# New Varactor Bridge Op-Amps Models 302, 303—Cost $110 Each Feature 0.01 pA Current Noise and 0.05 pA/°C Current Drift

**If you measure picoamps, work with multi-megohm sources, handle transducer output swings from picoamps to milliamps without range switching, or need better integrator and differentiator accuracy or day-long time constants, Models 302 or 303 will probably solve your problem. These two varactor bridge units out perform electrometer tubes and FET's, and can upgrade circuit accuracy and sensitivity at reduced cost.**

THE VARACTOR BRIDGE technique* has been long neglected as a practical means for instrumenting analog circuits and in particular operational amplifiers. As compared to chopper stabilized and differential amplifiers, very little design or application information has appeared in technical publications on varactor bridge amplifiers. In addition the price of presently available units, including our own Model 301, is reasonably high. For these reasons, most engineers regard the varactor bridge amplifier as a scientific curiosity . . . good for someone else's application, but certainly not for his own.

Analog Devices has launched a campaign to establish varactor bridge operational amplifiers as practical, low cost building blocks for everyday circuit problems which involve high impedances, low input current or wide dynamic range requirements. Spearheading the campaign are two new varactor bridge units, Models 302/303, priced below $100 in moderate quantities and featuring 0.01pA noise and 0.05pA/°C drift at 25°C.

The varactor bridge amplifier goes a step beyond the performance of FET amplifiers and offers a solid state alternative to electrometer vacuum tubes. We shall discuss here the performance of Models 302 and 303 and how it compares in various applications to other amplifier types.

## BACKGROUND

Analog Devices introduced the Model 301 Varactor Bridge Operational Amplifier in June, 1966 and since that time we have gained a great deal of insight into the applications for this type of amplifier. This experience showed that the primary objection to the 301 was its high price and that a low cost varactor bridge amplifier was needed to serve as a routine problem solver in everyday circuits.

The problem we faced was reducing prices without sacrificing circuit performance. Guided by our application experience, we were able to trim certain less pivotal specs, such as bandwidth, DC voltage gain, output rating, voltage noise, and yet compromise circuit performance in only minor ways. More important, the new amplifier design actually has fourfold better bias current and drift performance than the original Model 301.

The first step in re-designing for reduced cost was to split the bulk of high impedance low level circuits between two different models, one (Model 302) optimized for inverting applications and the other (Model 303) designed specifically for non-inverting configurations. Thus, instead of building one expensive "universal" amplifier like the Model 301 which operates inverting, non-inverting or differential, we can now offer two specialized units that involve a simpler circuit and reduced testing during manufacture.

Bandwidth was the first specification for review. Our application experience showed that most Model 301 amplifiers were used strictly as DC amplifiers, perhaps because wide bandwidth picoamp sources are few and far between owing to the omnipresence of capacitance strays that slug output response.

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*See page 13 for operating principles.

Consequently, trimming bandwidth from 500kHz to 20kHz paves the way for a whole domino effect of all round amplifier economizing.

The next parameter for consideration was output rating. It turns out that varactor bridge amplifiers are rarely used to "activate things" directly. As a rule, the amplifier's output signal feeds an instrument preamplifier or other cascaded circuitry that draws only microamp signals. Accordingly, the output rating of ±10V, 20mA for the Model 301 was reduced to ±10V, 2mA for the Models 302/303.

A further logical specification for cost trimming is open-loop DC voltage gain. Most voltage amplifier circuits based on Model 301 were used for impedance transformation, and operated with closed loop gain at or near unity. Therefore, a 10,000 DC gain provides abundant loop gain in most voltage amplifier circuits. In any event, a booster amplifier capable of raising total gain to 10 million or so can be added for about $10 extra.

None of the foregoing performance changes would have been significant by themselves. But taken altogether, along with the separation of applications between inverting and non-inverting models, the cumulative cost savings have reduced price below $100 in OEM quantities.

Since key specifications are simultaneously improved (bias current and drift specs raised fourfold, Model 303's $Z_{cm}$ raised from $10^{12}$ to $10^{13}$), many present users will be able to upgrade equipment performance while reducing cost. Also, many newcomers will now find it economical to use Model 302 or 303 to overcome the inherent limitations of FET or electrometer tubes amplifiers. The table below compares specifications for Models 301, 302 and 303.

| SPECIFICATIONS | | MODELS* | |
|---|---|---|---|
| | 301 | 302 | 303 |
| Bias Current, 25°C, max. | 2pA | .5pA | .5pA |
| Bias Current Drift 25°C, max. | .2pA/°C | .05pA/°C | .05pA/°C |
| Current Noise DC to 1Hz, p-p | .01pA | .01pA | .01pA |
| Voltage Noise DC to 1Hz, p-p | 1uV | 2uV | 2uV |
| Offset Voltage Drift, max. | 50uV/°C | 60uV/°C | 60uV/°C |
| Input Impedance | | | |
| Between Inputs | $10^{10}$ | $10^{9}$ | $10^{9}$ |
| Common Mode | $10^{12}$ | — | $10^{13}$ |
| Open Loop Gain, DC, min. | 500,000 | 10,000 | 10,000 |
| Rated Output, min. | ±10V<br>20mA | ±10V<br>2mA | ±10V<br>2mA |
| Unity Gain Bandwidth | 500kHz | 20kHz | 15kHz |
| Full Power Response, min. | 5kHz | 80Hz | 60Hz |
| CMRR | $10^{8}$ | — | $10^{6}$ |
| Price (1-9) | $198 | $110 | $110 |

*Model 301 — Differential, Inverting and Noninverting
Model 302 — Inverting Model 303 — Noninverting

## AMPLIFIER TYPES COMPARED

The varactor bridge amplifier, in common with all amplifiers based on parametric techniques (see "Operating Principles" and Analog Dialogue #2) is noteworthy for its very low noise levels. Particularly for 1/f noise, which plagues all DC amplifiers, the varactor bridge type has no equal among solid state devices.

The combination of low current noise (0.01pA), and low current drift (0.05pA/°C at 25°C), are the pivotal characteristics that place the varactor bridge amplifier beyond all other solid state types for circuit impedance exceeding roughly 10 megohms and for signal currents below 100pA. Electrometer tubes do offer higher input impedance and lower current drift and noise than varactor amplifiers. However, their low frequency voltage noise is about 100 times greater than the 302 and 303 and electrometer tubes are notorious for voltage offset aging — as much as 2mV/hour. In addition electrometer tubes are subject to microphonic noise and they suffer recovery times of hours or days following an input overdrive. Electrometer tubes are not as reliable as a solid state varactor bridge and replacing them usually involves some tricky adjustments in matched input pairs.

Since noise and drift determine final measuring accuracy, we've compared the noise and drift performance for Model 302 varactor bridge amplifier against three other types, and plotted the results for a current to voltage amplifier against increasing circuit sensitivity ($R_F$). The graphs, Figure 1, are drawn for varactor bridge, chopper stabilized, FET input, and transistor differential amplifiers, and show the errors due to noise and drift as functions of the current-to-voltage converter's feedback resistance $R_F$.

The total output noise error voltage consists of a current and voltage noise component, where the voltage error due to current noise is dependent upon the value of the feedback resistor, $R_F$, while the voltage component is constant. Likewise the voltage error due to drift is composed of a variable and constant component and the total voltage error due to drift is plotted for various values of feedback resistance. The effect of the feedback resistance and the constant and variable components is clearly seen in the graph. Where the curves are constant, (lower values of $R_F$) the current drift and current noise add negligible error, but at higher resistance values they take on major proportions as seen by the slope of the curves. Remember that the graph relating total voltage drift for the F.E.T. and Varactor Bridge applies to the temperature range from 25 to 35°C; the effect of current drift at higher temperature increases doubling each 10°C.

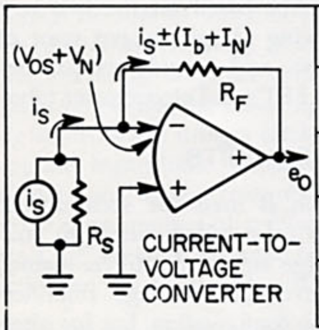
## ACCURACY

Circuit accuracy for a given sensitivity is determined by summing the output noise and drift errors, then calculating an imaginary input current that would produce these errors if applied to the amplifier's input terminal. Accuracy then becomes the ratio between the equivalent error current input and the true current signal applied to the input terminal.

# COMPARING VARACTOR BRIDGE AMPLIFIER WITH CHOPPER-STABILIZED, FET, AND TRANSISTOR DIFFERENTIAL TYPES

Curves demonstrate relative importance of drift and noise for current-to-voltage converter as function of feedback resistance, hence sensitivity. Left hand graph displays current and voltage noise referred to output in microvolts. Right hand graph plots output current and voltage drift error in microvolts/°C. Total drift error for 25°C-35°C interval is product of working temperature range and drift rate.

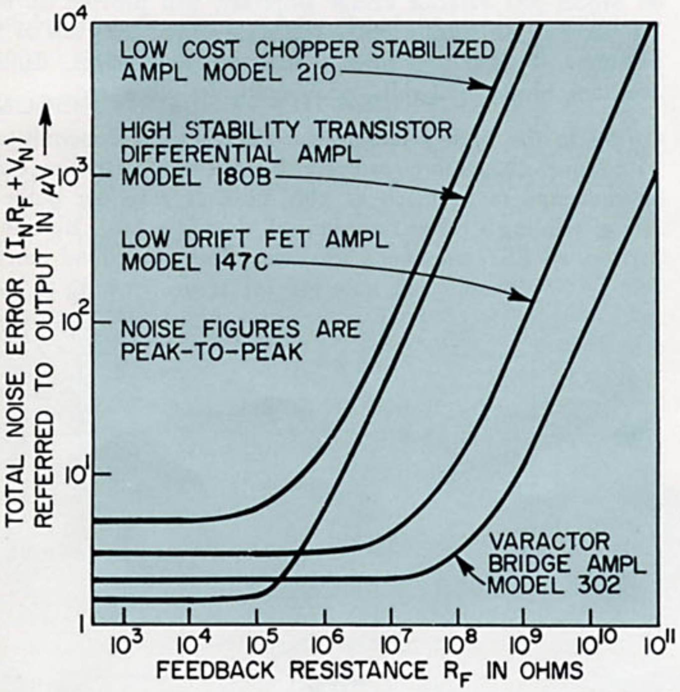
Noise and drift add to give total output error for selected amplifier. Dividing this error by the feedback resistance yields equivalent error current input. Circuit accuracy depends upon ratio between error current input and signal being measured.



| ERROR SOURCE | OUTPUT ERROR |
|---|---|
| Current Noise $I_N$ | $R_F \times I_N$ |
| Voltage Noise $V_N$ | $V_N$ |
| Current Drift $dI_b/dT$ | $R_F \times dI_b/dT$ |
| Voltage Drift $dV_{OS}/dT$ | $dV_{OS}/dT$ |

$$e_O = -R_F\left[\underbrace{i_S}_{\text{SIGNAL}} \pm \underbrace{\left(\frac{V_N}{R_F}+I_N\right)}_{\text{NOISE}} \pm \underbrace{\left(\frac{V_{OS}}{R_F}+I_b\right)}_{\text{DRIFT}}\right]$$

| PARAMETER | VARACTOR BRIDGE | CHOPPER STABILIZED | FET INPUT | TRANSISTOR DIFFERENTIAL |
|---|---|---|---|---|
| Current Drift 25°C-35°C | 0.05 pA/°C (AVG.) | 1 pA/°C (MAX. AVG.) | 1.5 pA/°C (AVG.) | 100 pA/°C (MAX. AVG.) |
| Current Noise DC-1 Hz | 0.01 pA | 10 pA | 0.1 pA | 5 pA |
| Voltage Drift | 60 μV/°C | 0.5 μV/°C | 2 μV/°C | 0.75 μV/°C |
| Voltage Noise DC-1 Hz | 2 μV | 5 μV | 3 μV | 1 μV |
| PRICE | $110 | $157 | $135 | $110 |



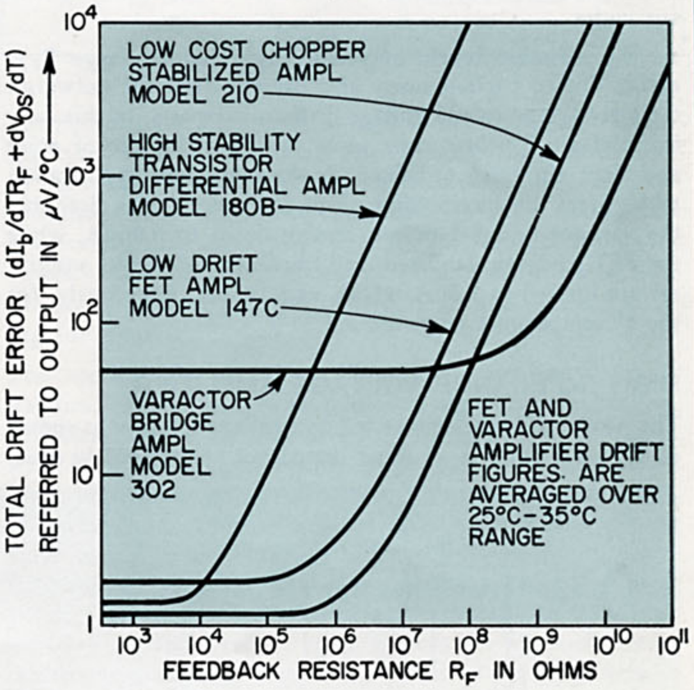


FIGURE 1. AMPLIFIER TYPES COMPARED

The equivalent input error signal is calculated by dividing the sum of the equivalent noise and drift components of output error by the feedback resistance value at the selected sensitivity. The Model 302, for example, develops 1000$\mu$V noise and 5000$\mu$V/°C drift error for a $10^{11}$ ohm feedback resistance. If the working temperature is a 10°C range from 25°C to 35°C, the total output drift error is 10 x 5000$\mu$V/°C, or 50,000$\mu$V. Thus the noise-plus-drift total is 51,000$\mu$V and the equivalent current error is 0.51 pA. The current error is found by dividing the total noise-plus-drift voltage error of 51,000$\mu$V by the $10^{11}$ ohm feedback resistor. Such a circuit, working over the specified 10°C temperature range, would then develop 10% error when handling signals of 5.1 picoamps. Likewise, a 1% error is developed for a signal current of 51 picoamps and 0.1% for 510 picoamps.

If, instead of the 10°C range, the amplifier works over a 1°C temperature interval, the drift curves give *total* offsets, rather than drift rate in $\mu$V/°C. For example, the drift error for the FET amplifier with a $10^8$ ohm feedback resistor and 1°C range is 150$\mu$V, while its output noise error is 13$\mu$V. The sum of the output errors is 163$\mu$V, leading to an equivalent error current input of $163 \times 10^{-6} \times 10^{-8} = 1.63$pA. The error current input for the varactor bridge amplifier with $10^8$ ohms feedback is $58 \times 10^{-6} \times 10^{-8} = 0.58$ picoamps. Thus, for circuit resistance values of $10^8$ ohms and above, the varactor bridge amplifier is definitely superior to the FET type. Even for lower resistance values, but for higher ambient temperatures, the varactor bridge unit still comes out ahead.

For a temperature controlled environment or for short term minute-by-minute data where slow varying temperature drifts are not important, then noise alone determines the ultimate resolution capabilities of the amplifiers. Here the 302 excels above impedance of 100Kohms in a limited bandwidth up to a few cycles.

At the ultimate levels of sensitivity (that is, large $R_F$), errors due to current noise and current drift far outweigh their voltage noise and voltage drift counterparts. In this case, the equivalent error current input is simply the sum of noise and drift currents as defined in the amplifier's specification table. From the specifications given in Figure 1 it is clear that the varactor bridge unit can resolve down to 0.06pA, while the FET, chopper stabilized, and transistor differential amplifiers are limited to 1.6pA, 11pA, and 105pA, respectively, for the 1° temperature range around 25°C.

## HIGH IMPEDANCE VOLTAGE AMPLIFIER

The Model 303 when connected as a voltage follower as shown in Figure 2 achieves an input impedance approximately equal to the common mode impedance ($10^{13}$ ohms). The Model 303 is therefore intended to amplify voltage signals from very large source impedances ($R_s$).

The comparative data presented in the graphs of Figure 1 can also be used to predict the performance of the voltage follower circuit above. In this case, you must replace $R_f$ in the graphs by $R_s$, the source impedance in Figure 2. To compute the accuracy, you combine the total noise and total drift over the temperature range of interest at a given source impedance and then compare the combined error to the signal voltage, $e_s$. As in the case of the Model 302 current to voltage amplifier, the Model 303 voltage follower offers better accuracy than the other amplifier types for source impedance above about 10 megohms.

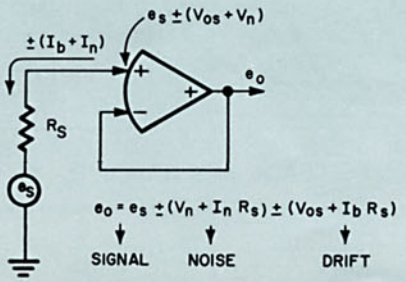


FIGURE 2. VOLTAGE FOLLOWER

## APPLICATIONS

Many different circuits not explicitly recognized as inverting and non-inverting amplifiers can be based on the two new varactor bridge units. The following paragraphs put some of these applications into perspective, and provide comparisons between alternative circuits using FET's and electrometer tubes.

## MODEL 302's INVERTING CIRCUITS

The basic inverting configuration is used for such diverse applications as current amplifiers (also called current to voltage converters), integrators, charge amplifiers, differentiators, and logarithmic amplifiers. Conventional voltage amplifiers may also be based on the inverting configuration, but for ultra-high impedance signal sources the non-inverting circuit based on Model 303 is actually superior to an inverting amplifier designed around Model 302.

As previously discussed, a current amplifier, Figure 3A, based on Model 302 varactor bridge amplifier, will provide up to 1% accuracy for signals whose full scale output is as low as 5 picoamps. Typical low level sources are ion gauges, flame detectors, biochemical cells, photomultiplier tubes, etc.

Owing to the high values of feedback resistance permitted with Model 302, each picoampere of input signal variation can be converted to as much as 100 millivolt amplifier output swing, yielding a conversion ratio of $V_o = I_{in} \times 10^{11}$. By comparison, an FET amplifier's sensitivity does not extend much below 100 picoamps full scale for 1% accuracy owing to the

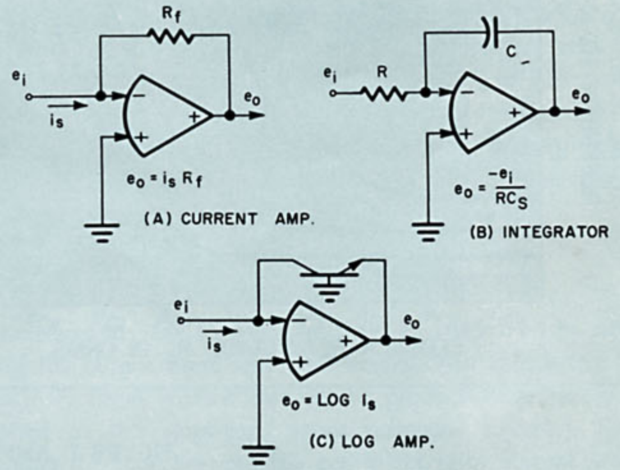


FIGURE 3. INVERTING CIRCUITS

substantially larger initial bias currents and the correspondingly high drift levels.

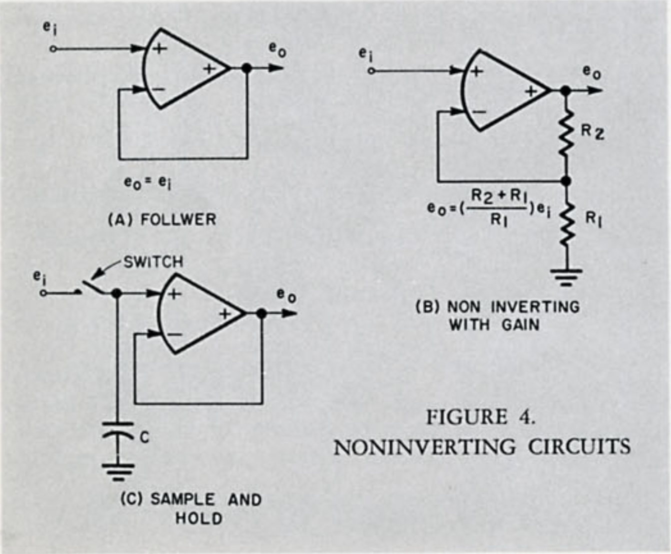
The advantages of Model 302 for integrator, charge amplifier and other capacitor charging circuits, Figure 3B, lies in the very long time constants that can be achieved . . . not untypically a day or more. A related advantage of Model 302 is the higher accuracy that can be achieved for shorter time constants owing to the amplifier's reduced bias current, which normally acts as a leakage current in capacitor charging applications. An even more subtle feature of the varactor bridge amplifier is the freedom it gives the circuit designer in selecting smaller capacitance values and larger resistance values for a given time constant ($T=RC$).

Such signal sources as photocells, flame detectors, photomultiplier tubes, sound transducers, electrochemical cells, among many others, develop an output signal that may span as many as nine decades of amplitude swing. A $10^9$:1 dynamic range would ordinarily require 18 switched steps on a VTVM, yet a varactor bridge amplifier using a nonlinear feedback element can accommodate the whole signal swing with no range switching at all. When using a semiconductor feedback element with accurate logarithmic response, Figure 3C, Model 302 can handle signal swings from about 2 picoamps ($2 \times 10^{-12}$ amps) to the same number of milliamps ($2 \times 10^{-3}$ amps), representing a $10^9 = 180$dB dynamic range. No solid state amplifier yet developed can equal such performance.

Differentiator circuits based on Model 302 have the basic attributes of the integrator and charge amplifier circuits, namely, very long time constants plus the ability to achieve proportionately higher accuracy with smaller capacitance and large resistance. Once more, bias current and drift are critical parameters. The varactor bridge amplifier's low noise is also important for differentiator circuits, as it is for any of the low level configurations discussed.

## MODEL 303 NON-INVERTING CIRCUITS

Two well known inverting configurations are the unity gain "voltage follower" circuit, which uses 100% feedback to achieve utmost input impedance; and its gain-producing counterpart, the non-inverting voltage amplifier.



(A) FOLLWER

(B) NON INVERTING WITH GAIN

(C) SAMPLE AND HOLD

FIGURE 4.
NONINVERTING CIRCUITS

The first of these, Figure 4A, is used as an "unloading" amplifier to reduce errors that occur when a measuring device draws its input signal from a high impedance source. The high common mode input impedance of Model 303 ($10^{13}$ ohms) and low current drift (0.05pA/°C at 25°C), ensures maximum accuracy for sources of 10 megohms and higher, where an FET amplifier's relatively large bias current and current drift degrade accuracy.

The non-inverting amplifier, Figure 4B, combines feedback stabilized voltage gain with minimum signal source loading. An advantage of the non-inverting configuration, compared with its inverting counterpart, is the ease with which high input impedance may be obtained. The inverting amplifier's closed loop input impedance is determined almost solely by the value used for the summing resistor. By contrast, the non-inverting amplifier's closed loop input impedance is independent of the feedback values, and is set by the amplifier's inherent common mode input impedance. This difference enables accurate high impedance non-inverting amplifiers to be designed around feedback resistors selected for best stability, whereas the high value resistors needed for high impedance inverting circuits tend to be relatively drift prone. In short, inverting circuits don't make good high impedance amplifiers: non-inverting circuits are inherently superior.

### OPERATING PRINCIPLES

The circuit of the new low cost varactor bridge amplifiers, Model 302/3, is shown in Fig. 5. The amplifier's input, $e_{in}$ alters the reactance of the voltage variable capacitors (varactor diodes), unbalances the bridge circuit, and feeds out a fraction of the excitation voltage in proportion to bridge unbalance. The bridge's 1 MHz excitation or carrier output voltage is amplified, demodulated, then fed to the final DC amplifier to raise the output level to a maximum of 10 volts. Overall voltage gain is 10,000.

Only one input terminal carries the full specification for lowest bias current and drift. This is because, for the inverting amplifier, Model 302, the positive input terminal is grounded, while for the non-inverting amplifier, the bias current is easily supplied by the output circuit. In Model 301, by contrast, both input terminals are isolated from ground for differential applications, and the unit carries a 300 volt common mode rating. However, the careful insulation of Model 303's single input terminal raises common mode input impedance to $10^{13}$ ohms, compared with Model 301's $10^{12}$ ohms.

The primary circuit difference between Models 302 and 303 is a reversal of varactor diode connections to provide either inverting or non-inverting operation from the insulated input terminal

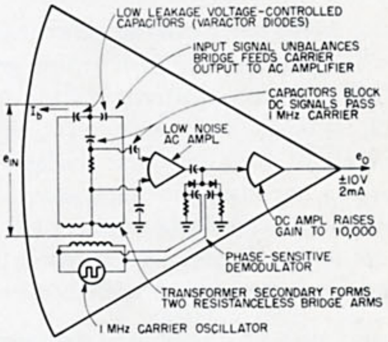


FIGURE 5.

A further important circuit based on the non-inverting configuration is the sample/hold amplifier, Figure 4C. Input signals are connected to this amplifier's input terminal during a "sample" interval so as to charge the storage capacitor C to the input signal level. Next, the input signal is disconnected (by a solid state or other switch), and the amplifier reverts to its "hold" operating mode. Output is then proportional to the stored voltage, enabling subsequent circuits to process the signal more or less at leisure.

A particular merit of varactor bridge amplifiers in sample/hold applications is that their low leakage current (i.e., bias current) enables *small* storage capacitors to be used without loss of accuracy. The smaller capacitors permit a shorter sampling interval, or alternatively, draw a smaller current from the source while acquiring the charge. An FET sample/hold amplifier would require a 100-fold larger capacitor for comparable accuracy.

## CONCLUSION

Varactor bridge operational amplifiers offer distinct advantages over FET types in four basic circuit groups: for measuring low level currents; measuring voltage from high impedance sources; accommodating wide input signal variations using logarithmic or other nonlinear feedback; and for charging/discharging capacitors in integrator, differentiator, charge amplifier and sample/hold amplifier circuits. All of these circuits are based on either the inverting or the non-inverting configurations for which Models 302 and 303 are designed.

Compared with FET amplifiers, the varactor bridge units feature an order of magnitude better bias current and current stability performance, yield comparable input impedance values, provide distinctly better noise performance in the DC to 1Hz range, but have inferior voltage drift characteristics. The rather large voltage drift ( 60uV/°C ) of varactor bridge types means that circuits based on these amplifiers do not outperform FET amplifier circuits until associated source impedances exceed roughly 10 megohm.

Additionally, of course, the varactor bridge amplifier is outstandingly superior to FET amplifiers for measuring currents down in the picoampere level. Even for currents in the nanoampere range the varactor bridge unit affords orders of magnitude better overall accuracy. Its superior bias current and current drift characteristics also enable the varactor bridge amplifier to outperform FET amplifiers in the logarithmic and capacitor charging groups of circuits.

Electrometer tubes outperform the varactor bridge amplifier in having higher input impedance and lower current noise and drift. However, electrometer tubes have excessive voltage noise and short term drift and also suffer the usual limitations of vacuum tube devices which includes microphonic noise, aging problems, questionable reliability and inconvenient power supply requirements. ▶

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# FET stabilizes amplitude of Wien bridge oscillator

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**When the drain-source voltage,** $V_{DS}$, of a field effect transistor approaches zero, the FET behaves very much like a linear variable resistance, and remains nearly linear at higher voltages below pinch-off. This characteristic makes FET's useful as a stabilizing element in oscillator circuits like the Wien bridge oscillator below.

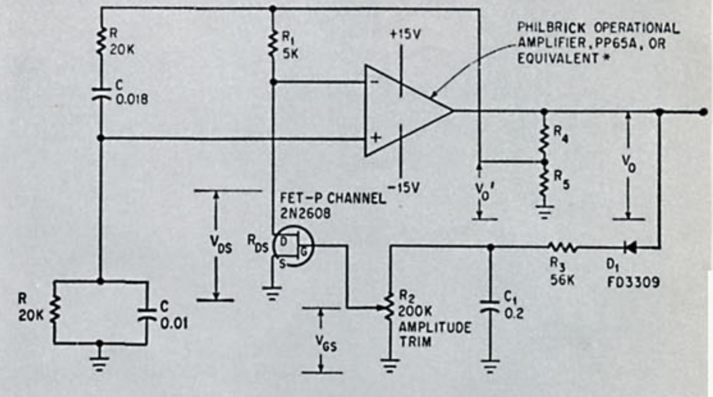
In the circuit, output voltage $V_o$ is rectified by $D_1$ and filtered by $R_3C_1$. Potentiometer $R_2$ sets the gate-source voltage, $V_{GS}$, which in turn established the output amplitude.

Oscillations occur when

$$V_{DS} = \frac{V_o'}{3}, \quad \text{where } V_o' = \frac{R_5}{R_4 + R_5}(V_o).$$

the frequency of oscillation $\omega = 1/RC$.

The circuit provides distortionless output over a frequency range of d-c to 100 kilohertz if the transistor's $V_{DS}$ does not exceed several hundred millivolts. The drain-source resistance, $R_{DS}$, becomes nonlinear at greater voltages than this. However, by adding a resistor in series with the FET drain, larger amplitudes can be obtained, with low distortion and very little sacrifice in control. ▶



Oscillator output $V_o$, will be distortionless if it exceeds 10 volts, provided $V_o/V_o'$ is greater than 10 to 1.

*Analog Devices' Model 105

Reprinted from Electronics (Oct. 3, 1966);