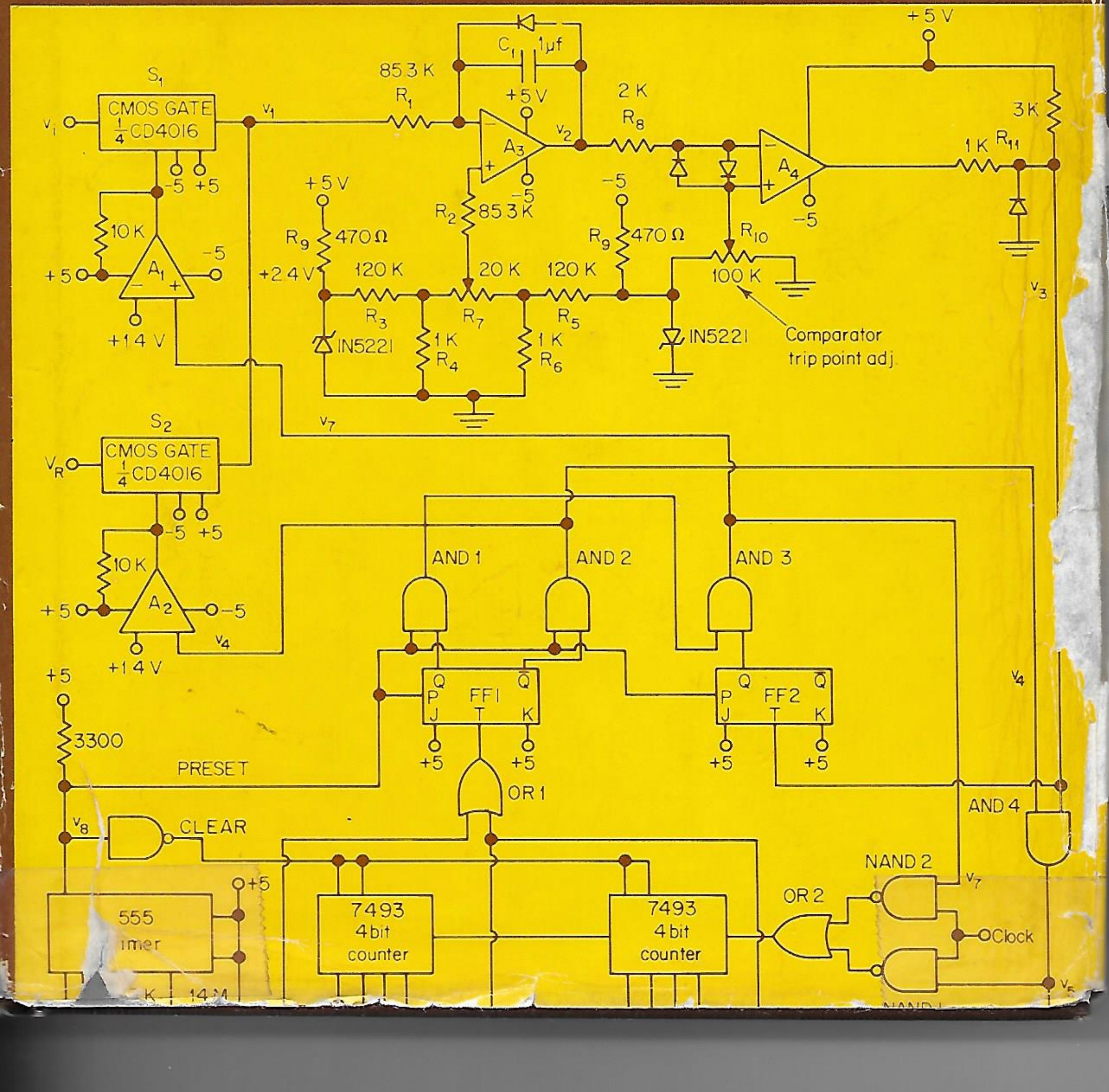
DAVID F. STOUT / MILTON KAUFMAN, Editor

HANDBOOK OF OPERATIONAL AMPLIFIER CIRCUIT DESIGN



Chapter 21

Oscillators

INTRODUCTION

In this chapter we will provide detailed design information on two popular oscillator circuits. First to be described is the popular Wien-bridge sine-wave oscillator. The circuit presented will be a superior design which has controlled amplitude and frequency stability. The second circuit presented is a voltage-controlled square-wave generator.

Other types of oscillators are presented elsewhere in this handbook. Chapter 20 contains detailed design information on the basic square-wave generator. Several types of waveform generators are presented in Chap. 27.

21.1 WIEN-BRIDGE SINE-WAVE OSCILLATOR

ALTERNATE NAMES Phase-shift oscillator, AGC oscillator, sine-wave generator.

EXPLANATION OF OPERATION A Wien bridge is made up of a series *RC* circuit in one branch of a bridge and a parallel *RC* circuit in another branch. In the Wien-bridge oscillator shown in Fig. 21.1 these components are R_1, R_2, C_1, and C_2. The circuit will oscillate at that frequency where the phase of V_1 is identical to the phase of V_o. This frequency, in terms of circuit components, is

$$f_o = \frac{1}{2\pi(R_1R_2C_1C_2)^{1/2}}$$

Oscillation cannot be sustained unless the positive feedback through R_1, R_2, C_1, and C_2 is exactly equal to the forward gain controlled by R_3, R_5, and R_6. The feedback factor (gain from V_o to V_1) through the Wien bridge is (at f_o)

$$A_f = 1 + \frac{R_2}{R_1} + \frac{C_1}{C_2}$$

The forward gain of the amplifier is (at dc)

$$A_{vc} = 1 + \frac{R_3}{R_5} + \frac{R_3R_4}{R_5R_1}$$

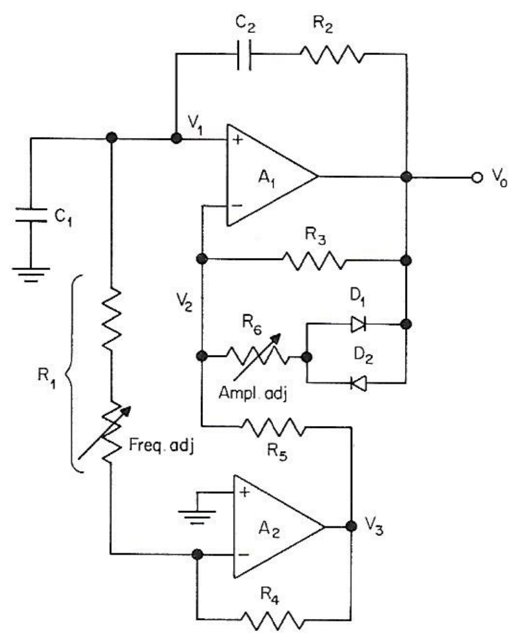


Fig. 21.1 A Wien-bridge oscillator which requires only one component for tuning.

These gains will be equal if we satisfy the following equalities:

$$R_2 = R_3 = R_4 = R_5 \qquad \text{(in practice } R_3 \text{ is made 5 to 10 percent higher)}$$
$$C_1 = C_2$$

In basic Wien-bridge oscillators R_1 is returned to ground. In the present circuit, however, it is returned to a virtual ground at the inverting input of A_2. This additional circuit, composed of A_2, R_4, and R_5, is added so that a single part R_1 can be used for tuning. The A_2 circuit forces the positive feedback to equal the negative feedback for all values of R_1.

The circuit composed of D_1, D_2, and R_6 is used to maintain V_o amplitude stability. If V_o tries to increase owing to load changes, diodes D_1 and D_2 conduct harder. This makes R_3 appear to be smaller, which lowers the gain of A_1 and restores V_o to its correct value. The diodes keep R_6 out of the circuit until a firm oscillation is present. Otherwise the circuit would have too much negative feedback and would not start.

If R_1 is to be variable, its limits should be controlled. The minimum R_1 is constrained by the maximum available gain of A_2 at f_o. Equation 5 must be satisfied, so that the gain of the A_2 circuit ($-R_4/R_1$) will never attempt to exceed the open-loop gain of A_2 at f_o. Conversely, very large values of R_1 will cause A_1 to have a dc output offset of $I_{b1}R_1$. The maximum R_1 is therefore constrained by the maximum allowable output offset.

DESIGN PARAMETERS

Parameter	Description
A_1	Op amp which oscillates
A_2	Op amp used to keep gain of A_1 constant as R_1 is adjusted
A_f	Feedback factor V_1/V_o of Wien bridge

Parameter	Description
A_{vc}	Gain of A_1 circuit from V_1 to V_o assuming Wien bridge is not present
C_1 to C_2	Determines frequency of oscillation along with R_1 and R_2
D_1 to D_2	Used to control gain (and output amplitude) of A_1 circuit
f_o	Frequency of oscillation
f_{u2}	Unity-gain crossover frequency of A_2
I_{b1}	Input bias current of A_1
R_1(min)	Fixed portion of R_1
R_1(max)	Variable portion of R_1
R_2	Controls frequency of oscillation along with R_1, C_1, and C_2
R_3	Sets basic gain of A_1 circuit
R_4 to R_5	Controls effect of A_2 circuit on the gain of A_1 circuit
R_6	Used to adjust stability and also output amplitude (to a lesser extent)
V_1 to V_3	Voltages at various nodes in Fig. 21.1
V_o	Output voltage
ΔV_o	Output offset due to input bias current of A_1
$V^{(\pm)}$	Power-supply voltages

DESIGN EQUATIONS

Eq. No.	Description	Equation
1	Frequency of oscillation	$f_o = \dfrac{1}{2\pi(R_1R_2C_1C_2)^{1/2}}$
2	Feedback factor of Wien bridge at f_o	$A_f(f_o) = \dfrac{V_1}{V_o} = 1 + \dfrac{R_2}{R_1} + \dfrac{C_1}{C_2}$
3	Gain of A_1 circuit from V_1 to V_o (assuming Wien bridge is disconnected)	$A_{vc} = 1 + \dfrac{R_3}{R_5} + \dfrac{R_3R_4}{R_5R_1}$
	Recommended resistor values:	
4	R_1 (variable portion)	$R_1(\text{max}) \leqq \dfrac{\Delta V_o(\text{max})}{I_{b1}}$
5	R_1 (fixed portion)	$R_1(\text{min}) \geqq \left(\dfrac{R_4^2}{4\pi^2R_2C_1C_2f_{u2}^2}\right)^{1/3}$
6	R_2, R_4, R_5	$R_2 = R_4 = R_5 = [R_1(\text{max})]^{1/2}$
7	R_3	$R_3 \approx 1.1\ R_2$
8	R_6	$R_6 \approx 100\ R_3$
9	Recommended capacitor values C_1 C_2	$C_1 = C_2 = \dfrac{1}{2\pi f_o R_2}$
10	Maximum f_o	$f_o(\text{max}) \approx \left(\dfrac{f_{u2}}{4\pi^2R_2R_4C_1C_2}\right)^{1/3}$
11	Minimum f_o	$f_o(\text{min}) \approx \dfrac{1}{2\pi}\left[\dfrac{I_{b1}}{R_2C_1C_2\Delta V_o(\text{max})}\right]^{1/2}$

DESIGN PROCEDURE

We begin by assuming the midband frequencies are most important. We then perform calculations to determine the maximum and minimum frequency limits of the oscillator.

DESIGN STEPS

Step 1. Compute a value for R_1(max) using Eq. 4.

Step 2. Sequentially apply Eqs. 6, 7, and 8 to determine the other resistor values.

Step 3. Determine nominal values for C_1 and C_2 using Eq. 9.

Step 4. Compute the fixed portion of R_1 using Eq. 5. The variable portion of R_1 should be a log-taper potentiometer if one wants a constant octave/degree control of frequency.

Step 5. Compute the approximate frequency limits expected from the oscillator using Eqs. 10 and 11.

Step 6. Double-check all previous calculations by computing f_o with Eq. 1 at R_1(min), R_1(max), and the square root of R_1(max).

WIEN-BRIDGE-OSCILLATOR DESIGN EXAMPLE An oscillator with a mid-range frequency of 1,000 Hz will be designed. The maximum output voltage (peak-to-peak) and output offset are specified. The op amps are also predetermined. We are asked to determine the upper- and lower-frequency limits of the oscillator.

Design Requirements

$V_o = \pm 10$ V
$\Delta V_o(\text{max}) = 0.1$ V
$f_o(\text{midband}) = 1{,}000$ Hz
A_1 and A_2 = LM 324
$V^{(\pm)} = \pm 15$ V

Device Data

$f_{u2} = 5 \times 10^5$ Hz
$I_{b1} = 3 \times 10^{-8}$ A

Step 1. The adjustable portion of R_1 is

$$R_1(\text{max}) = \frac{\Delta V_o(\text{max})}{I_{b1}} = \frac{0.1}{3 \times 10^{-8}} = 3.3\ \text{M}\Omega$$

Step 2. Equation 6 provides us with

$$R_2 = R_4 = R_5 = [R_1(\text{max})]^{1/2} = (3.3 \times 10^6)^{1/2} = 1{,}830\ \Omega$$

Equation 7 is approximately

$$R_3 \approx 1.1\ R_2 = 1.1(1{,}830) = 2{,}000\ \Omega$$

R_6 is found from Eq. 8:

$$R_6 \approx 100\ R_3 = 100(2{,}000) = 200\ \text{k}\Omega$$

Step 3. Equation 9 gives us nominal values for C_1 and C_2:

$$C_1 = C_2 = \frac{1}{2\pi f_o R_2} = \frac{1}{2\pi(1{,}000)1{,}830} = 0.087\ \mu\text{F}$$

The output will not be a pure sine wave unless these capacitors are closely matched.

Step 4. The fixed portion of R_1 is

$$R_1(\text{min}) = \left(\frac{R_4^2}{4\pi^2 R_2 C_1 C_2 f_{u2}^2}\right)^{1/3}$$

$$= \left[\frac{1{,}830^2}{4\pi^2(1{,}830)(0.087 \times 10^{-6})^2(5 \times 10^5)^2}\right]^{1/3} = 29\ \Omega$$

Step 5. We now substitute data into Eqs. 10 and 11 to find the oscillator range:

$$f_o(\max) = \left(\frac{f_{u2}}{4\pi^2 R_2 R_4 C_1 C_2}\right)^{1/3}$$

$$= \left[\frac{5 \times 10^5}{4\pi^2 (1{,}830)^2 (0.087 \times 10^{-6})^2}\right]^{1/3} = 7{,}900 \text{ Hz}$$

$$f_o(\min) = \frac{1}{2\pi}\left[\frac{I_{b1}}{R_2 C_1 C_2 \Delta V_o(\max)}\right]^{1/2}$$

$$= \frac{1}{2\pi}\left[\frac{3 \times 10^{-8}}{(1{,}830)(0.087 \times 10^{-6})^2 0.1}\right] = 23.4 \text{ Hz}$$

Step 6. The oscillator frequency is computed using Eq. 1 along with the results of steps 1, 2, 3, and 4.

$$f_o(\min) = \frac{1}{2\pi\ [R_1(\max) R_2 C_1 C_2]^{1/2}}$$

$$= \frac{1}{2\pi\ [(3.3 \times 10^6)1{,}830(0.087 \times 10^{-6})^2]^{1/2}} = 23.4$$

$$f_o(\text{nom}) = \frac{1}{2\pi\ [R_1(\text{nom}) R_2 C_1 C_2]^{1/2}}$$

$$= \frac{1}{2\pi\ [1{,}830(1{,}830)(0.087 \times 10^{-6})^2]^{1/2}} = 1{,}000 \text{ Hz}$$

$$f_o(\max) = \frac{1}{2\pi\ [R_1(\min) R_2 C_1 C_2]^{1/2}}$$

$$= \frac{1}{2\pi\ [29(1{,}830)(0.087 \times 10^{-6})^2]^{1/2}} = 7{,}958 \text{ Hz}$$

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1. Brokaw, P.: FET Op Amp Adds New Twist to an Old Circuit, *EDN*, June 5, 1974, p. 75.
2. Coers, G.: MOSFET Network Minimizes Audio Oscillator Distortion, *Electronics*, Jan. 3, 1972, p. 85.
3. Widlar, R. J., and J. N. Giles: Avoid Over Integration, *Electron. Des.*, Feb. 1, 1966, p. 56.

21.2 VOLTAGE-CONTROLLED OSCILLATOR

ALTERNATE NAMES VCO, voltage-controlled pulse generator, voltage-to-frequency converter, V/F converter, VFC.

EXPLANATION OF OPERATION The op amp circuit is an integrator which is constantly attempting to drive its output terminal high. The rate at which the output slews high is

$$\frac{\Delta v_1}{\Delta t} = \frac{v_m}{R_1 C_1}$$