_3} \right)^{1/2} \quad (6a)$$

bandpass circuit:

$$\omega_0RC = \sqrt{2} \left(1 + \frac{\beta R_3R_4(V_{GS} + V_0) - R_3}{\beta R_2R_3(V_{GS} + V_0) + R_3} \right)^{-1/2}. \quad (6b)$$

From this we observe that a choice of $R_4$ large negates the voltage control and $R_4$ small can lead to imaginary frequencies (exponential instabilities).

IV. Experimental Results

Both circuits were constructed using identical components and an n-channel enhancement FET. The results are shown in Fig. 4 where $\omega_0RC$ versus $V_{GS}$ is compared with the theoretical values obtained from (6). As can be seen reasonably close agreement was obtained over the operating range. Outside of the experimental ranges shown the oscillations were observed to persist but in a relaxation mode. Too, some of the bigger differences occurring at the higher values of $V_{GS}$ come from the
in the experiments the high-frequency rolloff of the operational amplifiers was also found to be an important factor in checking the measured and theoretical results.

In Fig. 5 we present typical sinusoidal and nonsinusoidal waveforms obtained for the bandpass realization. The sinusoidal waveform was found not to be distorted when \( K_1 \) varied within a range of \( \pm 1.4 \) percent of its nominal value. Measurements taken with a Tektronix 3L5 Spectrum Analyzer show that the rejection of any spurious responses is greater than 60 dB.

The study of the frequency stability to temperature shows that the oscillation frequency can be insensitive to temperature changes. The relative change of oscillation frequency can be expressed as [15, p. 104]

\[
\frac{\Delta \omega_0}{\omega_0} = \sum_{i=1}^{\mu} \Delta R_i - \frac{\Delta R_i}{R_i} + \sum_{j=1}^{c} \Delta C_j - \frac{\Delta C_j}{C_j} + \sum_{m=1}^{x} \Delta R_m - \frac{\Delta R_m}{R_m} \quad (7)
\]

where \( \mu \) is the number of resistors, \( c \) is the number of capacitors, and \( x \) is the number of amplifiers. For both configurations one finds

\[
\sum_{i=1}^{\mu} S_{R_i} \Delta R_i = \sum_{j=1}^{c} S_{C_j} \Delta C_j = -1. \quad (8)
\]

If all resistors and all capacitors have the same temperature coefficients, i.e.,

\[
\frac{\Delta R_i}{R_i} = \frac{\Delta R}{R} \quad \text{and} \quad \frac{\Delta C_j}{C_j} = \frac{\Delta C}{C}
\]

then

\[
\frac{\Delta \omega_0}{\omega_0} = - \left( \frac{\Delta R}{R} + \frac{\Delta C}{C} \right). \quad (9)
\]

The \( \Delta K \) is zero because \( K \) depends only upon the ratio of the resistances. From (9) it is easy to see that \( \Delta \omega_0 \) can be zero if

\[
\frac{\Delta R}{R} = - \frac{\Delta C}{C}
\]

which is possible to realize in practice with opposite temperature coefficients for the resistors and capacitors.

Finally, we comment that we have chosen Kerwin’s circuit because of the independent control of \( \omega_0 \) with \( K_2 \) once \( K_1 \) is fixed. This feature we have not located nicely in other active circuits with the same number of amplifiers, while the experi-
ments we have performed have shown the true practicality of this single parameter control of $\omega_0$. It should be mentioned that there are other biquadratic structures [16], [17] which also have the ability of varying $f_0$ and $Q$ independently with resistors, but they require three or more amplifiers and the position of the resistors is inconvenient.

REFERENCES


Video Amplifier Design Based on Op Amps

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Abstract—A design procedure for video amplifiers is discussed that will 1) determine if a specific op amp can be used to satisfy the design, 2) minimize the number of stages required, and 3) determine individual stage gains required to satisfy the design. A figure of merit, based on device parameters and the specific amplifier requirements, is developed to aid the design procedure.

The design procedure is directed toward practical application in that it minimizes component cost, eliminates trial and error methods, and is directly applicable to worst-case design.

I. INTRODUCTION

In the field of video amplifier design there is a well-known method available for optimizing the overall gain or bandwidth of an amplifier consisting of several noninteracting stages [1].

If a given overall gain is required, the overall bandwidth can be optimized by using identical stages with individual stage gains of 1.65. It has also been shown that if overall bandwidth is the specified figure, overall gain can be maximized by setting individual stage bandwidths equal. This result holds for non-identical stages as well as iterative stages so long as the stages are noninteracting [2].

The goals of a practical design procedure are:

1) to determine if a given device can be used to satisfy the specifications of the amplifier in terms of gain, bandwidth, and impedance levels;
2) to minimize the number of stages required for the design;
3) to determine the individual stage gains and bandwidths required to meet the overall specifications.

While the theory mentioned earlier is helpful in the first step of the design process, it is of little direct value in the remaining steps. The theory is most often directed toward the goal of achieving a required gain along with maximum bandwidth assuming no limitation on the total number of stages. Practical design, due to cost considerations, focuses on achieving the required gain and required bandwidth using the minimum possible number of stages. In the past, the primary method used to reduce stages was trial and error. This is by no means a trivial task. When the number of stages is reduced from the number used to maximize overall bandwidth, the individual stage gains must be adjusted, the individual stage bandwidths will consequently change, and the factor relating overall bandwidth to individual stage bandwidth also changes. The design process based on trial and error methods is highly inefficient. This paper presents a concise design procedure for op-amp stages that requires little time to complete and meets the three goals listed above.

II. THE OP AMP

The basic element in this procedure is the op amp compensated for unity gain which is shown in Fig. 1. These devices will exhibit a 20-dB/decade rolloff in gain above the upper corner frequency and will allow gain and bandwidth to be exchanged directly resulting in a constant gain–bandwidth product. This direct exchange of gain and bandwidth is in effect for gains of unity or higher.

Not only do most commercial op amps satisfy these assumptions, the input and output impedance levels of these devices lead to negligible interaction of stages when cascaded. Thus the gain and bandwidth of an individual stage can be adjusted without affecting gains or bandwidth of adjacent amplifier stages.

For the noninverting stage of Fig. 1(a) the gain is given by

$$A_{HI} = 1 + \frac{R_F}{R_2}$$

while the bandwidth can be found from

$$\omega_{HI} = GBW/A_{HI}.$$