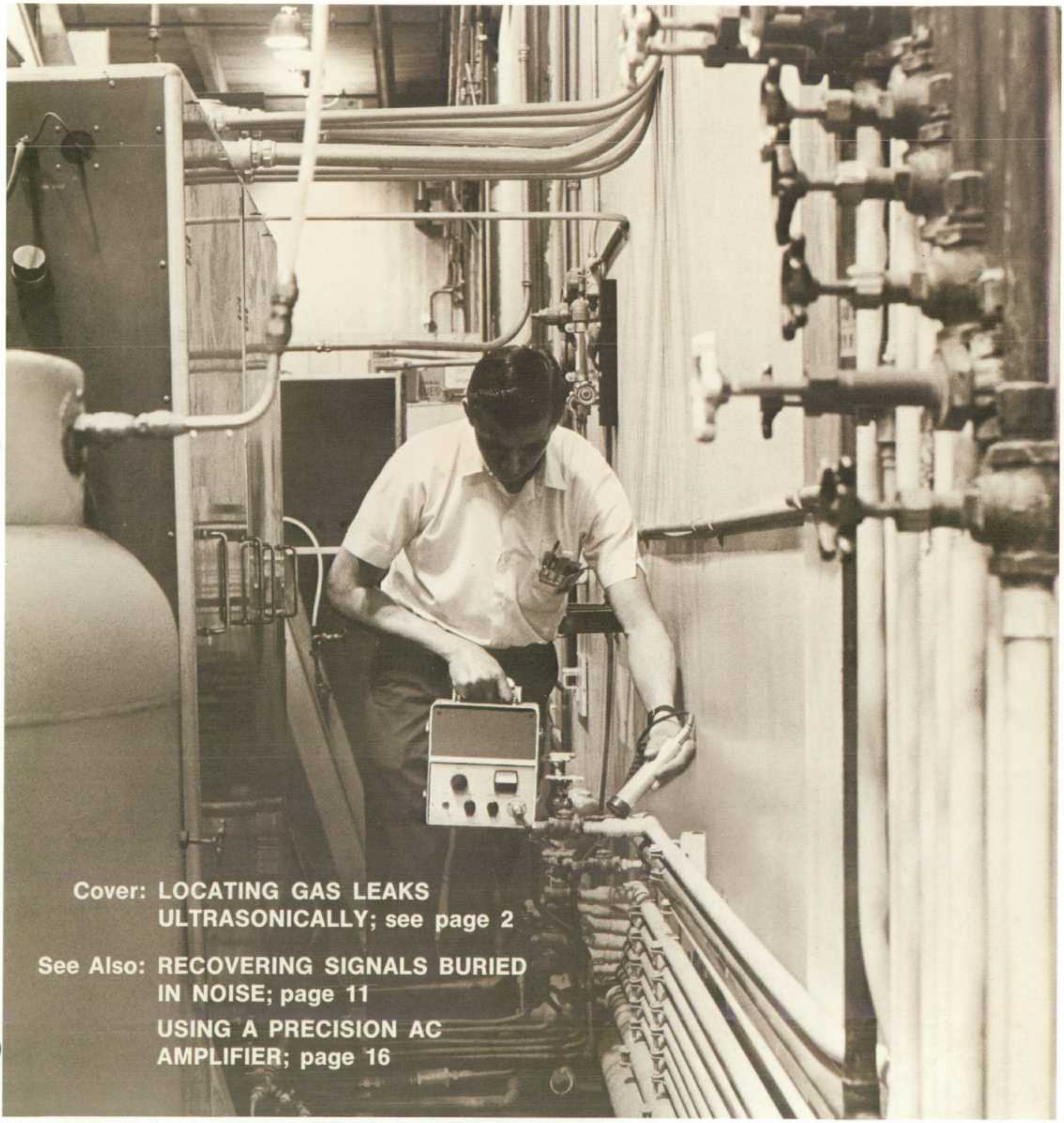
HEWLETT-PACKARD JOURNAL



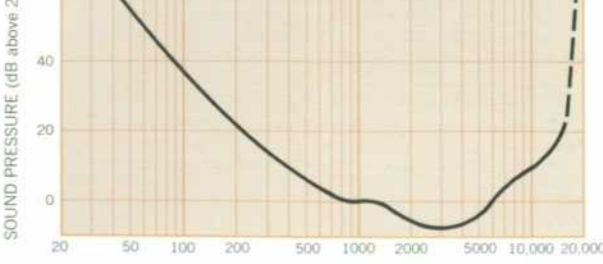
MAY 1967

Pinpointing Industrial Defects with Ultrasonic Ears

Gas leaks, corona, and other defects in industrial equipment can be located quickly by zeroing in on their high-frequency sounds. Ultrasonic translators allow men to hear and follow these normally inaudible sounds.

By Robert L. Allen

SOUNDS AUDIBLE TO THE BEST HUMAN EARS lie in a frequency range of about 20 Hz to 20 kHz. But acoustical energy is by no means limited to this range. Just as the human eye responds to only a small portion of the electromagnetic spectrum, the human ear provides man with only a part of the information that could be extracted from sonic energy.



Minimum sound pressure that can be heard by the best human ears.

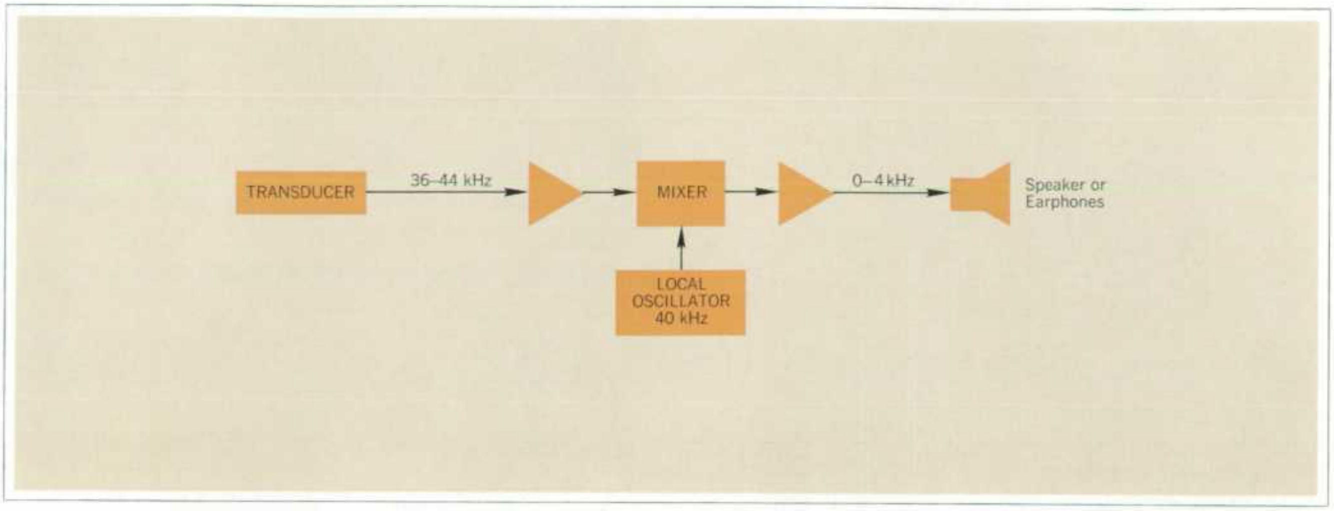
Sonic energy at frequencies above 20 kHz, i.e. *ultrasonic* energy, is generated by many common occurrences. For example, rubbing the hands together creates high-frequency sounds at about 40 kHz that can be heard by a dog or cat at a distance of 50 feet. Sibilant sounds in speech are also a source of ultrasonic energy. Another well-known producer of high-frequency sounds is the bat, which navigates by bouncing ultrasonic 'beeps' off nearby objects. Bat 'beeps' contain frequencies up to 150 kHz.

Many phenomena in industry also produce ultrasonic energy. Some of the stronger producers are defects like gas leaks, corona, vibrations, and friction. These defects induce random irregular motions in surrounding molecules, so the sonic energy they produce is spread over a wide range of frequencies. In many cases a defect can be recognized by its high-frequency sounds long before it worsens to a point where it becomes audible.

Ultrasonic Translators

A simple, yet effective means for human ears to hear the ultrasonic world is the ultrasonic translator, first developed in 1961 by what is now the Delcon Division of *–hp–*.* *–hp–* ultrasonic translators convert high-frequency sounds at frequencies between approximately 36 kHz and 44 kHz to audible sounds at frequencies less than 5 kHz, where human ears are most sensitive (see diagram at left). Unlike some ultrasonic test equipment, translators are not generators of ultrasonic energy.

*Besides ultrasonic translators, the Delcon Division also produces instruments for locating open circuits in cables and for locating faults in buried cables.



Basic ultrasonic translator block diagram.

They translate; that is, they make it possible to listen to sounds that are normally inaudible.

Translator operation is relatively uncomplicated. At the top of this page is a basic block diagram. Ultrasonic energy between 36 kHz and 44 kHz is converted to electrical signals of the same frequencies by a high-frequency microphone, located in a cylindrical probe. The electrical signals are amplified and heterodyned with a 40-kHz local oscillator signal, and the resulting signals are filtered to eliminate all frequencies above 5 kHz. The audio-frequency signals are connected to a loudspeaker or to earphones, or rectified and applied to a meter.

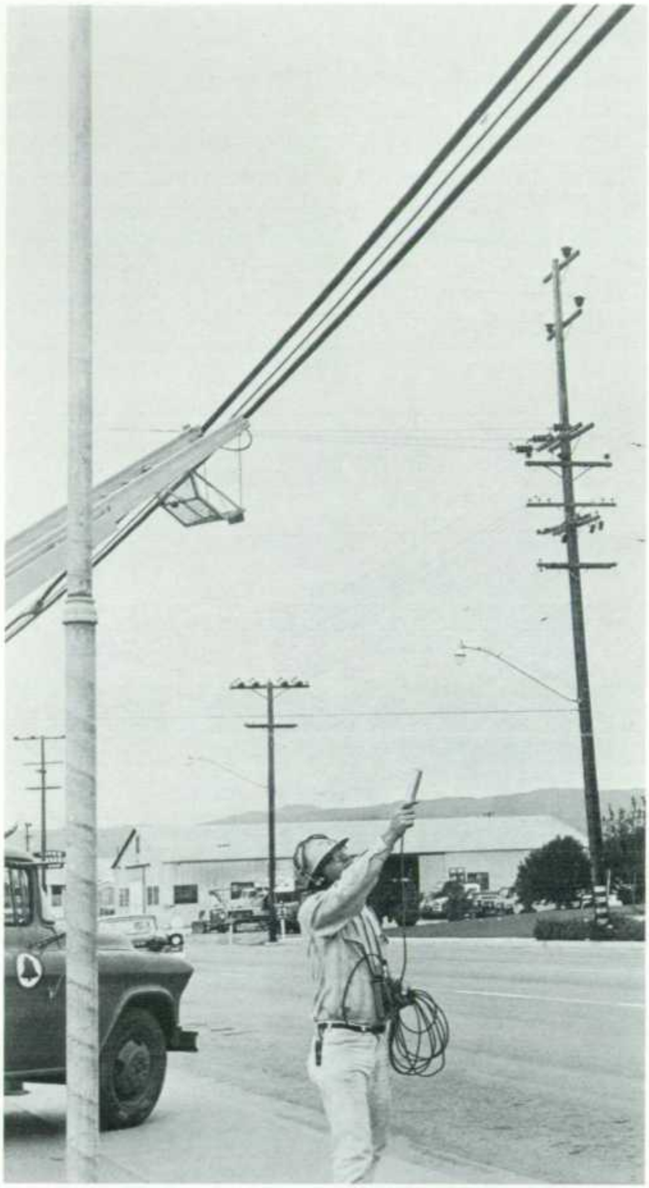
Translators have speeded and simplified the detection and location of many different kinds of ultrasonic sources. There are several reasons for their effectiveness.

First, the probes are directional, giving maximum response when they are pointed directly at a source of ultrasonic energy. It is easy to learn to locate a source by coordinating its direction with the intensity of the translator output.

Second, the high-frequency noises of many defects which are too small to make audible noises, when translated, sound very much like the audible sounds these defects would produce if they were larger and more serious. For example, the translated sound of a gas leak is a hissing noise, and a dry bearing makes high-frequency sounds which translate into a high-pitched squeal. Hence it is easy to identify the translated sounds of most common defects.

A third reason why translators are effective is that they are fast. It isn't necessary to dismantle anything to

Airline mechanic checks Boeing 720B cabin oxygen system for leaks using –hp– Model 118 Ultrasonic Translator and general-purpose probe with focusing extension.



Ultrasonic detection of leaks in pressurized telephone cables has eliminated old-fashioned soap-bubble method. Leaks can usually be heard from the ground, often from a truck driving along the cable path. Translator responds only to sounds between 36 kHz and 44 kHz and is not affected by audible traffic noises.

Logic and automatic alarm circuits are built into new ac-powered Model 4950A Ultrasonic Translator for automated ultrasonic production testing. Instrument responds either to ultrasonic signal or to its integral, and closes a relay whenever signal or integral exceeds level set with input attenuator.

use one. Usually a product or system will be operating when it is being checked. What's more, defects which broadcast their sounds through the air can be detected from some distance. This saves time, since the presence of a defect can be detected without examining every part of a system.

Types and Uses of Translators

The first translators were portable battery-powered units, designed principally for locating leaks in pressurized telephone cables and other pressurized systems (photos, pp. 3 and 4). Today, these translators are used for finding leaks in vacuum systems, for locating high-voltage breakdown and corona, for trouble-shooting operating fluid power systems, for pinpointing engine defects, for engineering design of transformers and mechanical devices, and for many other purposes. Some typical uses are illustrated on page 6.

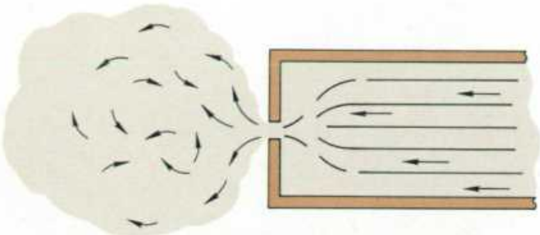
Recently, a new ultrasonic translator has been designed specifically for production testing (photographs, top of page). This new ac-powered instrument has switching and automatic alarm circuitry as well as the basic ultrasonic translator circuits. These extra circuits actuate a relay when the ultrasonic energy produced by a product under test exceeds a preset level. The relay can be used to set off an alarm or to cause a faulty product to be rejected.

Detecting Low-pressure Gas Leaks

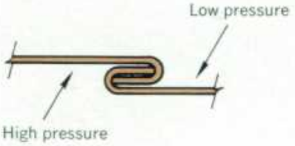
Of historical as well as practical significance, because it was one of the earliest applications of ultrasonic translation, is the detection and location of leaks in pressurized telephone cables. Pressurization of long-distance cables was begun by the telephone company in 1927, and subscriber cables were first pressurized in 1952.* Cable pressurization prevents moisture from penetrating the cable in the event of a break in the cable sheath. It has been found to substantially reduce the number of service-affecting cable troubles. Dry air circulating in the cable keeps the insulating paper dry, thereby reducing leakage, cross-talk, and noise. Sheath breaks are readily detected by noting excessive air consumption, and can be located roughly by plotting pressure gradients.

Before ultrasonic translators became available, precise location of leaks in telephone cables had to be accomplished by applying soap solution, inch by inch, to a suspected section of cable and watching for bubbles. Now, the same leaks can be detected much more rapidly by ultrasonic translation, often from a truck driving along the cable path.

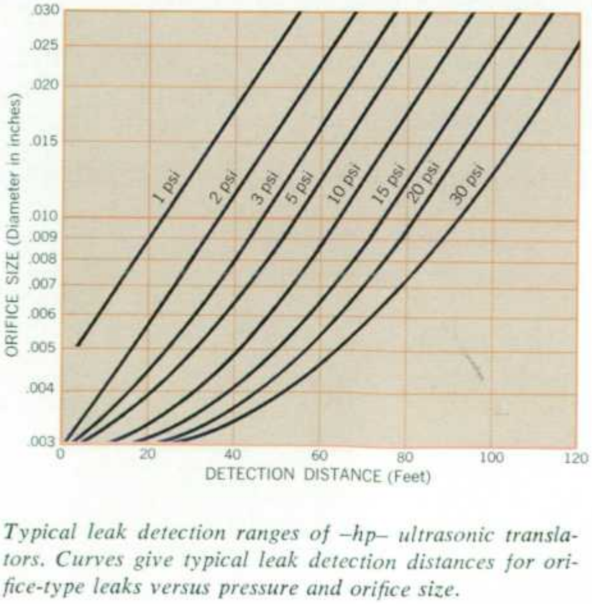
Ultrasonic leak detection depends upon the transition from laminar to turbulent flow as a gas leaks from an orifice, as shown in the diagram at upper right. Non-orifice leaks, i.e., diffused or labyrinth leaks (middle diagram at right), do not always create sufficient turbulence to be easily detected by ultrasonics. Orifice-type leaks, however, can be detected at distances beyond 100 feet. At lower right is a chart relating typical leak detection ranges for Delcon translators to the orifice size and pressure. Notice that at a pressure of 20 psi, a leak from an orifice havng a diameter of about 0.018 inch can be detected at 100 feet .



Gas flow through an orifice creates turbulence, resulting in molecular collisions which produce ultrasonic energy. -hp- ultrasonic translators can detect these leaks at distances given in diagram below.



Labyrinth leaks do not produce enough ultrasonic energy to be readily detected by ultrasonic translators.



Typical leak detection ranges of -hp- ultrasonic translators. Curves give typical leak detection distances for orifice-type leaks versus pressure and orifice size.

Production Testing

Either the portable or the new ac-powered ultrasonic translators can be used to accelerate and simplify production testing for leaks, corona, and other industrial defects. However, in most cases the ac-powered type will do the best job. Its logic circuits not only make it more versatile but also give it the ability to do automatic testing.

*John P. Adams, 'A History of Cable Pressurization,' The Delcon Detector, Vol. 2, No. 6, June, 1965. (Excerpted from a paper delivered at the Cable Pressurization Seminar, East Meadow, L.I., N.Y., April 21-24, 1963.)

Typical uses of Ultrasonic Translators

A

B

C

D

E

F

A. Maintenance technician inspects hospital networks carrying oxygen, nitrous oxide, vacuum, and medical air with Model 116 Ultrasonic Translator and general-purpose probe. Networks are tested under 150 psi. At this pressure, holes smaller than 0.00075 inch can be located.

B. Inspecting a substation for corona with Model 117 Ultrasonic Translator with general-purpose probe.

C. Cable repairman scans section of cable with Model 118 Translator. Cables are tested under several kVdc. Found on this 2000-ft. reel was a cross circuit resulting from a $\frac{1}{16}$-inch-long break in polyethylene coating.

D. Inspecting the flanged stainless-steel tube leading from a reformer in a chemical plant. Tube contains hydrogen at 1300°F, precluding leak detection by soap solution. High audible noise level precludes audible detection. General-purpose ultrasonic probe has focusing extension for pinpointing leaks.

E. Production engineer adjusts gain control of Model 118 Translator to predetermined test level as he holds contact probe near gas bearing component during start-stop cycles. Translator gives numerical dB readings of friction noises in production gyroscope components.

F. Ultrasonic inspection for valve blow-by eliminates compression tests. As starter turns engine, airline mechanic holds contact probe of ultrasonic translator against each rocker box cover and listens for faulty valves.

Because translators are sensitive only to ultrasonic energy, their performance is not affected by the loud audible noises usually present in a production area (provided, of course, that these audible noises aren't accompanied by ultrasonic sounds).

Detecting leaks in sealed containers is one type of production testing which is ideal for translators. The most common leak test now in use is water immersion: a container is placed in a tank of water and a technician watches for bubbles which reveal both the existence and the location of a leak.

Most leaks which can be located by water immersion can be located much more easily by pressurizing the container and listening with an ultrasonic translator for the characteristic hissing sound of the leak. In fact, many leaks which are too small to be detected by water immersion can be found using a translator.

In another typical production application, manufacturers of aerosol 'bombs' use ultrasonic translators to test their containers for proper operation. In one facility, a plunger strikes the valve of each can as it comes off the production line. The ultrasonic energy produced by the escaping spray is detected by one of the new ac-powered ultrasonic translators. If the valve doesn't hiss loudly enough, the internal logic and relay circuits of the translator cause the can to be rejected automatically.

Translators are also used to check for corona in high-voltage filament transformers and in the high-voltage horizontal transformers of television sets (see photo at right). With a translator, corona caused by faulty insulation or small metallic inclusions is readily detected, either automatically or by a technician. Corona produces a frying or crackling sound in the loudspeaker of the translator.

Ultrasonic inspection of high-voltage filament transformers for corona, using new Model 4950A Ultrasonic Translator. Translator alarm light indicates too much corona. Test voltage is 3.5 kV.

Logic Circuits

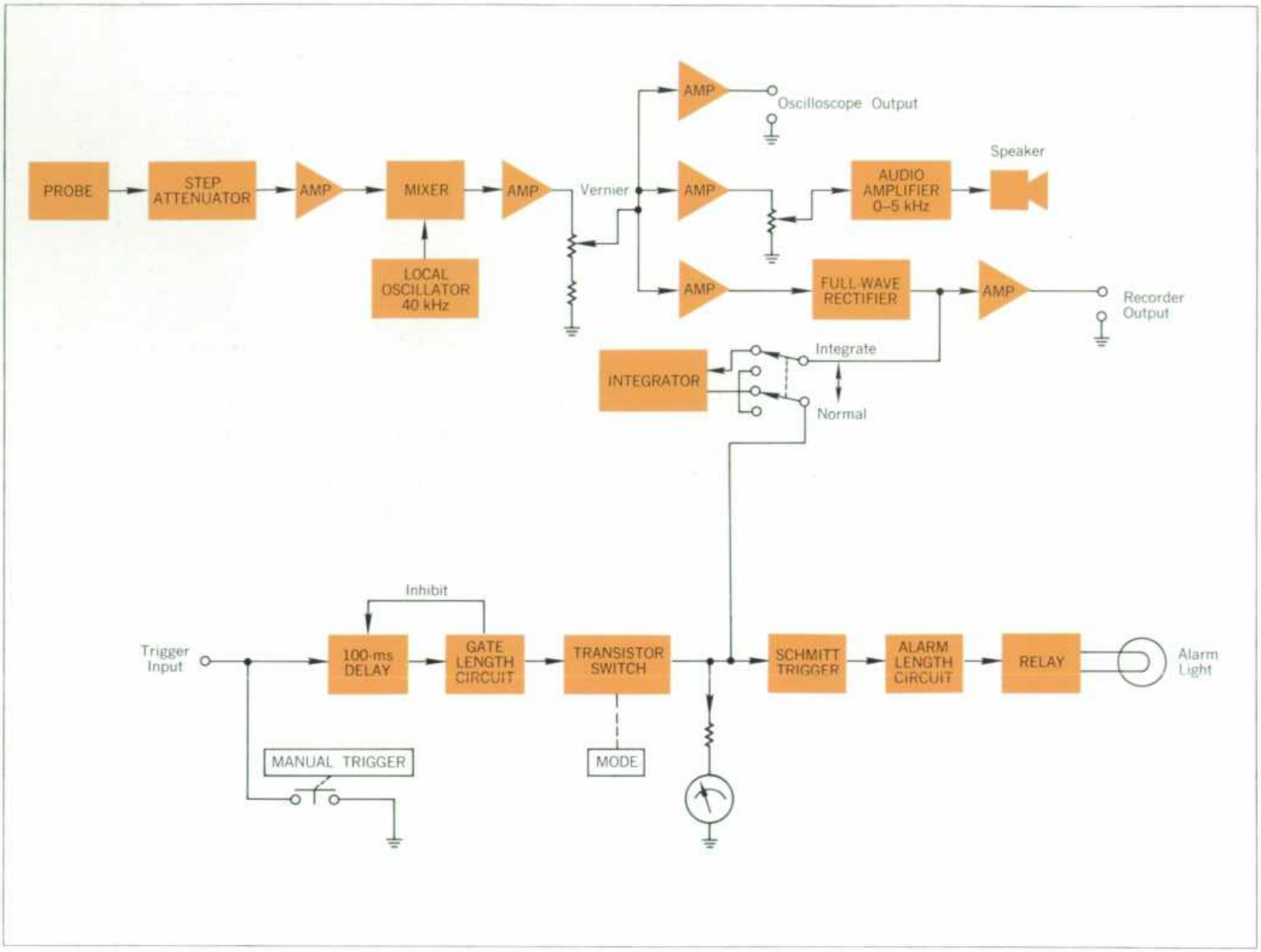
The logic and automatic alarm circuits of the ac-powered translator are shown in the block diagram on page 8. In the upper part of this diagram are the basic ultrasonic translator circuits, along with additional amplifiers and an input attenuators which give the user a choice of outputs and finer control of signal levels. The lower part of the diagram shows the logic, alarm, and meter circuits.

Whenever the ultrasonic energy impinging on the probe is strong enough to cause the front-panel meter to read more than 0 dB, the alarm relay closes and the alarm light comes on. An audible alarm, an automatic rejection mechanism, or any other device can be connected to the relay terminals on the rear panel.

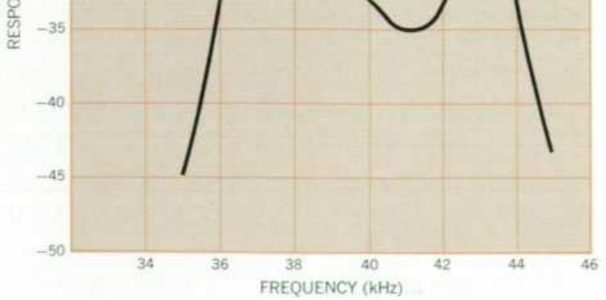
The amount of signal that will cause the meter to read 0 dB is determined by the input step attenuator and the vernier. Usually these attenuators are set so that 0 dB is some appropriate number of dB above a reference signal such as the background noise in the probe or some known ultrasonic signal.

Translator operation can be either continuous or triggered. Continuous operation is just what you would expect — the translated electrical signals corresponding to the ultrasonic input energy go directly and continuously to the meter and alarm circuits.

In triggered operation the meter and alarm circuits are inactivated by a transistor gate circuit until a trigger — a momentary contact closure to ground — is applied to the trigger input. Then the gate is opened and the translator is activated for a length of time determined by an adjustable monostable multivibrator. Gate lengths of



Block diagram of Model 4950A Ultrasonic Translator, showing logic and alarm circuits for production testing.



Typical frequency response of barium titanate transducer used in ultrasonic translator probes.

0.1 to 3.0 seconds can be selected. In the triggered mode, the alarm can be set off only during the time that the gate is open. This mode would be used, for example, in production test systems which make loud ultrasonic noises while moving each new product into the test position. The activating trigger would be applied to the translator after each move is complete, the system ultrasonically quiet, and the device ready to test.

If ultrasonic noise or fast transients are present and are strong enough to set off the alarm prematurely, the signal can be integrated during the time that the gate is open in the triggered mode. This will cause the noise to be averaged out and decrease the effects of fast transients so that meaningful measurements can be made. The meter will indicate the integral of the input signal.

Transducer and Probes

Either of two types of probes may be used with any of the ultrasonic translators. One is a general-purpose directional microphone which is used to detect and locate sources which transmit their ultrasonic energy through the air. The second type of probe is a contact probe whose sensing end is a long, 11-cm, stainless-steel stylus. Heavy metallic structures such as engine blocks readily conduct ultrasonic energy, but are so massive that their surfaces do not vibrate enough to broadcast this energy through the air where it could be detected by the general-purpose probe. The contact probe is designed to be placed in contact with solid objects and to be sensitive to ultrasonic energy propagating in them. It is insensitive to sound waves in air.

Both probes use the same transducer element to convert ultrasonic energy to electrical signals. The element is a thin rectangular piezoelectric crystal of barium titanate placed with its flat side perpendicular to the axis of the probe. This transducer element is one of the most sensitive types. Its frequency response has two peaks, typically at about 37 kHz and 43 kHz, as shown in the diagram on p. 8. As mentioned above, the defects of interest generate broad ultrasonic spectra, and all have significant energy in the 36-to-44-kHz range.

In the general-purpose probe the transducer element is preceded by a horn, or cone, which effects an efficient impedance match between airborne sound energy and stiff transducer, and contributes to directivity.

A small aluminum saddle at the end of the horn helps further to match the acoustical impedance of the air to the acoustical impedance of the barium titanate crystal. The horn, saddle, and crystal occupy about half the length of the general-purpose probe, and the other half of the probe contains a solid-state preamplifier.

In the contact probe, the transducer element is spring-mounted and placed in contact with a knife edge on the probe end of the stylus assembly. The contact probe also contains a solid-state preamplifier.

Robert L. Allen

This is Bob Allen's second contribution to the Hewlett-Packard Journal in as many months. Last month he authored an article on the new Model 5260A 12.4 GHz Frequency Divider, for which he was project leader while with the *–hp–* Frequency and Time Division. In this month's article, he is speaking in his new capacity of engineering manager of the *–hp–* Delcon Division.

Bob received his BS degree in electrical engineering from Utah State University in 1960. He worked the following summer for *–hp–*, then returned to Utah State, graduating in 1961 with an MS degree in electrical engineering. In September, 1961, he joined the Frequency and Time Division full-time. He contributed to the design of the 5275A and 5243L Counters and the 107A Quartz Oscillator, and was project leader for development of the 5260A Frequency Divider and the 5240A Digital Frequency Meter. He has a patent pending and has published a paper on the method of frequency division used in the 5260A and 5240A.

Bob is a member of IEEE, Sigma Xi, Phi Kappa Phi, and Sigma Tau.

Acknowledgments

Electrical design of the ac-powered ultrasonic translator was initiated by Hans H. Junker. The final design was done by Donald W. Lolli. Ole Volhontseff did the mechanical design. Invaluable assistance was rendered by the *–hp–* Corporate Industrial Design Group. ■

SPECIFICATIONS

–hp–
Model 4950A
Ultrasonic Translator

INPUT: Uses wide range probes which respond to ultrasonic noises in the band of 36–44 kHz.

SIGNAL ATTENUATOR: Step: 10 dB/step attenuator over 90 dB range.
Fine: Continuously adjustable over a range of 20 dB.

GATE MODES: Continuous: Instrument operates as a normal ultrasonic detector. Whenever the signal exceeds the trigger level, the relay is actuated.

TRIGGER: Instrument requires a trigger signal to open a gate in the meter circuit. The gate stays open for a preset gate time and then closes automatically. If the ultrasonic signal exceeds the trigger level while the gate is open, the relay is actuated. The required trigger signal is a momentary contact closure.

GATE LENGTH: Length of gate can be preset to 0.1, 0.3, 1.0, or 3.0 seconds. (This also sets the integrating time in the integrate mode.)

NON-INTEGRATE: Response of the instrument is directly proportional to the ultrasonic signal.

INTEGRATE: Response of the instrument is proportional to the integral of the ultrasonic signal.

ALARM MODES: Alarm length: Length of time the relay is actuated can be preset to 0.1, 0.3, 1.0 or 3.0 seconds.

NON-LATCH: Relay is actuated whenever the signal is above the trigger level and drops out when the signal is below the trigger level. Hysteresis is approximately 2 dB.

LATCH: Relay is reset by pushing alarm light switch when signal level drops below trigger level.

AUDIO: Has 2 watt audio amplifier, with a built-in loudspeaker.

AUXILIARY OUTPUTS: Oscilloscope: 1.0 V rms output for full scale meter deflection. Recorder: 1.0 V dc output for full scale meter deflection. Phones: Internal loudspeaker is disabled when earphones are connected.

TEMPERATURE: Operating temperature range 0°C to 55°C.

PHYSICAL CHARACTERISTICS: Dimensions: 16¾" wide, 5½" high, 11¼" deep. System weight: 18 lbs (8,26 kg). Shipping weight: 23 lbs (10,4 kg).

POWER: 105 to 125 or 210 to 250 volts, 50 to 60 Hz, 15 watts.

PRICE: Model 4950A, $1475, includes general-purpose probe and cord. Model 72007 Contact Probe available as optional accessory at $150 additional.

–hp–
Models 4918A and 118
Portable Ultrasonic Translators

CONSTRUCTION: Rugged aluminum chassis and cabinet with detachable front cover with operating instructions and accessory storage. Mil-Spec printed circuit board; outside quick-access battery compartment.

CIRCUITRY: Broad-range 4.5 volt transistorized circuitry with RF filter. Hermetically sealed power switch.

FREQUENCY RESPONSE: Translates frequencies between 36 and 44 kHz into audible sounds; other sounds within audio range are screened out.

PROBE AND COIL CORD: Hand-held; shielded against RF interference; output impedance 180 ohms; transistorized pre-amplifier; conical response ±11° at 3 dB points. Supplied with a six-foot coil cord employing latch-lock connectors. Less than 1 dB loss when used with 100-foot connecting cable. Probe size: 1¾" diameter x 6¼" long, including protective monel-screened cap. Power to probe supplied through cord from main unit.

METER: Ultrasonic sound intensity measured by output meter; sealed and gasketed to lock out dirt and contaminants; scale length 1.75 inches; linear calibration (0–100) on upper scale for logging relative measurements; lower scale calibrated from 0–30 dB.

SPEAKER: Incorporates 4 × 6 inch speaker; normal power to speaker 400 mW.

TEMPERATURE RANGE: Oscillator stability ±15 Hz, and signal to noise ratio within ±1 dB from 0°C to 55°C.

HAZARDOUS LOCATIONS (Model 4918A only): Meets requirements of Underwriters' Laboratories, Inc., for use in Hazardous Locations Class I, Group D. Listed under UL's Re-examination Service.

HEADSET JACK: Auxiliary 600-ohm output headset jack. Headset furnished as standard.

RECORDER JACK (Model 118 only): 1 mA dc available.

SIZE: 11" x 9" x 8½".

SYSTEM WEIGHT: 11 lbs; shipping weight 14 lbs.

BATTERY INFORMATION: 3 Eveready E-42 or equivalent (mercury type).

BATTERY LIFE: 500–700 hours.

PRICE: Model 4918A, $850.00, complete and including batteries, general-purpose probe, headset, 6-foot coiled cord and probe extension adapter. Model 72007 Contact Probe available as optional accessory at $150.00 additional. Model 118 (same as Model 4918A except that Model 118 has recorder output and is not UL-approved for use in hazardous locations), $850.00.

–hp–
Model 4905A
Portable Ultrasonic Translator

CONSTRUCTION: Rugged aluminum chassis and case; stainless steel hardware throughout; Mil-Spec printed circuit board; quick-access battery compartment; detachable cabinet side-plate for servicing.

CIRCUITRY: Broad-range 4.5 V transistorized circuitry with RF filter provides 100 dB dynamic range; circuit gain controlled by a single knob.

FREQUENCY RESPONSE: Same as 4918A.

PROBE AND COIL CORD: Same as 4918A.

METER: Same as 4918A.

SPEAKER: Incorporates 2.5 inch speaker; sealed against moisture; nominal power to speaker 25 mW.

TEMPERATURE RANGE: Same as 4918A.

HEADSET JACK: Auxiliary 600-ohm output headset jack.

SYSTEM WEIGHT: Net 6 lbs (2,7 kg); shipping weight 8 lbs (3,6 kg).

BATTERY INFORMATION: Three Eveready E-12 or equivalent (mercury type).

BATTERY LIFE: 360–500 hours.

DIMENSIONS: 8¼" wide x 4½" high x 2¼" deep (20,9 x 11,4 x 5,71 cm).

PRICE: Model 4905A, $595.00.

–hp–
Models 116, 117, 4917A
Portable Ultrasonic Translators
(Specifications on request)

MANUFACTURING DIVISION: –hp– Delcon Division
333 Logue Avenue
Mountain View, California 94040

Fig. 1. *This new all solid state –hp– Model 3410A AC Microvoltmeter will measure signals even when frequency and amplitude are unknown. A panel light helps in determining the proper setting of the range switch. Adjusting the front panel tuning control to within 1% of the signal frequency enables the phase-lock circuitry to lock on and track the input signal within the specified limits.*

How to Recover Weak Signals Buried in Noise

A new phase-lock synchronous detector enables this ac microvoltmeter to lock on to signals obscured by noise.

By Raymond C. Hanson

MEASURING LOW-LEVEL SIGNALS nearly obscured by noise or other nonrelated signals is required in many applications. Some general areas in which this condition is encountered include instrument calibration, communications and medical research.

The broadband, average responding voltmeter is limited in sensitivity by inherent noise and spurious signals. An extension of the average-responding voltmeter for very low level signals obscured by noise uses the synchronous rectifier. When driven at the fundamental frequency of a known waveform, the filtered output of a synchronous rectifier is proportional to the average value of that waveform. Noise and spurious signals are rejected.

Voltmeters using this technique require a clean, high-level reference signal input from the test signal source, or that the system under test use the local oscillator output of the voltmeter. In many cases such a hook-up is not convenient or is impossible.

A new ac microvoltmeter, Fig. 1, has been designed that uses a phase-lock oscillator to drive a synchronous rectifier, thus eliminating the need for a reference input. It operates at any frequency from 5 Hz to 600 kHz and has a high input impedance of 10 megohms. Sensitivity is 3 microvolts full scale on the most sensitive range. Noise and spurious signals up to 20 dB above full scale are rejected.

Operation of the Microvoltmeter

The circuit of the –*hp*– Model 3410A AC Microvoltmeter, Fig. 2, consists of four major sections: The input or signal conditioning circuit, the phase lock loop, an inhibit circuit, and a meter circuit. When tuned to any discrete frequency between 5 Hz and 600 kHz, the meter indicates the rectified average value of the signal. All noise and nonharmonically related signals are filtered out.

Rejection of Submultiple Frequencies. The synchronous rectifier will respond to any odd harmonic of its drive frequency in inverse proportion to its harmonic number. Thus, if an input signal is at a frequency of 5000 Hz with a level of 5 mV, and the drive frequency is at 1000 Hz, the output dc of the synchronous rectifier will pro-

Typical Applications of -hp- Model 3410A

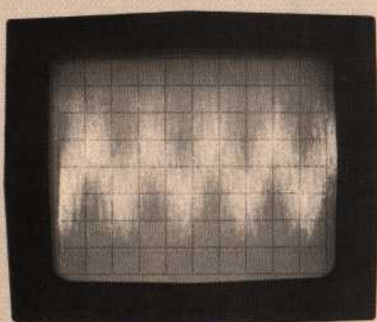
Measuring Frequency of Signals in Noise

A low-level signal in the microvolt region can easily be obscured by noise (a). Direct reading of frequency with a counter is not possible, even with a high-gain preamplifier. In addition, a counter may give erroneous readings if the amplitudes of the measured signals are fluctuating.

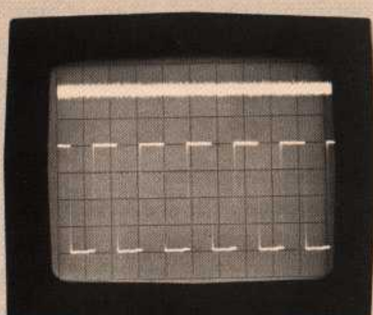
The ac microvoltmeter may be used as a preamplifier for a counter. When it locks to a signal, its local oscillator output (a 5 V square wave) is constant amplitude and at the input signal frequency (b).

It is very difficult to synchronize an oscilloscope to a low-level repetitive signal in noise. The ac microvoltmeter can be used as a sync source by locking it to the repetitive signal and applying its local oscillator output to the external sync terminals of the oscilloscope (c). Thus it is possible to see the repetitive nature of the noisy signal on the CRT.

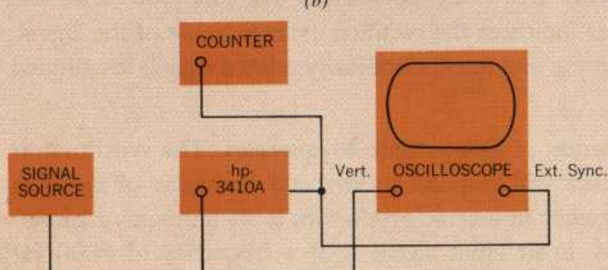
Because the *–hp–* Model 3410A is able to track a changing voltage and maintain voltage accuracy over a range of ±5% of the frequency range, it is possible to make measurements where the frequency of the input signal is changing. The input frequency can change as fast as 0.5% per second up to the 5% frequency range.



(a)



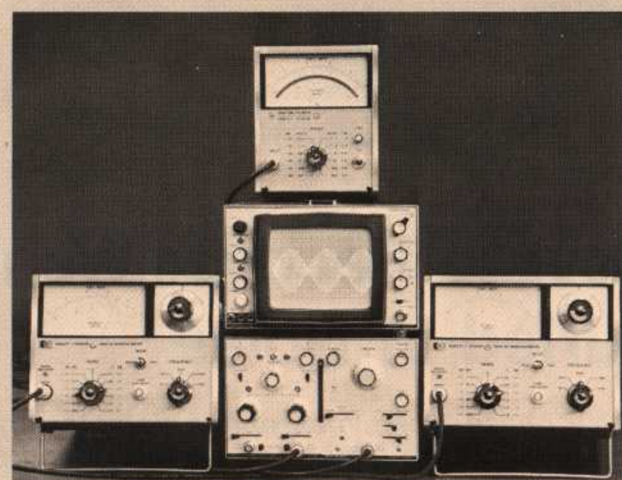
(b)



(c)

Separating Closely Spaced Coherent Signals

Two signals not related harmonically, but nearly the same amplitude and frequency can be measured independently. In this application, the microvoltmeter at the left is tuned to a 3000 Hz signal of 70 mV. At the right, the microvoltmeter is reading a 3100 Hz signal at a level of 90 mV. The sum of the two signals ($E = \sqrt{E_1^2 + E_2^2} = 114$ mV) is displayed on the true RMS voltmeter at the top. Displayed on the oscilloscope is the composite waveform illustrating the 100 Hz beat frequency.

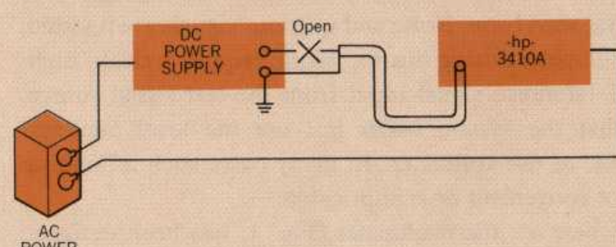


Measuring Power Supply Ripple

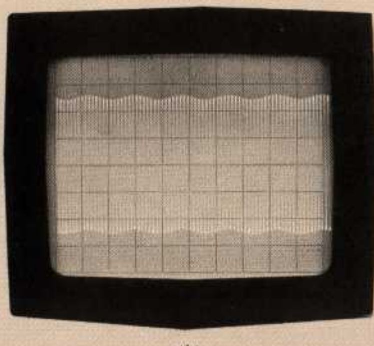
Ripple on a power supply of up to about 150 V dc can be measured with the *–hp–* Model 3410A Microvoltmeter. The instrument can measure microvolts at the usual ripple frequencies of 60, 120, 180 Hz and others.

Every system has some ground loop problem and it is difficult or impossible to predict ground loop voltage. One method of determining ground loop voltage is shown in the block diagram (a). By disconnecting the input lead, but keeping the ground connection on, the ground loop voltage may be measured as shown. This voltage is subtracted from the ripple voltage reading to obtain the true ripple voltage.

Ripple on the 1 V, 400 Hz source (b) is of the order of 1 mV.



(a)



(b)

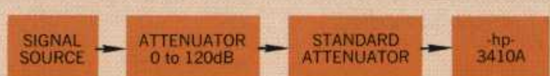
Measure Signal to Noise Ratio

Use an external variable attenuator to adjust the input level to the *–hp–* Model 3410A to be just sufficient to light the range indicator light. The range indicator light goes on when the postamplifier output is 10 dB or more above the amplitude required for a full-scale meter indication. The broadband input signal is then +10 ±1 dB above full scale for the particular range switch setting used. This procedure yields 1 dB resolution rather than 10 dB resolution provided by the range switch.

Next, the microvoltmeter is locked to the signal. The dB value of the signal as read on the meter minus 12 gives the signal-to-noise ratio.

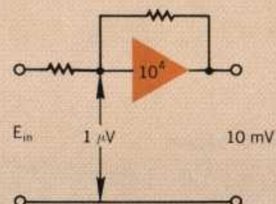
Calibrating Attenuators

Where an input power limitation restricts the input voltage to an attenuator, the output voltage at full attenuation will be low and likely buried in noise. For example, a coaxial attenuator such as the *–hp–* Model 355D has a total attenuation of 120 dB and a power limitation of 0.5 W. At 50 ohms, the maximum input signal is 5 volts, resulting in a 5 microvolt signal out at full attenuation. This 5 microvolt signal is smaller than the inherent input noise of broadband voltmeters. A typical attenuator calibration setup, uses the ac microvoltmeter to check deviation from the standard. The microvoltmeter can be used for calibration over a wide frequency range.

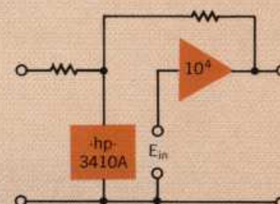


Measuring Summing Junction Voltages

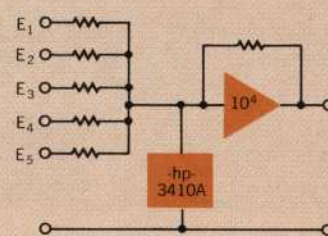
Voltage measurements made at the summing junction of a typical operational amplifier (a), require an instrument with high sensitivity and high input impedance to avoid loading. The new ac microvoltmeter is ideally suited for this measurement with its 3 μV full scale sensitivity and input impedance of 10 megohms. By reconnecting the operational amplifier (b), a loop gain plot can be obtained by plotting the magnitude of the return voltage as a function of frequency. Where a number of voltages of different frequencies are summed at the input (c), they may be measured independently provided their frequencies are sufficiently separated.



(a)



(b)



(c)

Providing AGC to a Signal Source

The dc recorder output of the *–hp–* Model 3410A AC Microvoltmeter provides a dc level proportional to the amplitude of the input signal at its tuned frequency. The dc may be fed back to the source as an AGC voltage.

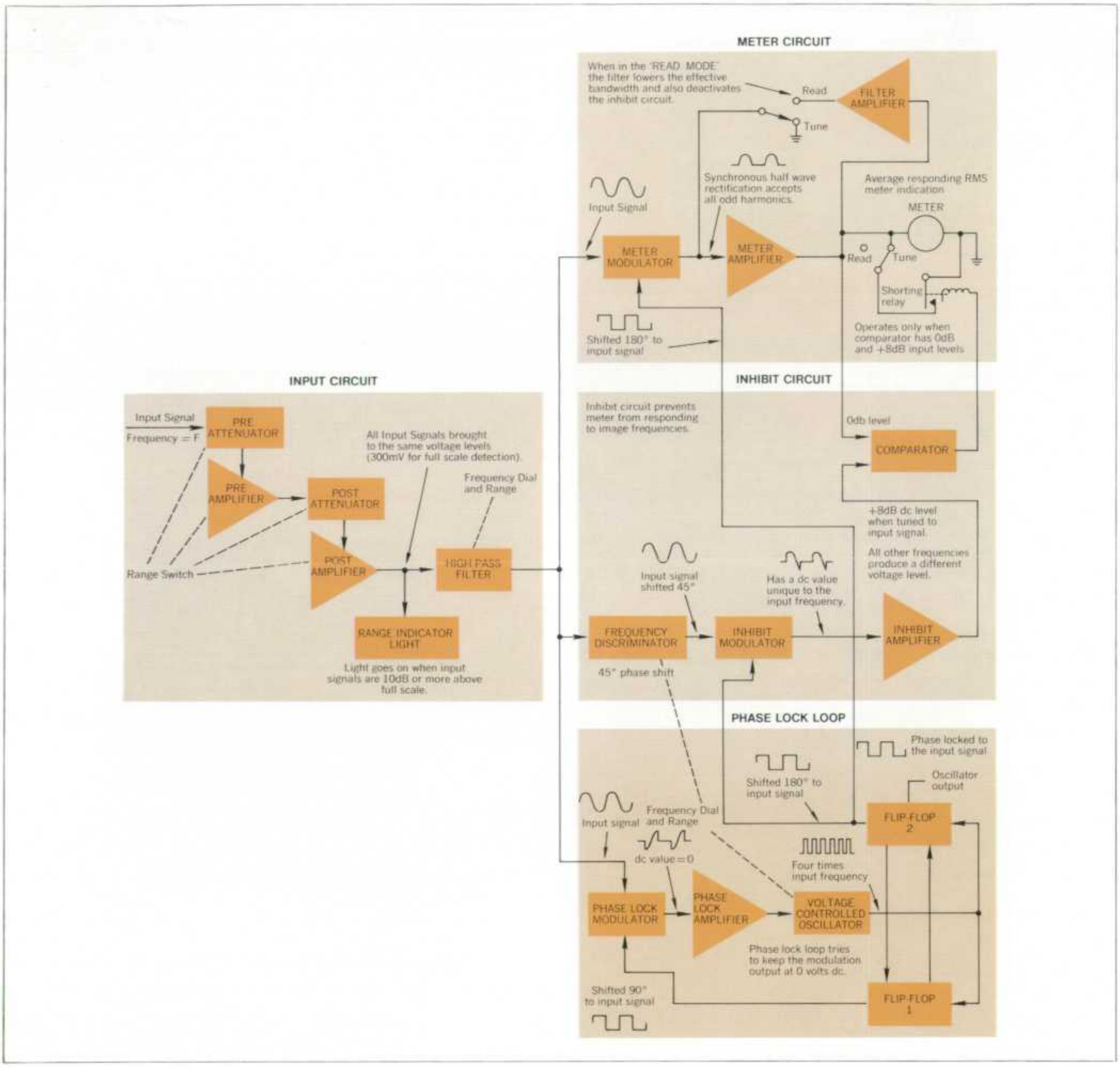


Fig. 2. *In the Model 3410A, the input signal is applied to the meter modulator which is driven by the square wave output of flip-flop 2 in phase with the input frequency. Thus the output from the meter modulator is a synchronous half-wave rectification of the input signal which rejects even, but not odd harmonics.*

duce a meter indication of 1 mV. This constitutes an erroneous response since there is no input signal at the tuned frequency of 1000 Hz. To prevent this type of error, the microvoltmeter has an inhibit circuit. The inhibit circuit consists of signal processing circuits similar to that of the metering circuit except that it is preceded by a tuned frequency discriminator. The output of the inhibit circuit and meter circuit are fed to a comparator which controls a reed relay connected across the meter. The reed relay shorts out the meter except when the input signal is at the tuned frequency of the local oscillator.

Response to Harmonics. The microvoltmeter does not respond to even harmonics of the signal to which it is

Raymond C. Hanson

Ray Hanson received his Bachelor of Science in Electrical Engineering from the University of California in Berkeley in 1959, and his Master of Science in EE from New York University in 1961. While attending NYU and after graduation, he worked at Bell Laboratories on voice frequency test equipment.

Ray joined the Hewlett-Packard Loveland Division in 1963 and began investigation of low-level detection systems out of which grew the Model 3410A AC Microvoltmeter. He became project leader on the 3410A.

locked. It responds to odd harmonics in proportion to their amplitude and phase relationship to the fundamental as do all average-responding voltmeters. If the instrument is tuned to a harmonic of some signal, it will respond to the odd multiples of that harmonic in proportion to the amplitude and phase relationship of these odd multiples to the tuned harmonic.

Phase Lock Oscillator. The purpose of the phase-lock oscillator is to develop a drive signal for the synchronous rectifier. This drive signal must be in phase with the input signal, while the nature of the phase-lock oscillator is to lock at 90 degree phase with respect to the input signal. Therefore, to drive the synchronous rectifier, the phase-lock oscillator must produce two signals phase shifted by 90 degrees. This is accomplished by operating the voltage-controlled oscillator at four times the frequency indicated on the frequency dial. The VCO provides a clock input for two flip-flops which are interconnected to divide by four and give two outputs with the proper 90 degree phase relationship.

The VCO is a free-running, multivibrator linearly tuned by means of voltage-controlled current sources. A low-pass filter in the phase-lock loop is changed each decade so that the frequency characteristic provides a capture range of 1% at full-scale frequency and full-scale meter deflection. Lock range is defined here to be the frequency range over which the oscillator will track a drifting signal while maintaining a sufficiently small phase error to maintain rated accuracy in the microvoltmeter meter reading. The lock range is ±5%.

Range Indicator. Selective voltmeters may give erroneous readings due to spurious signals overloading the input. To avoid this problem, a range indicator light tells the operator which range switch setting can be used with rated accuracy. It saves the operator time by indicating the range switch setting at which phase lock can be achieved, since the phase-lock loop has a finite dynamic range over which phase lock can be achieved. In the *-hp-* Model 3410A, this range is 20 dB above full-scale signal to —20 dB below full scale. For larger signals, the active filter in the phase-lock loop does not operate linearly. For smaller signals, the capture range is reduced to the point where phase lock cannot be achieved.

The range indicator is a broadband detector which responds to the average value of the composite input signal. It lights the range indicator light when the signal level is about 10 dB above full scale. If the input is a "clean" signal and the range switch is stepped down until the light comes on, the signal level will be between 10 dB and 20 dB above full scale and phase lock can be obtained. When phase lock is achieved by tuning, the meter will be pegged and it is necessary to up-range to obtain an on-scale indication. If spurious signals and/or noise exceeds the desired signal, then the meter indication may be less than full scale. If phase lock is not achieved, then the signal is too far below the noise to be recovered by the instrument.

Acknowledgment

James L. Crooks was responsible for the product design of the *-hp-* Model 3410A AC Microvoltmeter.

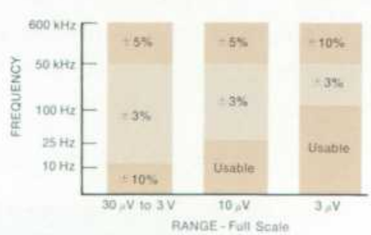
SPECIFICATIONS

-hp-

Model 3410A AC Microvoltmeter

VOLTAGE RANGE: 3 μV full scale to 3 V full scale (−110 dBm to +10 dBm).

VOLTAGE ACCURACY: (% of full scale).



FREQUENCY RANGE: 5 Hz to 600 kHz in decade ranges.

FREQUENCY DIAL ACCURACY: ±10% full scale (unlocked). Linearly tuned over each decade (5 decades).

PHASE LOCK RANGE: Pull in ±1% of full scale frequency.
Track ±5% of full scale frequency.
Tracking speed ½% of full scale/s.

MAXIMUM NOISE REJECTION: 20 dB rms above full scale on all ranges for rated accuracy.

INPUT IMPEDANCE: 10 MΩ shunted by 20 pF.

METER: Reads rms value of sine wave; voltage indication proportional to average value of applied wave. Linear voltage scale 0 to 1, 0 to 3; dB scale −12 to +2 dB (0 dB = mW into 600Ω).

LOCAL OSCILLATOR OUTPUT: 5 V square wave, 1000Ω output impedance.

RECORDER OUTPUT: 1 mA into 1000Ω, ±0.5 V adjustable offset level.

AC POWER: 115 or 230 V ±10%, 50 to 1000 Hz, 22 W.

PRICE: *-hp-* Model 3410A, $800.00

MANUFACTURING DIVISION: *-hp- Loveland Division*
P. O. Box 301
Loveland, Colorado 80537

Using a Precision ac Amplifier for Measurement and Calibration

Good gain accuracy and low distortion in a general purpose amplifier make it possible to extend the range of many instruments.

By Rex James

PRECISION AC AMPLIFIERS, that is with stable, calibrated amplification characteristics, can extend the useful range of many existing devices and instruments. A combination of accurate gain and low distortion makes a precision amplifier useful as a preamplifier in precision low-level ac measurements. Where the amplifier has a relatively high voltage output, it may be used as a post-amplifier for oscillators and function generators.

One such amplifier, the *-hp-* Model 463A Precision Amplifier, Fig. 1, has been designed to meet these requirements. The desired characteristics were achieved by a combination of several features. Good gain accuracy and low distortion is dependent upon the differential input amplifier. Since this is the summing junction of the overall feed-back loop, Fig. 2, it is designed to have good common-mode rejection to assure stable gain accuracy and low distortion.

Distortion is generally introduced in the output amplifier. A high-current capability with solid state devices with low distortion was accomplished using a push-pull emitter-follower stage. The high voltage characteristics (100 V rms) were accomplished by stacking high voltage transistors so that they share the output voltage.

Fig. 1. *Gain accuracies of better than ±0.001 dB of the -hp- Model 463A Precision Amplifier make it useful for precision low-level signal measurements, calibration and many other applications.*

The forward gain of the open loop amplifier is maintained at 10,000 with a stability of approximately 1.0%. Then the feedback ratio is set with the precision feedback divider to set the closed loop gain of the amplifier. This feedback ratio can take on values of 0.1, 0.01, and 0.001 giving closed loop gains of 10, 100, and 1000. As the closed loop gain increases, the "loop gain" decreases. Therefore the gain accuracy, distortion, and other characteristics are better on the X10 gain range. Of course, the feedback divider is the heart of the amplifier as far as determining the gain characteristics. For this reason, precision high frequency wire-wound resistors were used. Long-term stability of the feedback attenuator is shown in Fig. 3.

Low-Level Precision Measurements

Low distortion, high gain accuracy and high output levels inherent in a precision amplifier make it possible to enhance the specifications of many existing instruments. One of the most accurate ac voltage measuring devices is the indirectly heated thermocouple calibrated by the National Bureau of Standards. In this technique, the ac/dc transfer measurement (comparing the ac signal to be measured with a known dc signal) is a rather slow and tedious process even if an ac/dc transfer voltmeter is used.

A problem associated with this method is the low input impedance of the thermocouple — about 200 ohms per volt. This low input impedance can cause errors because of loading. By using the *-hp-* Model 463A as a preamplifier or buffer amplifier with the thermal transfer

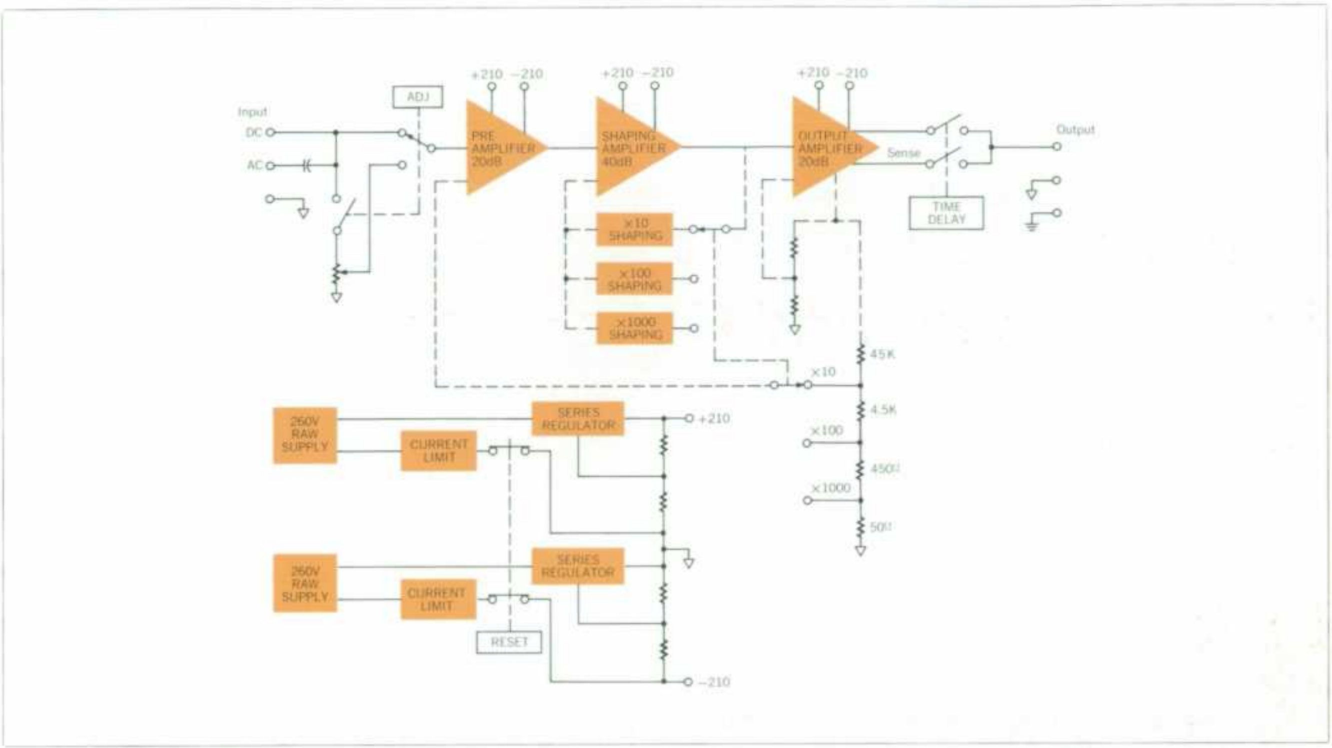


Fig. 2. *Fixed gains in the -hp- Model 463A are selected by changing amplifier feedback characteristics by means of a precision feedback attenuator. The attenuator is made up of wire-wound resistors designed for good high-frequency characteristics, low temperature coefficient and good long-term stability.*

voltmeter, a high input impedance can be achieved. Using the -hp- Model 463A with an NBS calibrated thermocouple in the configuration shown in Fig. 4, ac voltages from 1 mV to 10 V may be measured with accuracies over the frequency range shown in Table 1.

Since a precision amplifier normally has gain, it can be used in the measurement of signals that are below the normal minimum operating level of a thermocouple, that is, below about one-half volt.

Fast, but somewhat less accurate measurements of low level signals may be made using a precision amplifier as a preamplifier to extend the range of an ac differential voltmeter or an ac/dc converter-digital voltmeter combination. For example, using the -hp- Model 463A Precision Amplifier as a preamplifier with the -hp- Model 741B ac/dc Differential Voltmeter, allows the Model 741B to be used as low as 1.0 mV full scale. Combined accuracy at 1.0 mV is in the neighborhood of 0.4% over its frequency range.

Amplifying Oscillator Outputs

Since most solid-state oscillators do not have high-level output signals, an amplifier may be used as a post-amplifier to achieve high-level outputs. Because of the low distortion of the 463A, using it in this fashion introduces very little distortion. For instance, used with the 203A oscillator, an output of 100 V rms with less than 0.07% distortion can be achieved from 0.005 Hz to 10 kHz.

Because of the high-level output of an amplifier such as the -hp- Model 463A, it is useful in bridge measurements. The sensitivity requirement on the null detector is decreased by having up to 100 V rms available.

Since the -hp- Model 463A Precision Amplifier is dc coupled, it can be used with a low frequency oscillator or function generator to provide power for a servo loop.

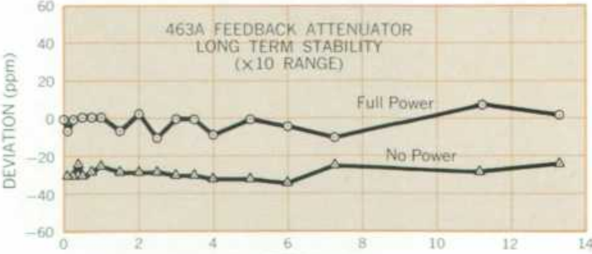


Fig. 3. *Long-term stability of the feedback attenuator varies no more than ±10 ppm over a period of one year.*

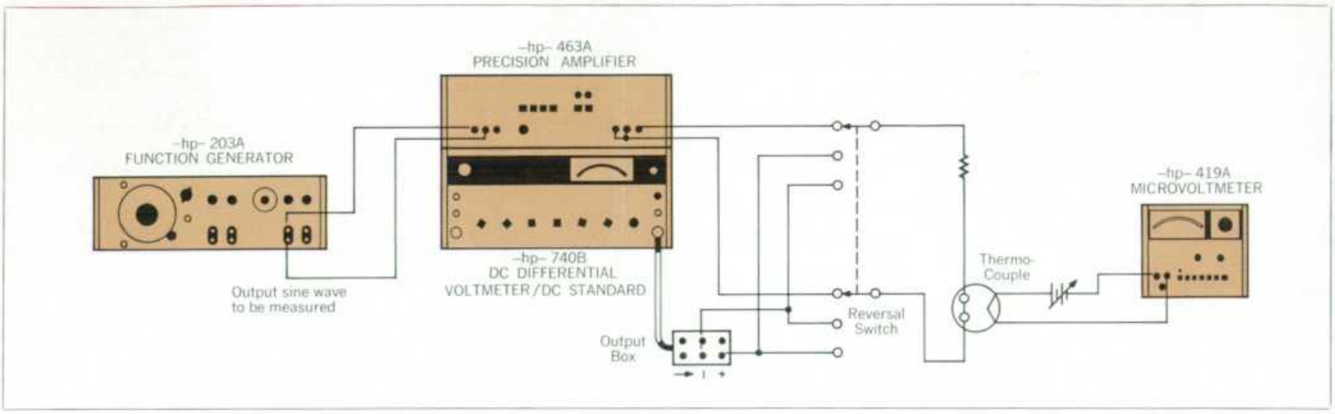


Fig. 4. *Measuring the output of an oscillator using a precision amplifier as a buffer with an indirectly-heated thermocouple.*

Its low frequency response makes it applicable for amplification of very low frequency signals such as in biomedical experiments and geophysical measurements.

Calibrating Voltmeters and Attenuators

One method of generating accurate signals for calibration is shown in Fig. 5. Output A is for low-level signals; output B is for high-level signals. If a 1 mV signal is needed at A, the gain of the amplifier should be set to 60 dB (x1000) and 1 V measured at the amplifier output. Since some measuring instruments are degraded in accuracy at very low levels, it is more desirable to accurately amplify the unknown and measure it at a higher level. Accuracy of the output at A is determined by the accuracy of the measuring instrument plus the accuracy of the amplifier. Noise generated in the amplifier and any distortion introduced also affect accuracy.

Output B furnishes higher-level signals and is limited by the output capabilities of the amplifier. The gain accuracy of the amplifier is not a factor in the accuracy of this signal, but noise and distortion is a factor.

The instrument used to measure this calibration voltage may take a number of forms. The indirectly heated thermocouple previously mentioned as a low-level voltage measuring device can be used. Another technique uses an ac differential voltmeter whose accuracy approaches that of the thermal transfer technique, and is much more convenient to use. The ac/dc converter used with a digital voltmeter is probably the most convenient method.

Accuracy

Low-level signal measurements and precision calibration voltages are limited in accuracy to the gain accuracy of the amplifier. Also, the noise and distortion of the amplifier can affect the measurement accuracy. For small signal to noise ratios ($<1/10$), it can be shown that the percent error introduced into average reading and true rms reading instruments by Gaussian noise is:

$$\%\ \text{Error}_{\text{AVG}} \cong 25\left(\frac{\sigma}{e_s}\right)^2$$

$$\%\ \text{Error}_{\text{RMS}} \cong 50\left(\frac{\sigma}{e_s}\right)^2$$

Table I
Combined Accuracy of -hp- Model 463A Precision Amplifier and an NBS Calibrated Thermocouple

463A Gain	Measurement Level	±% Reading (ac-dc difference) 10 Hz – 10 kHz	10 kHz – 20 kHz	20 kHz – 50 kHz	50 kHz – 100 kHz
x 10	10 V	0.02	0.12	0.12	0.30
x 10	1 V	0.015	0.11	0.11	0.15
x 10	100 mV	0.026	0.12	0.12	0.16
x 100	10 mV	0.12	0.12	1.0	1.1
x 1000	1 mV	0.43	0.43	3.1	3.2

Rex James

Rex is a graduate of Brigham Young University with the degree of Bachelor of Engineering Sciences, a five-year course. He is studying for his MS degree at Colorado State University. After graduation from Brigham Young in 1963, Rex joined the research and development laboratory at Loveland. He worked on the *-hp-* Model 741A AC-DC Differential Voltmeter, then had project responsibility for the *-hp-* Model 463A Precision Amplifier. He is presently working on digital instrumentation. Rex is a member of Eta Kappa Nu and Tau Beta Pi.

SPECIFICATIONS

–hp– Model 463A Precision Amplifier

FIXED GAIN (DC Coupled)

× 10 Range

Accuracy: DC to 10 Hz, <±0.03%
10 Hz to 10 kHz, <±0.01%
10 kHz to 100 kHz, <±0.1%

DC Linearity: ±0.01%

Distortion (100 V Output, Full Load): 10 Hz to 10 kHz, <0.01%
10 kHz to 100 kHz, <0.1%

× 100 Range

Accuracy: DC to 10 Hz, <±0.2%
10 Hz to 20 kHz, <±0.1%
20 kHz to 100 kHz, <±1.0%

DC Linearity: ±0.03%

Distortion (100 V Output, Full Load): 10 Hz to 10 kHz, <0.03%
10 kHz to 100 kHz, <0.1%

× 1000 Range

Accuracy: DC to 10 Hz, <±0.3%
10 Hz to 20 kHz, <±0.3%
20 kHz to 100 kHz, <±3.0%

DC Linearity: ±0.1%

Distortion (100 V Output, Full Load): 10 Hz to 10 kHz, <0.1%
10 kHz to 100 kHz, <0.5%

FIXED GAIN (AC Coupled)

Identical to dc coupled except coupling capacitor causes a 0.01% error (25 Hz) to a 3-dB error (0.35 Hz).

ADJUSTABLE GAIN (AC or DC Coupled)

Gain may be adjusted from 0 to 100% of the fixed gain range.

Distortion and dc linearity characteristics identical with fixed gain range.

INPUT CHARACTERISTICS

Input Impedance:
Fixed gain: 1 MΩ (±5%), <35 pF
Adjustable gain: 50 kΩ, <200 pF

Maximum Input Voltage: Protected to ±150 volts. AC coupling capacitor ±500 volts peak.

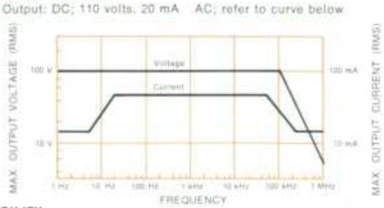
Noise (rms referred to input):

GAIN RANGE	<1 k SOURCE	>1 k SOURCE*
× 10	1.5 mV	1.5 mV
× 100	150 μV	300 μV
× 1000	50 μV	200 μV

* With input shielded.

OUTPUT CHARACTERISTICS

Maximum Output: DC; 110 volts, 20 mA AC; refer to curve below



LOAD CAPABILITY

Maximum Output Power: 5 watts continuous

Current Limit (Nominal): <20 Hz, 30 mA peak
>20 Hz, 90 mA peak

Minimum Resistance, All Ranges: 100Ω

Maximum Capacitance: Capacitance drive capability of 463A increased by adding a resistor in series with the output as indicated below.

Gain Range	Series Resistance	Maximum Capacitance
x 10	0 600Ω	300 pF No Limit
x 100	0 50Ω	1000 pF No Limit
x 1000	0 50Ω	5000 pF No Limit

OUTPUT IMPEDANCE

Gain Range	Output Impedance (Ohms)	
	DC to 10 kHz	10 kHz to 100 kHz
x 10	0.05	0.5
x 100	0.2	2
x 1000	2	20

PHASE SHIFT (Fixed Gain)

Gain Range	Phase Shift	
	<1 kHz	>1 kHz
x 10	0.1	$0.1 + 7 \frac{f}{10^5}$
x 100	0.2	$0.2 + 20 \frac{f}{10^5}$
x 1000	1.0	$1.0 + 50 \frac{f}{10^5}$

SQUARE WAVE RESPONSE (Fixed Gain)

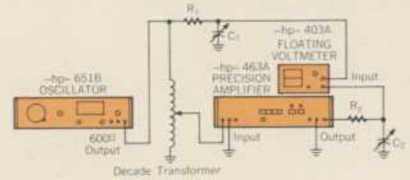
x 10: 40 V p-p, 0.5 μs rise time
x 100: 80 V p-p, 1 μs rise time
x 1000: 200 V p-p, 2 μs rise time

MANUFACTURING DIVISION: –hp– Loveland Division
P. O. Box 301
Loveland, Colorado 80537

How the -hp- Model 463A Amplifier is Calibrated

One of the problems associated with building an amplifier with the specifications of the 463A is checking the specifications. Three of the hardest measurements to make are the gain accuracy, the gain accuracy with frequency or frequency response and the low distortion measurements. A method used to check the basic 1 kHz gain accuracy *(a)*, uses an autotransformer of the inductive divider type or decade transformer, as they are sometimes called. The decade transformer

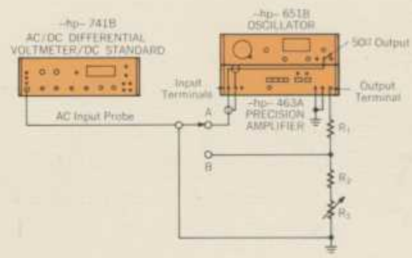
(a)



used has terminal linearity specified at ±½ ppm at 1 kHz. By adjusting this decade transformer for a null reading on the null indicator (*-hp-* 403A) in conjunction with the phase shift compensators of R1, C1 or R2, C2, the gain of the amplifier can be read accurately from the ratio indicated on the decade transformer.

A method used to check the frequency response is shown at *(b)*.

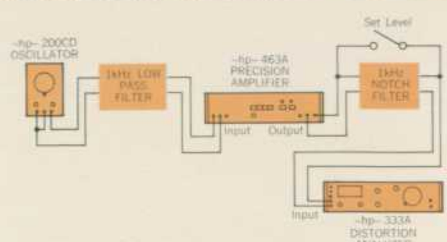
(b)



Assuming the amplifier has been calibrated for good gain accuracy at 1 kHz, the resistive divider of R1, R2 and R3 can be adjusted so that the voltage read at point A and point B is exactly the same at 1 kHz. This is read to 0.004% resolution on a 741B Differential Voltmeter. By using metal film resistors for the resistive divider and care in constructing the divider, its frequency response can be guaranteed to within approximately 0.01% at 100 kHz. Since the 741B Differential Voltmeter is checking the same level at points A and B, its accuracy does not enter into the measurement. Its only function is to provide the sensitivity and stability necessary to read in the area of 0.01% error. Therefore, after the resistive divider has been set at 1 kHz, the oscillator can be swept over the frequency range of operation and the error in gain at these various frequencies can be read by the difference in the 741B reading at points A and B.

For distortion measurements at 1 kHz *(c)*, a good low distortion oscillator such as the *–hp–* Model 200CD can be used with a low-pass or band-pass filter to filter out the harmonics generated within the oscillator. This produces a low distortion signal for the input of the ampli-

(c)



fier. To measure the output distortion, the output signal is fed first into a 1 kHz notch filter. By utilizing this notch filter to reject the fundamental signal, we can increase the sensitivity of the Distortion Analyzer because of the level of the output signal of the amplifier. This method allows measurement of distortion 85 dB down below the fundamental.

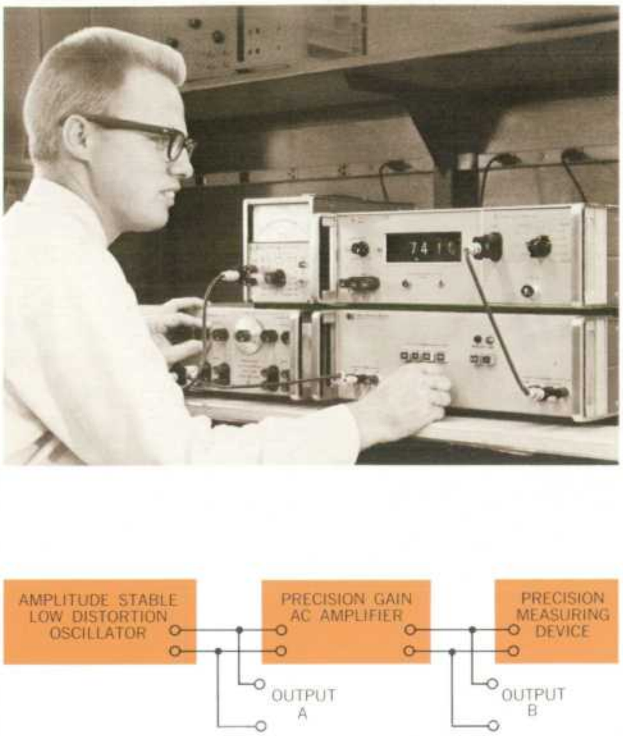


Fig. 5. *Generating precision high and low level calibration voltages. In the photo, a digital voltmeter is being used as the precision measuring instrument.*

where σ is the rms value of the Gaussian noise and e_s is the rms value of the noiseless signal.

The percent error introduced by distortion in average reading and true rms instruments (where total harmonic distortion relative to fundamental is less than 1%) can be shown to be:

$$100\left[\frac{1}{3}\left(\frac{e_3}{e_1}\right)+\frac{1}{5}\left(\frac{e_5}{e_1}\right)+\cdots\right] < \%\ \text{Error}_{AVG} <$$

$$100\left[\frac{1}{3}\left(\frac{e_3}{e_1}\right)+\frac{1}{5}\left(\frac{e_5}{e_1}\right)+\cdots + \frac{1}{2}\left(\frac{e_2}{e_1}+\frac{e_4}{e_1}+\cdots\right)^2\right]$$

$$\%\ \text{Error}_{RMS} \cong \frac{100}{2}\left[\left(\frac{e_2}{e_1}\right)^2+\left(\frac{e_3}{e_1}\right)^2+\left(\frac{e_4}{e_1}\right)^2+\cdots\right]$$

where $\frac{e_3}{e_1}$ is the ratio of the 3rd harmonic signal to the fundamental signal, etc. For instance, if the following measurements were made with a wave analyzer:

Harmonic	dB Below Fundamental	e_n/e_1
2	60	0.001
3	66	0.0005
4	80	0.0001
5	70	0.0003
6	100	0.00001
7	90	0.00003

the worst possible errors introduced would be:

$$\%\ \text{Error}_{AVG} = 100\left[\frac{0.0005}{3}+\frac{0.0003}{5}+\frac{0.00003}{7} + \frac{1}{2}(0.001+0.0001+0.00001)^2\right]$$

$$= 100\left[0.000231+\frac{1}{2}(0.00001)\right]$$

$$= 0.024\%$$

$$\%\ \text{Error}_{RMS} = \frac{100}{2}\left[(0.001)^2+(0.0005)^2+(0.0001)^2 + (0.0003)^2+(0.00001)^2+(0.00003)^2\right]$$

$$= 0.000068\%$$

As can be seen, there can be an appreciable error introduced into an average reading instrument. Also, it should be noted that in the case of the average reading instruments that usually the even harmonic contribution will be negligible with respect to the odd harmonic contribution.

Acknowledgments

The mechanical and product design of the 463A was led by Robert B. Moomaw with assistance by Billy E. Thayer. Front panel ideas were contributed by Roger L. Lee. Electrical design was by the undersigned under the helpful direction of William G. Smith and Donald F. Schultz. ■

HEWLETT-PACKARD JOURNAL **MAY 1967** *Volume 18 • Number 9*

TECHNICAL INFORMATION FROM THE LABORATORIES OF THE HEWLETT-PACKARD COMPANY PUBLISHED AT 1501 PAGE MILL ROAD, PALO ALTO, CALIFORNIA 94304
Editorial Staff: F. J. BURKHARD, R. P. DOLAN, L. D. SHERGALIS, R. H. SNYDER Art Director: R. A. ERICKSON