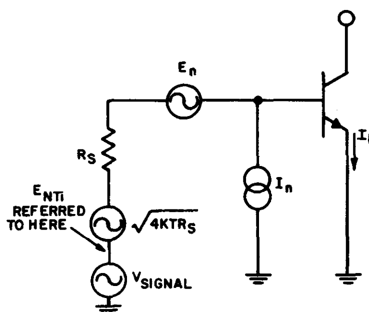
Measurement of Burst ("Popcorn") Noise in Linear Integrated Circuits

by T. J. Robe

The advent in recent years of very high-gain operational amplifiers operating in the 1/f noise-frequency spectrum has placed emphasis on the need for very low-noise devices. This need is particularly true for operational amplifiers which have either low-offset characteristics and/or offset-null capability.

Considerations in Low-Noise Performance

Fig. 1 shows the schematic diagram of a noise model useful in a review of the considerations pertinent to optimizing low-noise performance in amplifier operation.



TOTAL INPUT-REFERRED NOISE VOLTAGE $/\sqrt{Hz} = E_{NTi}$ FOR AMPLIFIER DRIVEN FROM SIGNAL-SOURCE HAVING SOURCE RESISTANCE R_S, E_{nti} (in $V/\sqrt{Hz}$) $= \sqrt{4KTR_s + (\overline{I_n R_s})^2 + (E_n)^2}$

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Fig. 1 - Sources of noise in the transistor-amplifier stage.

This model illustrates that consideration must be given to three major sources of noise:

1. Noise contributed by the "thermal-noise" voltage developed across the signal-source resistance, R_S. The magnitude of this voltage in $V/\sqrt{Hz}$ is approximately equal to $\sqrt{4KTR_S}$ for a 1-cycle bandwidth, where k is Boltzmann's constant (1.38×10^{-23} joule/°K), T is the temperature in degrees Kelvin, and R_S is the source resistance in ohms.
2. The noise voltage, E_n, resulting from the combined effects of shot noise due to emitter current flow and thermal noise due to transistor base resistance. These effects add in rms fashion to give a total E_n equal to $(E_{shot}^2 + 4KTr_{b'b})^{1/2}$. The shot-noise component, E_{shot}, is inversely proportional to the square root of I_{EQ}, and has a value
$$E_{shot} = \frac{14.2 \times 10^{-12}}{\sqrt{I_{EQ}}} \quad (V/Hz.)$$
3. The noise current, I_n, resulting from the combined "shot noise" generated by the flow of base current and the 1/f noise generated in the transistor. The magnitude of I_n is approximately proportional to $\sqrt{I_{IB}}$, where I_{IB} is the base current.

When each input terminal in a differential amplifier is driven from a source resistance (R_S), the total noise voltage (referred to the input, see Fig. 1) per unit bandwidth is given by:

$$E_{nti} \text{ (in } V/\sqrt{Hz}) = \sqrt{2KTR_S + 2(\overline{I_n R_S})^2 + (E_n)^2}$$

When amplifiers are driven from low source impedances, E_n is the predominant factor in noise contributions, whereas the effect of I_n predominates when input signals are supplied from high source impedances.

The traditional methods used to select very-low-noise devices for operational amplifiers involve the measurement of either spot or wideband (≈ 10 kHz) noise figures in the 1/f frequency range (10 Hz to 10 kHz) at various source resistances. This type of measurement, however, only provides an indication of the average noise power at the measurement frequency and does not reveal the burst ("popcorn") noise characteristics of the Device Under Test (DUT). The metering circuits cannot respond fast enough to measure the effects of burst-noise. Fig. 2a shows a photograph of typical burst-noise as a function of time for an operational amplifier having poor burst-noise characteristics. This photo illustrates burst noise which is characterized by random abrupt output voltage-level changes that persist for periods from approximately 1/2 millisecond to several seconds. Additionally, the random rate at which the bursts occur ranges from approximately several hundred per second to less than one per minute. Furthermore, these rates are not necessarily repetitive and predictable. Consequently, the nature of burst-noise prevents its measurement by means of the standard averaging techniques. Instead, a technique to detect individual bursts must be used and a DUT must be under observation for a period in the order of 10 seconds to one minute. Fig. 2b shows a photo of the output of a virtually burst-noise-free operational amplifier, the RCA CA6741T.

Test Configuration

Some of the major questions relevant to the type of test required are:

1. What characteristics of the burst-noise should be detected?
2. What test-circuit configuration is most suitable to detect these characteristics?

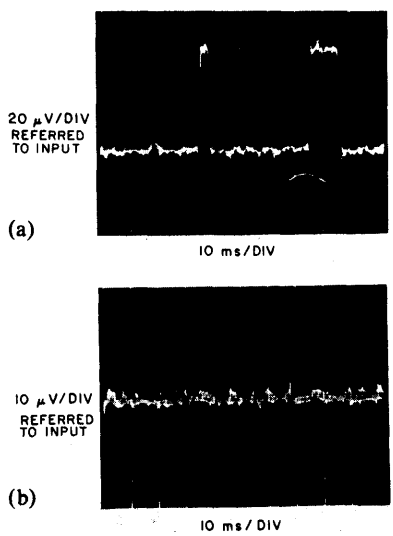

Fig. 2 - (a) Photo of output waveforms for amplifier with poor burst-noise characteristics; (b) photo of output waveform for the RCA-CA6741T.

3. What are the "Pass-Fail" criteria?

There are three major characteristics of the noise burst which have an impact on the suitability of a device from the standpoint of applications: burst amplitude, duration, and rate of occurrence. Of these, burst-amplitude and rate of occurrence are of primary interest to potential users of a particular device. Long duration bursts (of sufficient amplitude) seriously degrade the performance of dc amplifiers; however, suitable devices could be selected by the rejection of any unit which produced even one burst during some prescribed test period. Therefore, an absolute measurement of burst duration is not a prime necessity.

The rate of occurrence, on the other hand, as measured by the burst-count in a given test period could conceivably be considered as a variable of prime importance in the selection process. For instance, a burst-rate of 100 per second is clearly objectionable in almost any low-level low-frequency application, whereas the occurrence of only one low-amplitude burst in a one-minute period might be quite acceptable. Consequently, it is desirable to include flexibility in the testing system so that "Pass-Fail" criteria can be established on the basis of burst-noise count in some prescribed period of time. The test equipment described herein detects total noise (l/f noise plus burst noise) bursts with amplitudes above a preset threshold level during a given test period and allows acceptance or rejection on the basis of the number of noise voltage excursions beyond the threshold level, in the selected test period.

Another factor to be considered is the bandwidth of the test system. Excessive bandwidth allows the normal "white" noise of the terminating resistors and the DUT to obscure burst-noise occurrences and does not realistically simulate the low-frequency applications in which burst-noise is particularly objectionable. On the other hand, a test circuit having excessively narrow bandwidth prevents detection of the shorter-duration bursts (≈ 1/2 ms) even if their amplitude is relatively high. A suitable compromise is chosen in which the system rise time permits a burst of "minimum" duration to reach essentially its full amplitude. Because the rise time and bandwidth of an amplifier are related by the equation:

$$BW \approx \frac{0.4}{t_r}$$

the minimum bandwidth to detect a 0.5 ms burst is approximately:

$$BW_{min} = \frac{0.4}{(0.5)(10^{-3})} = 0.8 \text{ kHz.}$$

Consequently, a 1 kHz bandwidth has been selected as a reasonable one for a burst-noise test system and, therefore, prescribes the need for a low-pass filter in the system.

The test requirements outlined above can be implemented with the following circuit elements shown in the block diagram of Fig. 3a. Fig. 3b shows the complete system schematic:

1. A fixed high-gain amplifier incorporating the DUT as the first stage to amplify the microvolt-level burst to an easily detectable level (this should be a burst noise-free unit);
2. A low-pass filter to limit the test bandwidth to approximately 1 kHz,
3. A comparator to produce a fast-rise high-level single-polarity output pulse whenever an input burst-noise pulse (of either polarity) exceeds a preset (but adjustable) threshold level;
4. A counter to tally the number of pulses emanating from the comparator during the test period: a single decade counter is adequate.

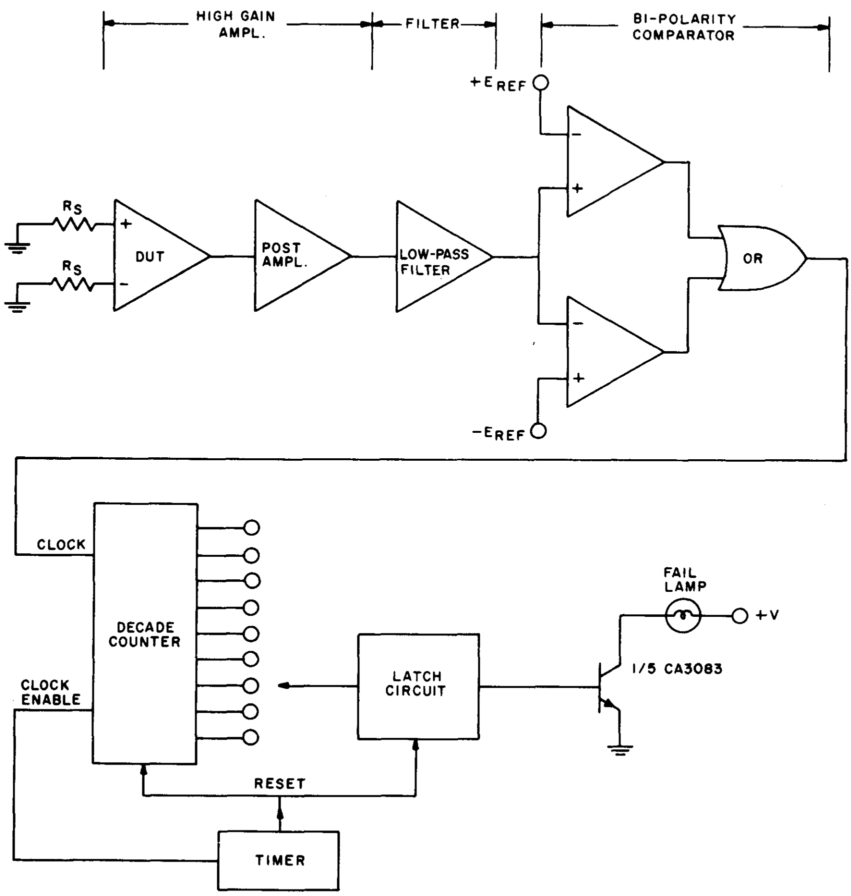

Fig. 3a - Block diagram of burst-noise test set-up.

5. A latch circuit which trips to the "latched" state when the count exceeds a preselected number (e.g. 1 to n). The latch circuit, if tripped, energizes an indicator lamp.
6. A timer to control the period over which the counter is enabled. It should incorporate the capability to reset both the counter and the latch circuit at the beginning of each test period.
7. Power supplies for the DUT and other auxiliary circuits.

Test Conditions

Some of the conditions which affect the burst-noise performance of the DUT include bias-level, source resistance (Rs), and ambient temperature (T_A).

The quiescent operating conditions in operational amplifiers are normally set by the magnitude of the positive and negative supplies. Many of the newer Op-Amp types, however, have bias-terminals into which fixed currents can be injected to set their performance characteristics. The RCA-CA3060, CA3080, and CA3080A Operational Transconductance Amplifiers (OTA's) and; the RCA-CA3078 and CA3078A Micropower Op-Amps are examples of such devices. For best low-frequency and burst-noise performance, these amplifiers should be operated at the lowest bias currents consistent with the gain-bandwidth requirements of the particular application.

In the test for burst noise, the source resistance (Rs) seen by the input terminals of the DUT, is a key test parameter. Burst noise causes effects which are equivalent to a spurious current-source at the device input and, therefore, burst-noise current generates an equivalent input noise-voltage in proportion to the magnitude of the source resistance through which it flows. Accordingly, to increase the sensitivity of the test system, it is desirable to use the highest source resistance consistent with the input offset-current of the DUT. For example, an Op-Amp which has 0.1 μA input offset current could realistically be tested with source-resistance in the order of 100KΩ (10 mV input offset), whereas a 1 MΩ source-resistance (100 mV input offset) could cause excessive offset in the output. For 741 type Op-Amps a 100kΩ resistance is recommended.

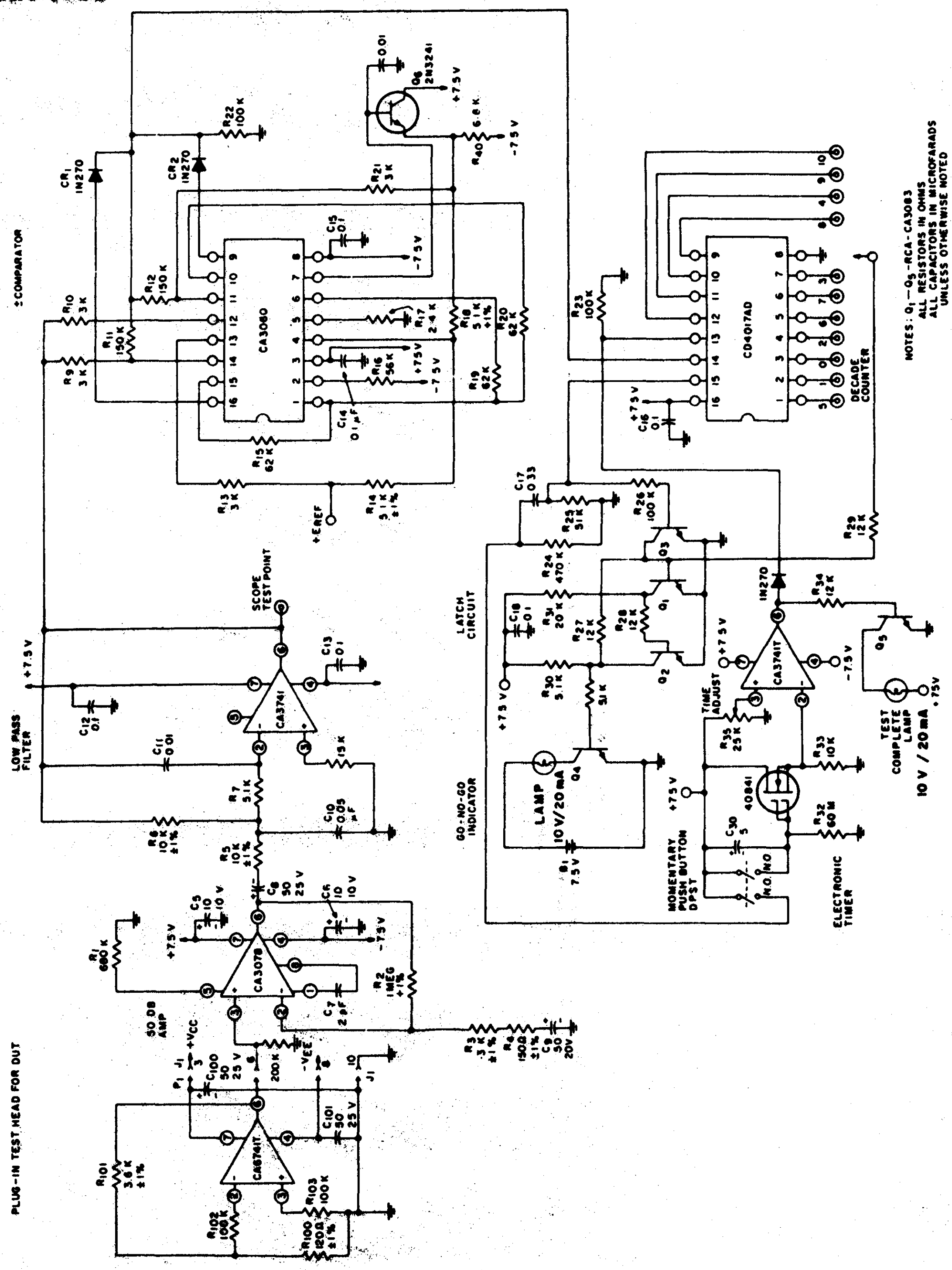

Fig. 3b - Complete schematic diagram for burst noise test-set.

Burst-noise generation in amplifiers is usually more pronounced at lower temperatures (particularly below $0^{o}C$). Consequently, consideration must be given to the temperature of the DUT in relation to the temperature range under which the device is expected to perform in a particular operation.

A test parameter of importance is the time duration of observation. Because the frequency of burst-noise occurrence is frequently less than once every few seconds, the minimum test period should be in the range of from 15 to 30 seconds.

Pass-Fail Criteria

A test system built to accommodate the test philosophy outlined above has the ability to reject or pass a DUT on the basis of two variables: burst-amplitude and the frequency of burst occurrence. The burst-amplitude which will trip the counter can be no lower than the background l/f noise peaks of burst-free units, otherwise normal background noise will fail the DUT.

The background noise peaks depend on the source termination Rs, the wide band l/f noise figure of the DUT, and the test system bandwidth. A good estimate of the normal background noise-peak levels can be computed from the definition of noise factor and an empirically determined noise-crest factor of approximately 6:1. The crest-factor is the ratio of the maximum peak-noise voltage to the RMS noise voltage. The noise factor is defined as the ratio of the total noise power at the amplifier output to the output-noise power due to the source resistors alone. In terms of the RMS noise voltages at the input terminals of the amplifier this is equivalent to:

$$\text{Noise Factor (F)} = \frac{E^2\text{input noise total}}{E^2\text{noise source resist}} = \frac{(E_{NTi})^2}{(E_{NRS})^2} \qquad (1)$$

E_{NTi} is the total input noise-voltage, i.e., the sum of noise generated in the source termination resistance and noise generated by the DUT.

E_{NRs} is that part of E_{NTi} due to Rs alone.

$$\text{Therefore,} \quad E_{NTi} = (\sqrt{F})(E_{NRs}). \qquad (2)$$

E_{NRs} can be computed by using the well known expression for "white-noise" generated across the terminals of a resistor (R):

$$E_{NR}(\text{RMS}) = \sqrt{4kTBR} \qquad (3)$$

where k = Boltzmans Constant = 1.372×10^{-23} j/^{o}K

T = Absolute Temperature in ^{o}K
B = Noise Bandwidth in Hz
R = Value of the resistor in ohms.

Thus, at a room temperature of 290^{o}K

$$E_{NR}(\text{RMS}) = 1.28 \times 10^{-10}\sqrt{BR}$$

For example, a 100 kΩ resistor preceding a system with a bandwidth of 1 kHz will generate a noise-voltage of

$$(1.28 \times 10^{-10}) \quad (\sqrt{10^3 \cdot 10^5}\,) \quad = 1.28\,\mu V_{RMS}$$

Both inputs of an Op-Amp are usually terminated in Rs, hence it is necessary to combine the effects of both resistors to determine the effective E_{NRs} at the input of the DUT. Because the noise voltages from these two resistors are uncorrelated their voltages must be added vectorally rather than algebraically.

$$E_{NRs}\,(\text{effective}) = \sqrt{(E_{NR_{s1}})^2 + (E_{NR_{s2}})^2} \qquad (4)$$

because $E_{NR_{s1}} = E_{NR_{s2}}$, when $R_{s1} \doteq R_{s2}$

$$E_{NRs}\,(\text{effective} = (\sqrt{2})\ (E_{NRs})$$

and for 1 kHz bandwidth at 290^{o}K

$$E_{NRs}\,(\text{effective}) = (\sqrt{2})\,(1.28\,\mu V) = 1.81\,\mu V_{RMS}.$$

If in this example, the DUT has a wideband l/f noise figure of 4 dB (2.5:1 power ratio) the total RMS background noise-voltage at the input will be

$$E_{NTi} = (\sqrt{F})\ (E_{NRs})\ (\text{from eq.(2)})$$
$$= (\sqrt{2.5})\ (1.81) = 2.9\,\mu V_{RMS}$$

If a crest factor of 6:1 is assumed, the peaks of the background noise will be approximately (6) (2.9) = 17 μV peak. This voltage is the lower limit of the burst-amplitude rejection level. A reasonable threshold for burst detection and rejection might be 50-100% greater than this minimum value.

An alternate method used to set the burst-threshold limit involves a direct measurement (at the output of the high gain amplifier-filter combination) using a storage oscilloscope or a "true RMS" voltmeter. By this method the noise peak or RMS noise voltage of burst-free units is determined. This measurement provides a good practical check on the accuracy of the computation outlined above. Selection of the acceptable number of burst counts in the test period is arbitrary, but dependent on the type of application intended for the DUT. To be acceptable in some critical applications, the DUT may not generate even a single burst-pulse in a relatively long period of time.

Burst-Noise Test System Circuits

1. High gain Amplifier – Filter

Fig. 4 shows the schematic diagram of the high-gain amplifier-filter which provides a fixed gain of 80 dB with a 12 dB octave roll-off above 1 kHz. The gain-function is somewhat arbitrarily distributed between the DUT and

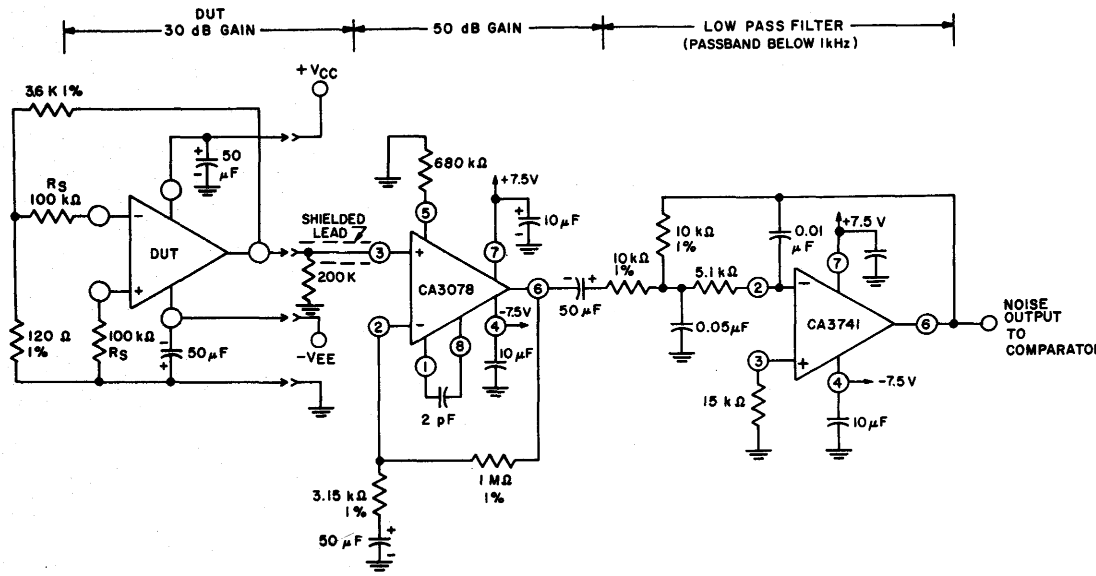

Fig. 4 - Schematic diagram of high-gain amplifier/filter.

post-amplifier: 30 dB and 50 dB respectively. This distribution is based on the need for sufficient gain in the DUT portion to eliminate significant noise-signal contributions from the second stage while simultaneously allowing adequate loop-gain in each stage to provide accurate gain-setting with precise external resistors. The first stage is shown as a plug-in module so that any type of DUT configuration having 30 dB gain can be tested.

The capacitive coupling employed provides a low frequency cutoff of about 1 Hz and eliminates the need for dc-offset zero-adjustments. The dc offset-voltage at the filter output is less than 5 mV which corresponds to less than 0.5 μV error when referred to the noise input (an 80 dB gain is assumed.) Several seconds must be allowed, however, for the DC operating point to stabilize after the power is applied to the DUT.

2. Bi-Polarity Comparator

Fig. 5 shows the schematic diagram for the threshold-detecting comparator. Because bursts of either polarity must be detected and converted to positive output pulses, two comparators are required: one having a positive-threshold reference and the other having a negative-threshold reference of equal magnitude. The RCA CA3060 triple OTA is convenient to use because a single package provides circuits for both comparators plus a reference inverter for the negative threshold reference. The positive feedback provided by the R_f and R_i connections produces a hysteresis effect with reference to the input switching threshold, (i.e., the comparator does not return to its quiescent state until the input noise signal drops well below the initial threshold trip-level). This feature is necessary to prevent multiple triggering by the background noise signals superimposed on top of the burst-noise pulse. By this means, multiple counting of a single burst-noise pulse is avoided.

The magnitude of the threshold reference voltage E_R determines the burst-level which trips the comparator. If a voltage gain of 80 dB is provided by the amplifiers, a 200 mV reference voltage will enable the circuit to be triggered when a burst-noise pulse (whose amplitude is equivalent to the level of 20 μV referred to the DUT input) is present.

3. Counter-Latch-Timer Control Circuits

The remaining circuits of the go-no-go burst-noise tester are shown in Fig. 6. The decade-counter is incorporated in single COS/MOS IC (RCA CD4017AE) which has clock, reset, and enable inputs, and an output terminal for each of ten count-positions (0 to 9). A carry-out signal is available if the use of more than a single decade is desired. The clock input-signal must be positive-going and have a magnitude of

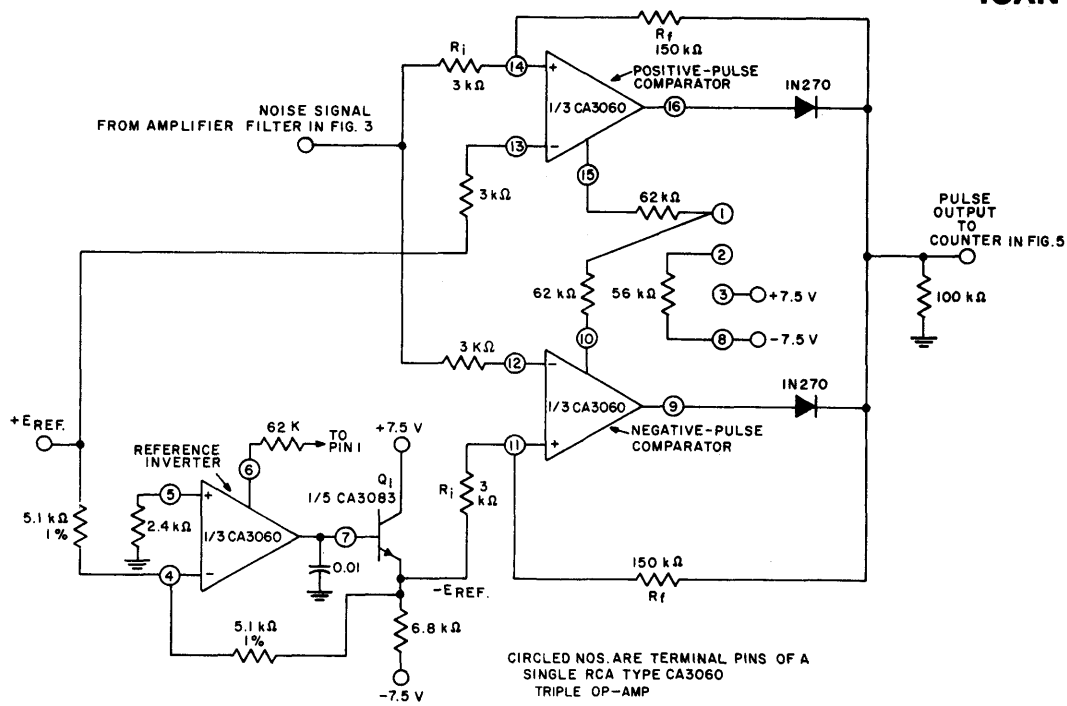

Fig. 5 - Schematic diagram of threshold-detecting comparator.

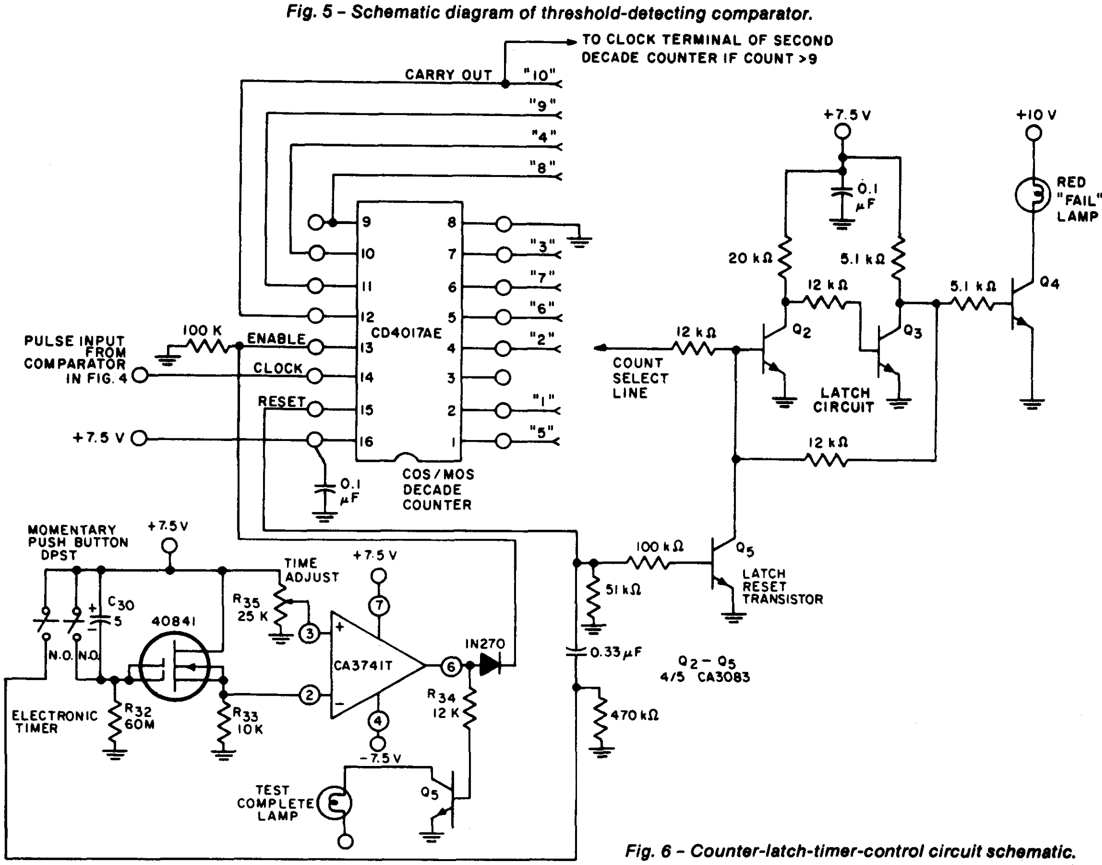

Fig. 6 - Counter-latch-timer-control circuit schematic.

at least 70% of the supply-voltage and rise-time equal to or less than 15 μs. The comparator shown in Fig. 5 provides an output signal which meets these requirements.

Selection of the reject count is made by a pin-jack connection of the latch-circuit input-lead to the appropriate output terminal of the counter. Whenever the selected count-position voltage goes "high" the latch-circuit is switched to the latched-state, and the fail-indicator lamp "on". The latch and lamp will remain "on" until the reset button of the electronic timer is switched to the "Timer On" position. This action provides a momentary reset signal ($\approx$ 20 ms) to both the latch and counter circuits and places a continuous enable voltage on the counter for the duration of the test period.

Spurious Noise Sources and Their Suppression

The very low voltage levels and the high source impedances normally used for burst testing render the system highly susceptable to external spurious noise sources. This problem is particularly serious if a test unit is going to be rejected for as little as one or two input burst-noise pulses exceeding 20-30 μV. The major sources of spurious noise encountered in the development of this test system were:

1. 60-Hz hum pickup,
2. power supply transients,
3. electromagnetic pick up of switching transients.

60-Hz hum is introduced by capacitive or inductive coupling or as power-supply ripple. Power-supply ripple is not normally a problem when testing operational amplifiers with regulated supplies, because the Op Amps generally have good power-supply rejection. This source of noise must be considered, however, when testing devices that do not have good inherent power-supply rejection. Capacitive or inductive coupling of hum can occur when 60-Hz line cord leads are within a few inches of the input terminals of the DUT. Precautions, such as proper lead dress and twisting of the 60-Hz leads, eliminate this problem.

Power-supply transients, as distinguished from power-supply ripple, can be of sufficient amplitude to introduce detectable noise pulses at the operational amplifier input. Such transients are produced when other equipment on the same ac line is switched on or off. A typical power-supply rejection ratio for an operational amplifier is 50 μV/V (i.e. a 1 volt transient on the power-supply is equivalent to a 50 μV noise pulse at the DUT input). This example demonstrates that the test system cannot tolerate power-supply transients greater than approximately 100 mV even when testing units with good power-supply rejection. Unless the power-supply is known to be free of such transients, a battery-operated system is recommended. Even when this system is battery-operated, "On-Off" switching of nearby equipment introduces detectable transients into the system. These problems are eliminated by placing the test circuitry in a completely shielded enclosure with a hinged top for easy access to the test unit. The external noise problem is best solved by use of a shielded enclosure and by use of a battery-operated power-supply contained within the enclosure. Fig. 7 shows a photo of the circuit board layouts of the test unit.

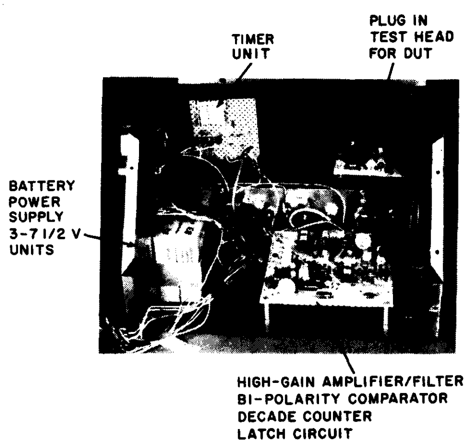

Fig. 7 - Photo of circuit-board layout.