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The Signal Path: II Sine Wave Oscillators

Sinusoidal oscillators come in various forms, producing a variety of configurations, according to need.

IN A PREVIOUS Signal Path article I examined some techniques for signal sources using waveform generators which produce triangle, square, sawtooth, pulse, and sine waves. This time we take a look at methods for generating higher purity sine waves, both rudimentary and state-of-the-art in quality.

There are a seemingly endless variety of ways one can configure circuits to produce sine waves.[1] Seen from afar, one can easily wonder why are there so many of them—that is, what distinguishes them in terms of performance. The best general answer to that question would depend on what is expected out of the circuit, what you want it to do for you, how well you want it to perform, how complicated, how easy to reproduce or manufacture, how stable, how expensive, and so on. As performance levels increase, so do parts count and cost, although, it is not always true that cost increases linearly with performance. Good design techniques which take advantage of modern high performance devices can really hold cost down while wringing a lot of performance from an i.c. or two. So, this article will attempt to discuss a bag of tricks useful in oscillators of various complexities and quality.

WIEN BRIDGE OSCILLATORS

One of the first types of sine wave oscillators to pop up is the family (and there are many members, believe me) based on a Wien network. Or, as it is more popularly known in oscillator form, the *Wien bridge oscillator*. For starters, a single example is shown in FIGURE 1.

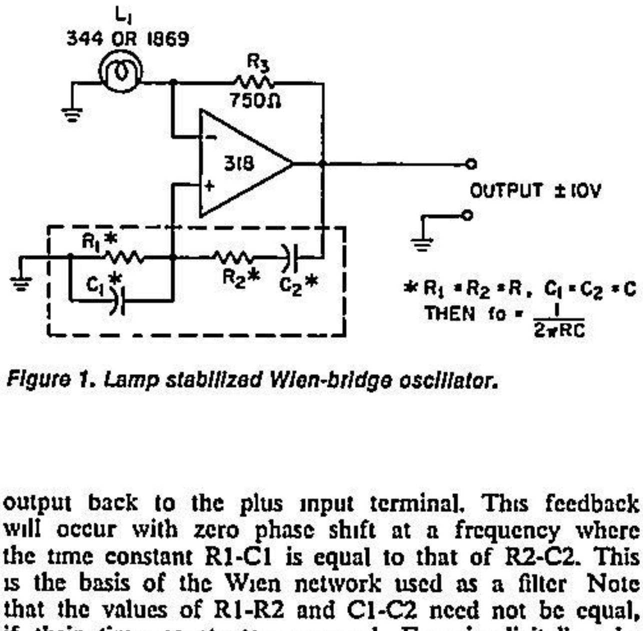

Figure 1. Lamp stabilized Wien-bridge oscillator.

In operation, the Wien network, consisting of R1-C1 and R2-C2 provides positive feedback from the amplifier output back to the plus input terminal. This feedback will occur with zero phase shift at a frequency where the time constant R1-C1 is equal to that of R2-C2. This is the basis of the Wien network used as a filter. Note that the values of R1-R2 and C1-C2 need not be equal, if their time constants are equal. For simplicity's sake however, R1 is normally set equal to R2, and C1-C2. With this arrangement, resonance occurs at a frequency *fo* which is simply

$$fo = \frac{1}{2\pi RC}$$

where R and C are the values of R1 (R2) and C1 (C2).

As this frequency, the attenuation of the network will be 3/1; that is, one-third of the output is fed back to the plus input. Therefore, oscillations will be sustained if the amplifier gain is 3 to 1 or more (the value required to

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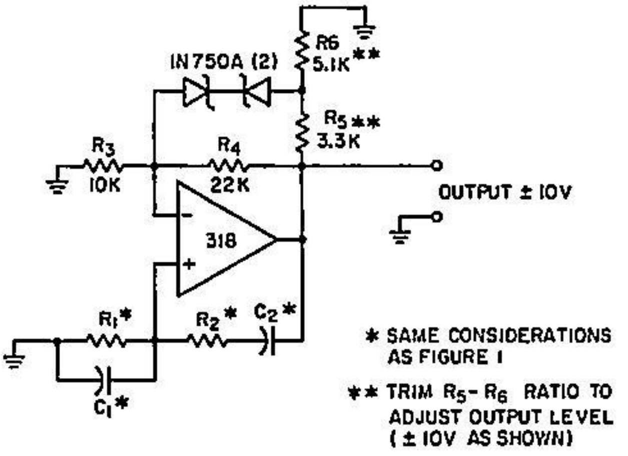
This is the second of a series of articles on the Signal Path, as followed by Walter G. Jung.



* SAME CONSIDERATIONS AS FIGURE 1

** TRIM R_5-R_6 RATIO TO ADJUST OUTPUT LEVEL (± 10V AS SHOWN)

Figure 2. Zener stabilized Wien-bridge oscillator.

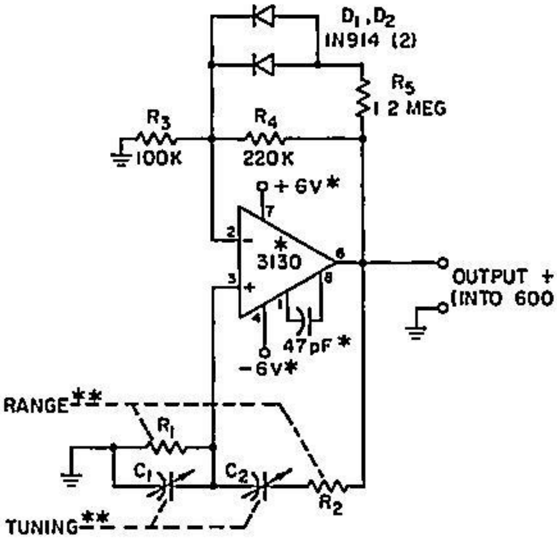
make up for the network's loss). Here lies the key to a successful and undistorted sine wave oscillator—getting the gain of the amplifier just right.

Gain must be precisely held equal to the Wien network's loss, for if it is too low the oscillator will never start, if too high it will build up until clipping occurs. Any practical oscillator of this type must incorporate some means of stabilizing the output by dynamically changing the amplifier's gain. Many means exist of doing this (for various reasons, as we'll see) but the example shown here uses the non-linear resistance of lamp L1 Since incandescent lamps have the property of increasing resistance with applied voltage, an increase in output voltage will be counteracted by a rise in L1's resistance, which lowers gain. Conversely, output which tends to decrease will be stabilized by a decrease in L1's resistance (an increase in gain). The net result is an output sine wave which is stable at a level where L1's resistance is half R3's nominal value.

What are the keys to making the circuit work up to its capability? The lamps specified are 10V, 14mA models, but will typically exhibit variance in impedance. So, you will probably find it desirable to trim R3 to adjust the output to ±10V. You cannot make it work properly below the natural thermal time constant of the lamp This allows use down through the audio range, but not at 1 Hz, for instance. Also, since stabilization is inherently acquired by thermal means, the lamp is sensitive to temperature (and also shock). The main virtue of this circuit is its simplicity; it will work just as shown without tweaking or coddling, with a thd content of 0.25 per cent or less.

Considerations should also be given to the op amp used and the Wien components (these comments will apply to many of the circuits which follow, also). The 318 shown is an excellent audio range choice and has no limitations, except for its input currents which will place an upper range on R1 (and R2) values of about 100 k or so. 741s, including 741 dual and quad derivation, will function up to a few kHz, but are best used below 1 kHz. The 356 is also a good choice, and since it is an f.e.t. input unit, allows use of resistances up to hundreds of megohms if desired. Supply voltages for the op amp are ±15V and should be rf-bypassed at the socket, especially with wider bandwidth units like the 318.

Don't skimp on the quality of the Wien network and you will be rewarded by trouble-free service. Stick to poly-styrene and/or poly-carbonate caps if possible, and stable low t.c. resistors. Both should match as well as practical, 1 per cent or better preferred. If R1-R2 are used for tuning, the dual pot sections should track well. And, if high impedance components are used, shield the network to reduce noise pickup. Tuning may be via R1-R2 or C1-C2 with, the other component pair switch selected for range in decade steps.



*SEE TEXT

**TABLE 1

RANGE	R_1,R_2	
20-200 Hz	20 MEG	C_1,C_2 = 40-400pF
200Hz-2kHz	2 MEG	
2-20 kHz	200 K	
20-200 kHz	20 K	

Figure 3. Battery operated Wien-Bridge oscillator.

ZENER STABILIZED WIEN BRIDGE

A version of the Wien bridge which is quite similar, differing only in its form of amplitude control, is shown in FIGURE 2. This one uses zener diodes as soft limiters to control output amplitude. As the Wien network and amplifier considerations here are similar to that of FIGURE 2, the discussion will will be limited to the stabilization method.

In this circuit, a pair of 4.7V diodes are connected back-to-back as a symmetrical clipper. The advantage of zeners is that they do not have a limiting time constant and there is no theoretical lower limit on frequency of operation. Also, they are smaller, lighter, and easier to get your hands on than miniature lamps. The R4-R3 ratio is set at 3.2, a value greater than 3, which ensures starting of the oscillator by regeneration.

Once oscillations build up to a level where the zener threshholds are exceeded, stabilization occurs by reduction of the net gain to 3. For a ±10V output, R5 and R6 reduce the level fed back to the zeners to scale their clipping level upward. Although the clipping process is inherently more non-linear than a lamp, thd is still reasonable, at 0.8 per cent. Best operation will be realized with matched diodes, such as i.c. transistor E-B junctions.[2] If a pair of diodes can be selected for low thermal conductivity, the stage will be temperature-compensated also

Quite often, a portable, battery-operated signal source is a handy device to have around a studio or workbench. Battery operation for low output levels is entirely feasible, as illustrated in FIGURE 3.

This circuit is a modification of FIGURE 2, using gen-

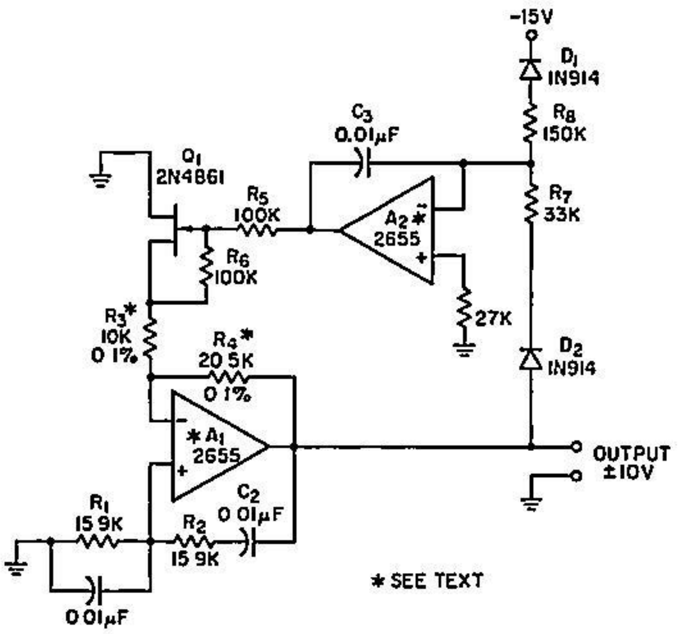


Figure 4. Low distortion f.e.t. stabilized Wien-bridge oscillator.

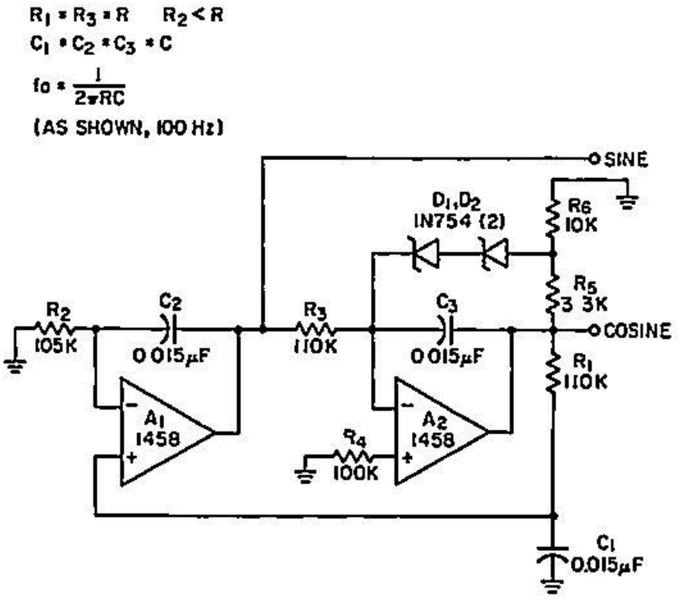


Figure 5. Quadrature (sine/cosine) oscillator.

eral purpose diodes for amplitude control. In general impedances are scaled upward to minimize power waste, and a low voltage fet input op amp is used. This allows operation from 6V batteries, and the low op amp input current allows R1-R2 values up to 20 megs (or more), a factor which allows a dual 400 pF miniature tuning capacitor to be used for C1-C2. If C1-C2 are padded for a 40-400 pF tuning range, R1-R2 can be switched, selected to cover a 3 or more decade range (see TABLE I for details).

Output is set at approximately +4 dBm by R5 (which may be trimmed if desired). Distortion is slightly higher than the zener version, measuring 0.9 per cent. The circuit may be used at higher supply voltages also, such as ±9V or ±15V, if higher voltage op amps are used, such as the 356 or 8007, both fet types.

A circuit which improves considerably on the performance of the previously described "passively stabilized" Wien bridge oscillators is shown in FIGURE 4. This is a Wien bridge circuit with active automatic gain control, which is provided by Q1, an fet. Here the variable channel resistance of the fet is used to control the gain of the amplifier about its nominal value of 3.

There are several keys to making the circuit work well in this form. You may note that feedback resistors R3 and R4 are specified as close tolerance types with a ratio only slightly more than 2/1. The actual gain will be determined by the R3 resistance, plus that of Q1 in relation to that of R4. It is desired that this ratio be very close to (but in excess), of 2/1. The actual gain will be determined by the R3 resistance, plus that of Q1 in relation to that of R4. It is desired that this ratio be very close to (but in excess) of 2/1. It must be in excess to ensure starting, but the closer it is to 2/1, the less the channel resistance of Q1 need be varied. You may also note that Q1's nominal resistance of 100 ohms is a very small percentage of R3, so it provides only minimal correction. This ensures a low p-p voltage across Q1, a factor necessary for lowest distortion. The close tolerances specified for R3-R4 may be dispensed with if a 2 k or so rheostat is inserted in series with R4, and adjusted for positive startup with lowest distortion. Alternately, R3-R4 may be a 10k/22k pair, at the expense of higher distortion.

Local feedback around Q1, provided by R5-R6, lowers its contribution to distortion even further. Output distortion is considerably below a figure of 0.1 per cent due to these measures. At lower frequencies, integrator capacitor C3 should be increased in proportion, to maintain lowest distortion.

D.c. bias for Q1 is provided by from the integrator, A2. The high d.c. gain of this stage automatically compensates for unit-to-unit bias variations of Q1. The output is rectified by D2, and compared against the −15 V supply as a reference. R7 may be adjusted to scale the output, if desired.

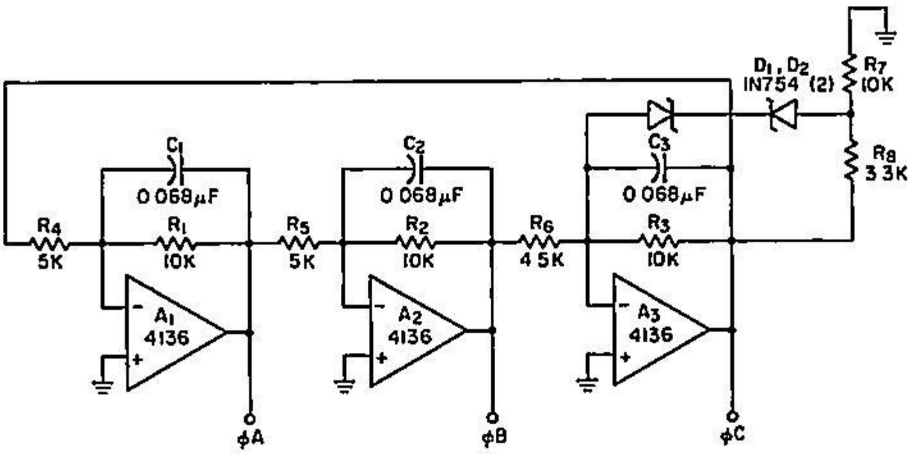
The op amp used is a new Harris unit, the 2655, a dual, 8 MHz bandwidth device with a 5V/µS slew rate. This is the best current choice in a single package dual. Lower performance alternates are the Raytheon 4558, and the standard 1458, a dual 741 type. All are pin-compatible.

Having discussed four different variations on Wien bridge oscillators and their ramifications, we've hardly begun to scratch the surface of Wien bridge variations. The Wien bridge is the most widely used and versatile type—a good combination of simplicity and performance. Other types, as we'll now see, sometimes sacrifice a feature to achieve another objective.

QUADRATURE OSCILLATOR (SINE/COSINE)

FIGURE 5 illustrates an oscillator featuring two outputs which differ in phase by 90 degrees. Thus, it is called a quadrature, or sine/cosine oscillator. The main reason for using this oscillator is the fixed phase difference; it is quite cumbersome to tune because of the three time constants involved. Because of these three time constants, it requires closer tolerances for best performance.

The circuit consists of a regenerative loop consisting of a conventional integrator A2, and a non-inverting double integrator, A1. The three time constants are R1-C1, R2-C2 and R3-C3. R1-C1 provide 45 degrees of phase shift, as do R2-C2 and A1. An additional 270 degrees of phase shift through A2 (and R3-C3) provide



DESIGN PROCESS:

1) SELECT R_1 (R_2 & R_3)

2) CALCULATE C_1 (C_2 & C_3)

$$C_1 = \frac{\sqrt{3}}{2\pi f_o R_1}$$

3) CALCULATE R_4 (R_5 & R_6)

$R_4 = \frac{R_1}{2}$, AND $R_5 = R_4$

THEN LET $R_6 < R_4$

$R_1 = R_2 = R_3 = R$

$C_1 = C_2 = C_3 = C$

$$f_o = \frac{\sqrt{3}}{2\pi RC}$$

Figure 6. Three-phase oscillator.

the 360 degrees (or in-phase) condition around the loop necessary to sustain oscillation.

As illustrated previously, a zener clamping network is used to stabilize the output level at A2. R5 and R6 adjust output, and the values shown yield ±10 V. Limiting such as this does introduce some distortion at the *cosine* output, but because of the further filtering at the *sine* output, distortion here is lowered. With close tolerance components, thd of considerably less than 1 per cent is possible.

In the example shown, which operates at 100 Hz, a 1458, as indicated, is adequate for good performance.

THREE-PHASE OSCILLATOR

As may be already obvious from above, multi-phase oscillators of virtually any arbitrary phase angle may be implemented, using op amps in phase shift stages with defined gain(s). The necessary condition for oscillation is net feedback in phase, and a gain of one or more at the frequency where the phase shift is zero. Exactly how you partition the phase shift(s) is really not limited to any great extent, at least not in theory.

An example is the three-phase oscillator showing FIGURE 6, which divides the total 360 degree phase shift requirement equally between three similar stages. In a sense, this one is reminiscent of the familiar phase shift oscillator, one main difference being that it delivers three buffered outputs in a wye configuration (balanced to ground).

This particular example splits the phase shift equally between stages A1, A2 and A3, or a phase shift per stage of −240 degrees. The total phase accumulation is then 720 degrees (or equivalent to an in-phase condition). Each stage is also designed for an input/output transfer gain of unity, making all three outputs equal in amplitude.

To ensure startup, the input resistor to one stage (A3) is lowered 10 per cent to give it initial gain > 1. Then, after oscillatory buildup, the zener network reduces gain and stabilizes the output at the desired level.

A big virtue of this type of oscillator is the large reduction in distortion due to filtering of two stages. For example, although distortion at the φC output is about 0.5 per cent due to limiting, this is reduced to well below 0.1 per cent at the φB output. This can be improved even further if desired by using an active AGC network in series with R6 for amplitude control (similar to FIGURE 4)

Frequency of operation is set by three r-c networks, R1-C1, R2-C2, and R3-C3. To retain the 120 degree phase difference, all time constants must be modified simultaneously when scaling, frequency wise. Hence this is not an easily tunable oscillator, unless a 3-gang capacitor is used (with good tracking). Resistors R4, R5, and R6 set the gain and should remain fixed. Stability and accuracy of components is even more important in this oscillator, since all those mentioned have a bearing on performance. Given proper ingredients, this oscillator is capable of precision performance with output thd of 0.01 per cent or better.

A quad device is an excellent choice for the op amp here, a 4136 as shown, or the Raytheon 4137, the Harris 4741, or the Exar 4212, all wideband quad units which will perform well at audio frequencies.

STATE-VARIABLE-FILTER OSCILLATORS

At this point, your appetite may be whetted for a more highly developed form of multi-phase oscillator which takes advantage of multiple stage filtering and high Q operation. The next two circuits discussed refer to just such an oscillator, in two different forms.

FIGURE 7 shows an oscillator circuit based on the state variable filter, an active filter configuration which is capable of extremely high Q with excellent stability. It also happens to be one which is easily tuned and programmed; therefore circuits of this type are readily adapted to automated control. In this circuit, the state variable filter itself consists of A1, A2, A3 and their associated elements. A4, Q1-Q2 and R8-R9 are added to provide a positive feedback path with amplitude stabilization.

This oscillator is different from the above previous types in that the zener amplitude control is *not* a soft limiter, it actually truncates the sine wave at A2's output, through the use of A4 and zener diodes Q1-Q2. The resulting *squared* waveform is well limited in amplitude, as applied to R7. A constant amplitude square wave fed into a bandpass filter will result in a very stable output sine wave amplitude. With sufficiently high Q in the filter, the square wave harmonics can be removed, with low resulting thd. This circuit is capable of thd well below 0.1 per cent, with short term amplitude stability of 0.05 per cent or less.

Of course, as with the previous circuits, performance actually realized will be dependent upon the quality of the components used. Tuning components are obviously

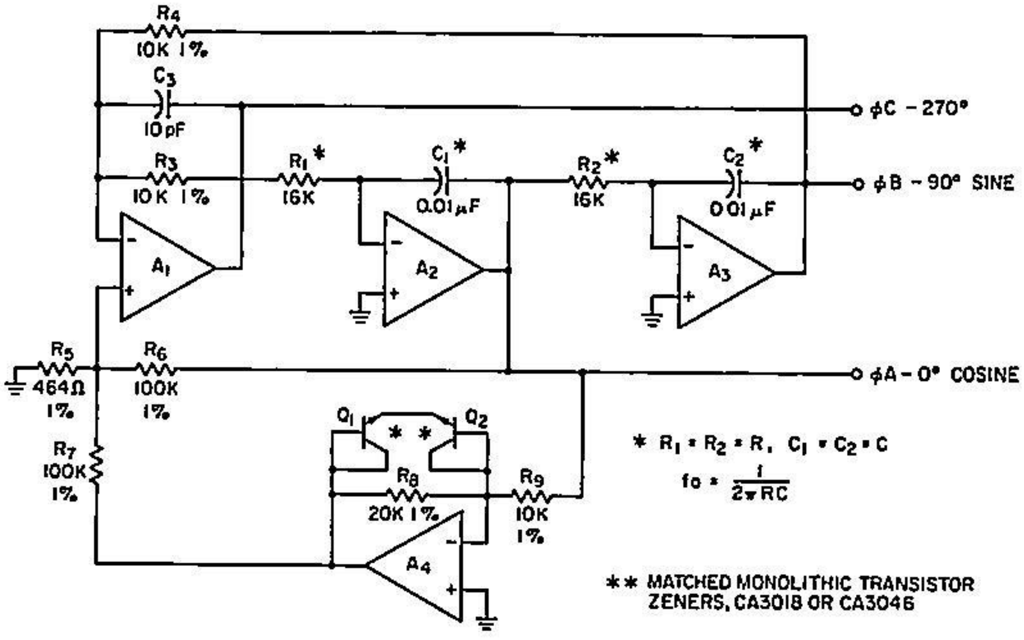


Figure 7. Zener-stabilized state-variable-filter oscillator.

important, namely R1-C1 and R2-C2. If the excellent amplitude stability mentioned is desired, the remaining resistors should be close tolerance, low t c units. The op amps used should be wide bandwidth for this kind of performance at frequencies above a few hundred hertz. Quad units should be a 4136 or one of the others mentioned, but even better performance can be realized with 318s or 301As operated feedforward

Three outputs are provided, phased as shown—two in quadrature with the complement of the *sine* output as a bonus. The *sine* output will be the lowest of the three in terms of distortion, for previously mentioned reasons. All are equal in amplitude.

Tuning, as in the Wien bridge oscillator, is accomplished by simultaneous (and tracked) variation. You can add an additional control as in FIGURE 8, namely R_A and R_B. Here this linearly varied dual pot reduces the per cent of signal applied to R1 and R2, thus changing the frequency downward as R_A (and R_B) are reduced. The shift can be calibrated linearly in terms of frequency if care is taken that R1 and R2 do not load the output of R_A-R_B excessively. C1-C2 are then assigned as decade range switches. The arrangement of R_A and R_B may well suggest an even further variation to many readers

FET STABILIZED STATE-VARIABLE-FILTER OSCILLATOR

As a final touch, FIGURE 9 illustrates an oscillator circuit which is capable of state-of-the-art performance in terms of distortion. It is similar to the device shown in FIGURE 7 in that it is based on the state variable filter, but has a lower distortion form of automatic gain control.

The oscillator circuit itself is quite similar to the one in FIGURE 7 except that a positive feedback path is added, via R5. The positive feedback is greater than the negative at switch on, which ensures startup. After oscillations start, automatic gain control voltage is developed to drive Q1 off and balance the loop at a stable low distortion operating point. When operating properly, thd at the ϕC output is on the order of 0.02 per cent, while the ϕ_A and ϕ_B outputs are even cleaner.

No selection of fets is necessary, due to the gain of A4, which automatically adjusts to the required bias. If desired, R7 can be trimmed to optimize distortion performance, but there is a tradeoff between lowest distortion and fastest settling

A 4136 op amp is indicated as an inexpensive single chip which will work as well as described above. Even

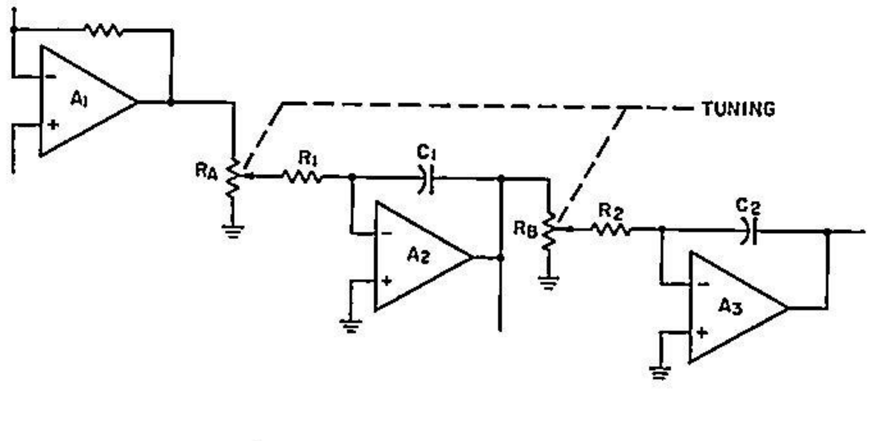


Figure 8. Tuning method for state-variable-filter.

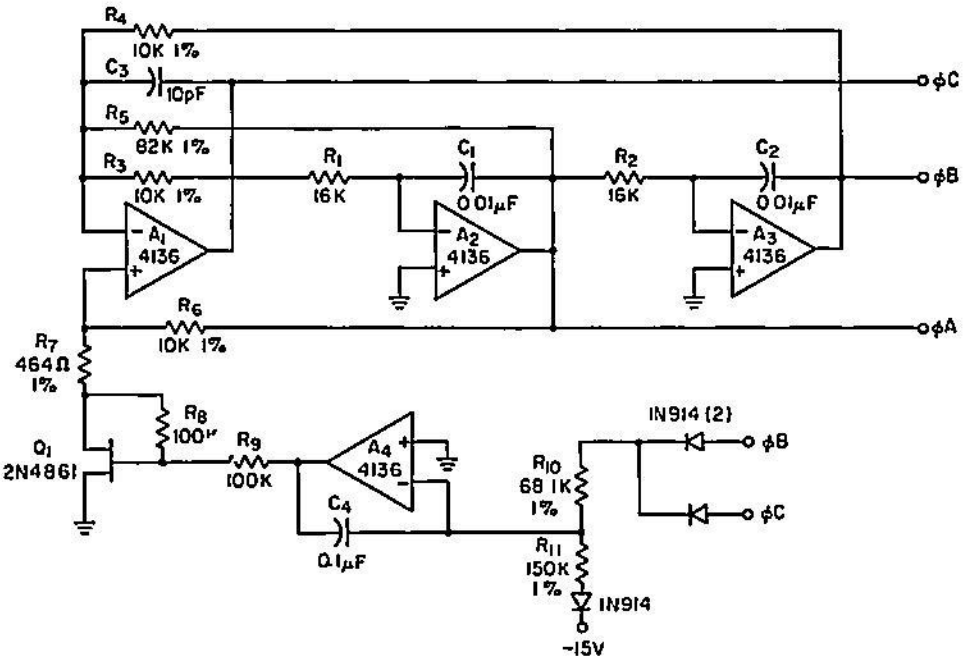


Figure 9. F.e.t. stabilized state-variable-filter oscillator.

better performance may be realized by using the wide bandwidth units mentioned for the FIGURE 7 circuit.

OUTPUT BUFFER STAGE

For the absolute highest performance from any of the oscillators described, particularly the state variable versions, a buffer stage is desirable. A suitable circuit is shown in FIGURE 10.

This circuit will drive a level of +26 dBm into 150 ohms with diminishing small distortion across the band, because of its wide bandwidth. This is due to the 301A in its feedforward mode, one which features a 30 MHz gain-bandwidth. Wideband buffer transistors are also used, and biasing to minimize parasitics. Bypass capacitors should be tantalum or other rf types. Short circuit protection is provided by the 27 ohm emitter resistors.

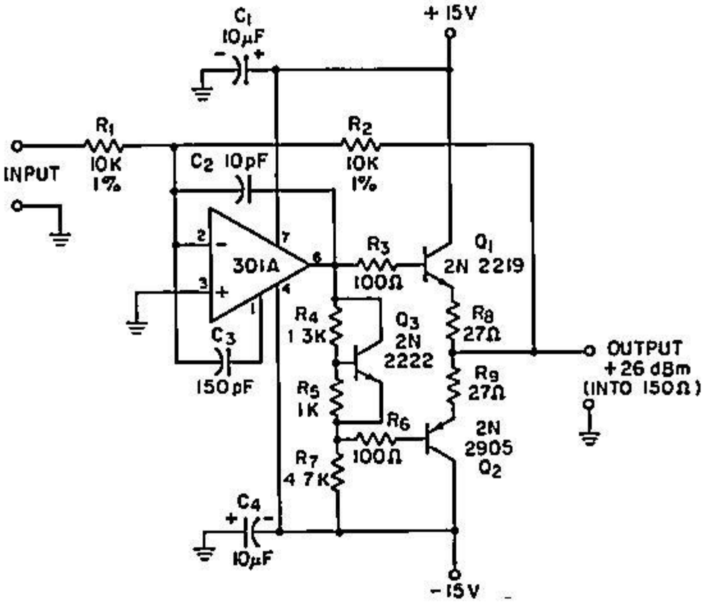


Figure 10. High performance buffer/line driver.

PRODUCT SOURCES

Resistors: Allen Bradley type CC metal film resistors (1%)
Allen Bradley
Milwaukee, Wisconsin 53204

Capacitors: KEMET F300 series film capacitors (to 0.5%)
Kemet-Union Carbide
P.O. Box 5928
Greenville, S.C. 29606

Op Amps.

Exar Integrated Systems 750 Palomar Avenue Sunnyvale, Ca. 94086	4212
Intersil 10900 N. Tantau Avenue Cupertino, Ca. 95014	8007
Harris Semiconductor P.O. Box 883 Melbourne, Fl 32901	4741 2655
National Semiconductor 2900 Semiconductor Drive Santa Clara, Ca 95051	318, 356, 301A
Raytheon Semiconductor 350 Ellis Street Santa Clara, Ca. 95051	4136, 4137, 4558
RCA Solid State Division Route 202 Somerville, N.J. 08876	3130

REFERENCES

1. Jung, Walter G. *Ic Op Amp Cookbook*, Howard W. Sams, 1974.
2. Ibid. ■