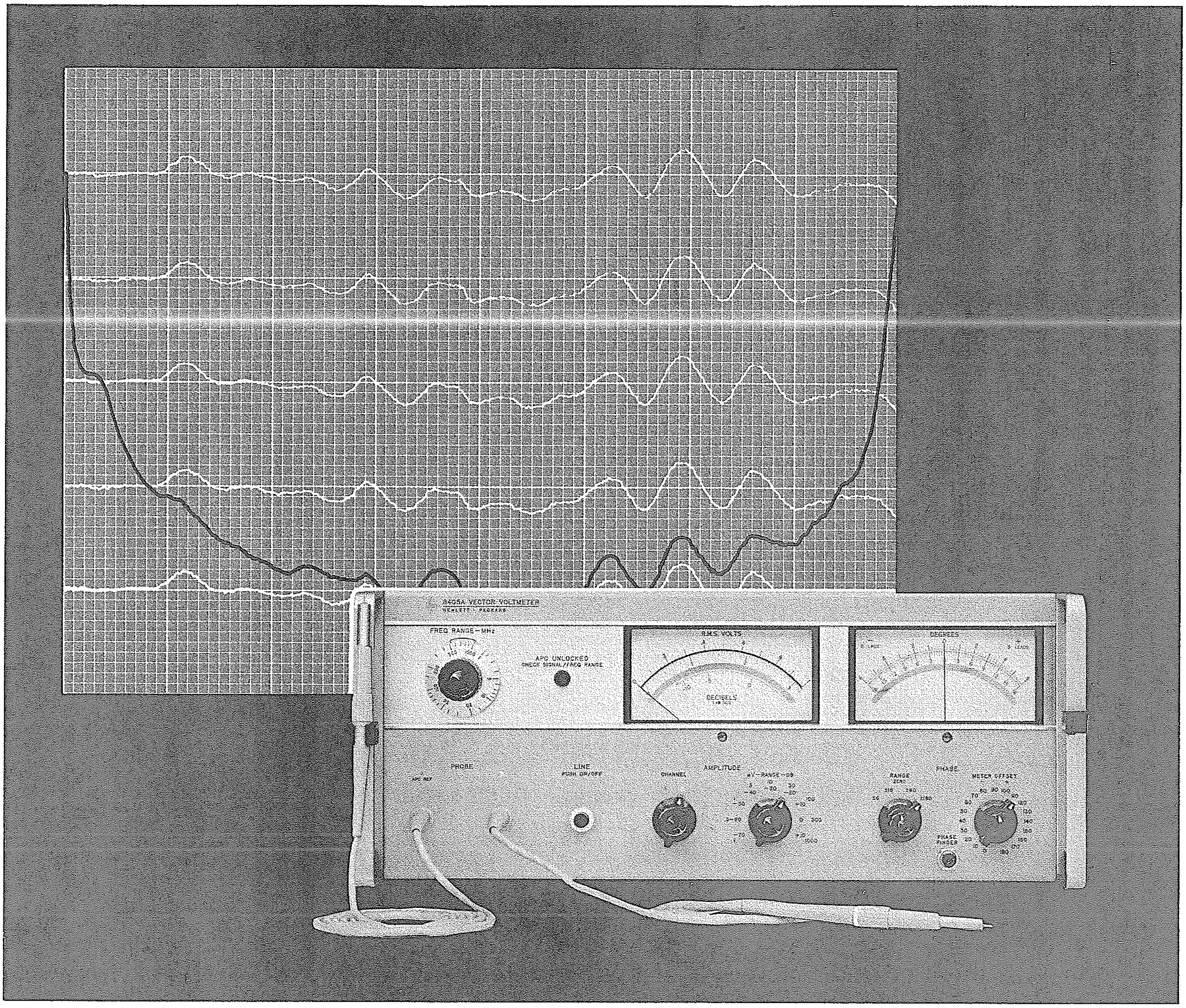
APPLICATION NOTE 77-4

Swept-Frequency Group Delay Measurements



HEWLETT PACKARD

APPLICATION NOTE 77-4

SWEPT-FREQUENCY
GROUP DELAY MEASUREMENTS

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HEWLETT PACKARD

SWEPT-FREQUENCY GROUP DELAY MEASUREMENTS

WHAT IS GROUP DELAY?

An important characteristic of any transmission device is its ability to transmit a signal with minimum distortion. Distortion results when the phase shift through a device is a nonlinear function of frequency. A convenient indication of nonlinear phase shift is group delay. If the phase shift through a device is a linear function of frequency, the group delay ($-d\theta/d\omega$ see Figure 1) will remain constant and a signal can be transmitted without distortion.

Knowing the group delay over the passbands of filters, amplifiers, mixers, cables and all other transmission devices is important when evaluating the performance of these components.

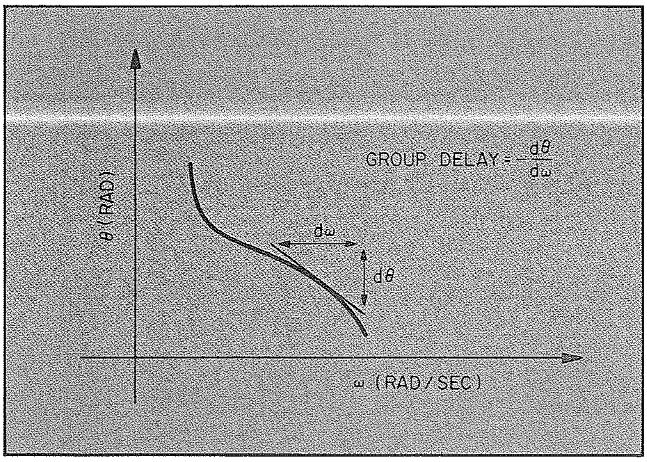


Figure 1. Phase vs. Frequency through a Transmission Device

HOW IS GROUP DELAY MEASURED?

Single-frequency measurements of group delay can be made by slightly changing the frequency of a CW signal which passes through the test device and noting the corresponding change in phase. A simple calculation ($\Delta\theta/\Delta\omega$) then gives the average group delay over the range over which the frequency was changed. However, measurements of this type need to be repeated several times in order to determine the group delay across a band of frequencies.

The Hewlett-Packard Model 8405A Vector Voltmeter can be used to make swept-frequency measurements of group delay quickly and accurately over a range of frequency from 1 MHz to 18 GHz. The method consists of first amplitude-modulating a CW signal, transmitting it through the test device, and then measuring the phase shift of the envelope (see Figure 2). The group delay of the test device at the CW frequency will then be directly proportional to the envelope phase shift. The relationship of group delay to the phase shift and the modulation frequency is given by Equation (1).

$$t_d = \frac{\phi_e}{f_m \times 360°}, \text{ (See Appendix for derivation)} \qquad (1)$$

where

ϕ_e = envelope phase shift in degrees

f_m = modulation frequency in Hz

t_d = group delay in seconds .

Since phase measurements are made at only one frequency (f_m), accurate group delay measurements can be made while RF or microwave source is being swept between any desired frequencies from 1 MHz through 18 GHz. The only limitations are the ability to modulate the signal and to detect the envelope after it passes through the test device.

WHAT MODULATION FREQUENCY SHOULD BE USED?

Certain trade-offs need to be considered when choosing a modulation frequency. The modulation frequency is a measure of the smallest bandwidth within which fluctuations in delay can still be measured; the period of the modulation frequency is equal to the largest group delay measurable. Thus, ideally the smaller the modulation frequency, the larger and more accurate a measurement can be made. However, it is apparent from Equation (1) that the smaller the modulation frequency, the smaller the resulting phase shift will be for a group delay measurement. In other words, resolution will be decreased when the modulation frequency is decreased.

For small delay measurements, modulation frequencies between 1 and 10 MHz are ideally suited. In fact, if a frequency of 2.778 MHz is chosen, group delay can be read directly in nanoseconds per degree of phase shift. For large group delay measurements it is desirable to use a 20-kHz modulation frequency. This can be done by by-passing the RF section of the vector voltmeter and using only the 20 kHz IF phase meter. Other convenient modulation frequencies are given in Table I.

Table I. Group Delay Calibration Factor

Calibration Factor t_d/ϕ_e	Modulation Frequency f_m (MHz)
0.5	5.555
1.0	2.778
1.5	1.852
2.0	1.389
139.0	0.020

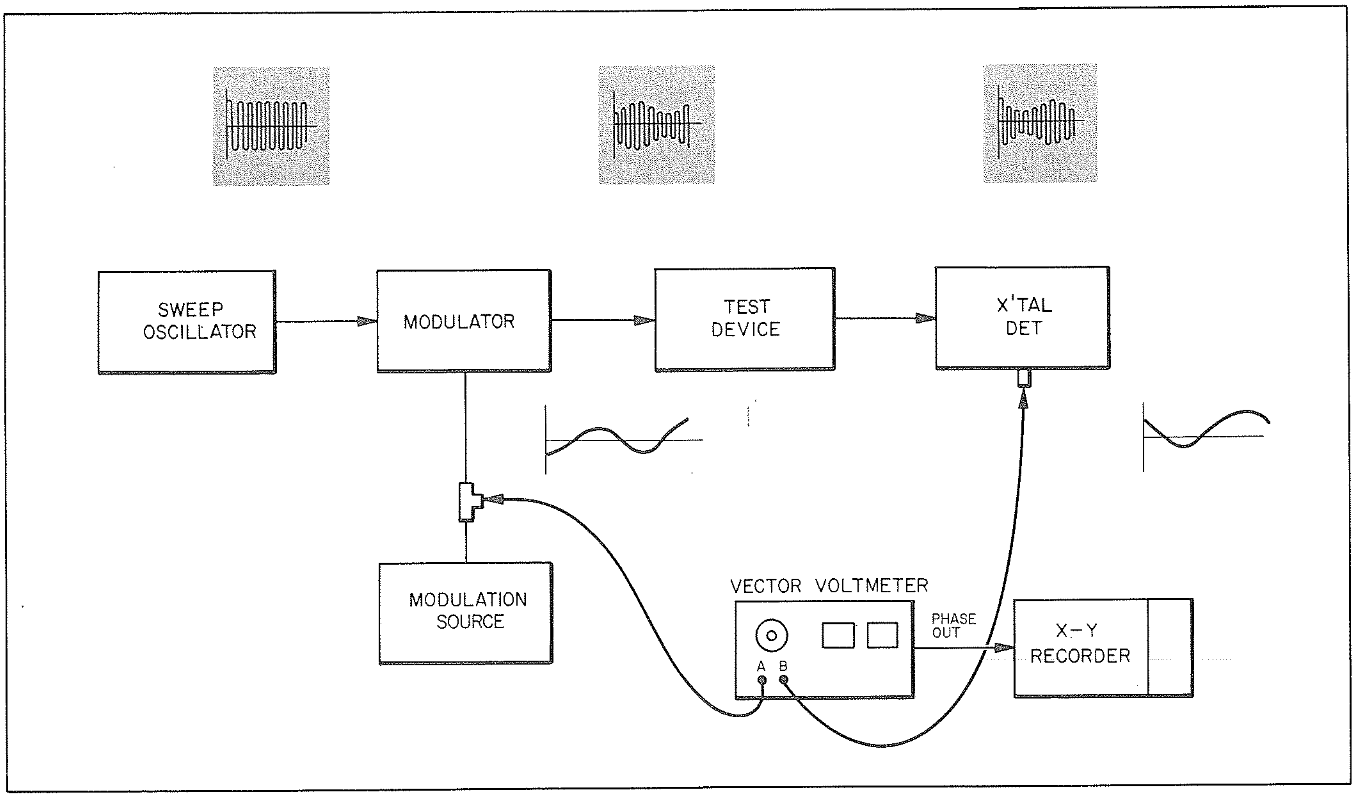


Figure 2. Block Diagram of Setup for Swept-Frequency Group Delay Measurement

HOW IS THE MEASUREMENT MADE?

Test setups for making swept-frequency group delay measurements using the 8405A are shown in Figures 3 and 4. The setup in Figure 3 is used when the modulation frequency is greater than 1 MHz. This setup is shown for coax measurements, but measurements can also be made for waveguide test devices by using appropriate waveguide components. The setup in Figure 4 is used when the modulation frequency is 20 kHz.

In both setups either an X-Y recorder or an oscilloscope can be used as the display unit. In general, an X-Y recorder is used when a permanent record of total group delay is desired. Figure 5 shows an X-Y recording trace of the total delay of an 8 to 10 GHz bandpass filter. An oscilloscope is generally used to see relative changes in delay across a frequency band. In particular, an oscilloscope display is helpful when tuning a test device for best transmission characteristics. Figures 6, 7, and 8 show the different stages in alignment of an FM receiver passband filter. The amplitude characteristics of the filter are also shown by connecting the 8405A amplitude recorder output to the oscilloscope.

The RF signal can be modulated in several ways. HP 8730-series PIN modulators cover the frequency range from 800 MHz through 12.4 GHz, and the HP 33001A adsorption modulator extends this range to 18 GHz. The B Model 8690-series RF plug-in units are equipped with PIN modulators. A convenient means of modulating a signal below 500 MHz is with an HP 10514A Mixer as shown in Figure 4.

1. The recommended test procedure using a modulation frequency greater than 1 MHz is as follows:

a. Set up equipment as shown in Figure 3 without the test device and turn on all equipment.

b. Set modulation source for desired modulation frequency.

c. Bracket the modulation frequency with the 8405A FREQ. RANGE switch.

d. Adjust start and stop sweep controls on sweep oscillator for desired frequency range; SWEEP SELECTOR for trigger and SWEEP TIME between 10 and 100 seconds.

e. Adjust RF power output and modulation signal amplitude for maximum undistorted sine wave detected by Channel B. This can easily be done by observing the 8405A Channel B 20-kHz IF output on an oscilloscope. (Typical values are 50 mW RF power and 1 volt modulation signal for low attenuation passive test devices.)

NOTE

> A larger signal with less distortion can be obtained by using a HP 8403A Modulator to drive the PIN modulator.

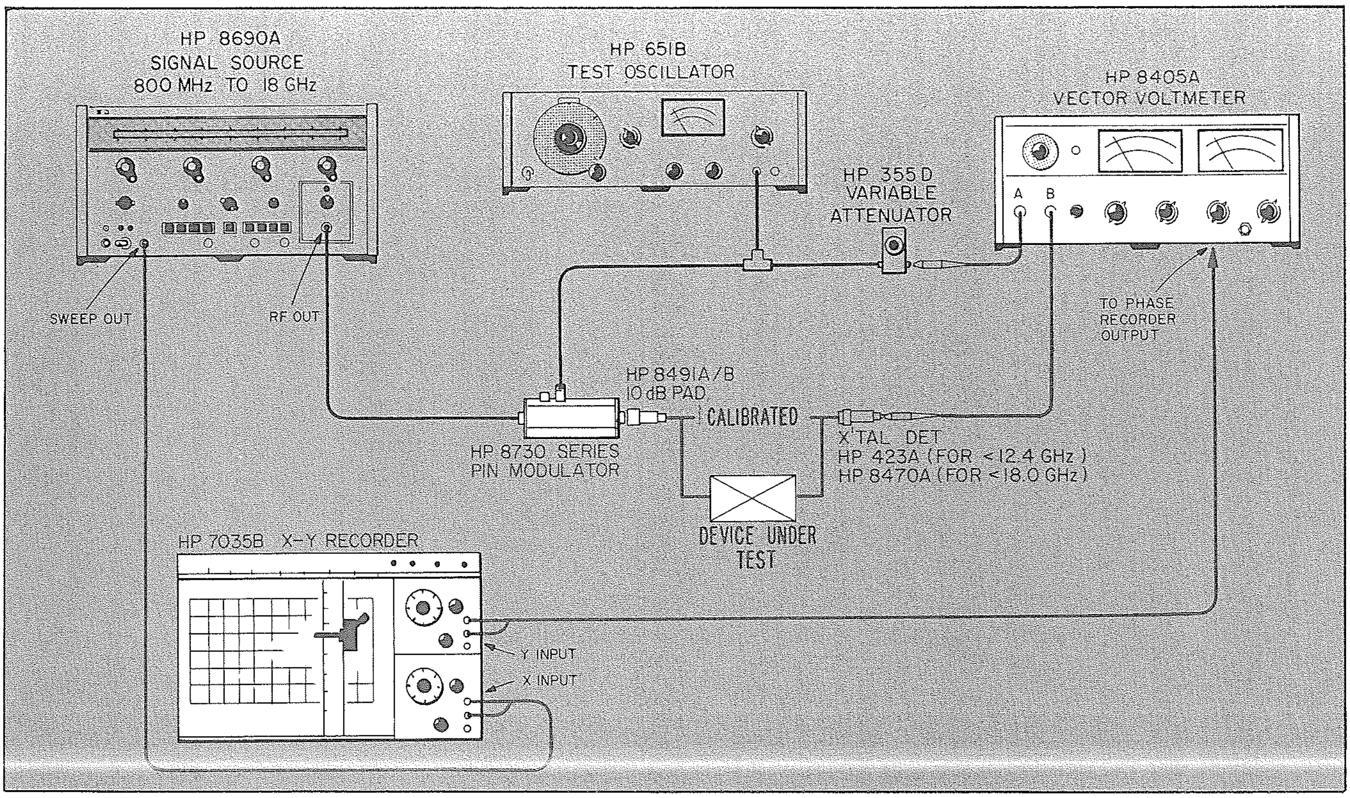


Figure 3. Setup for Making Swept-Frequency Group Delay Measurements

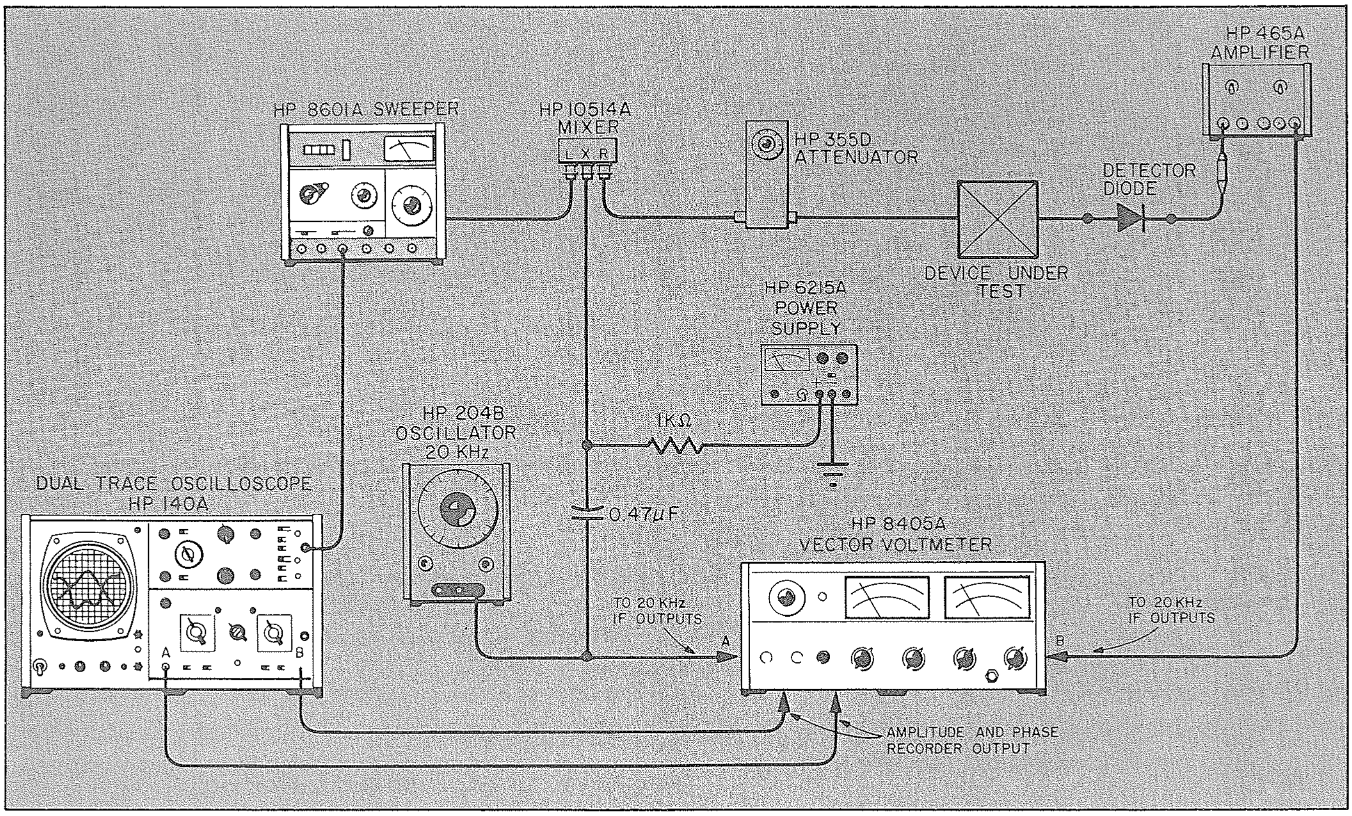


Figure 4. Test Setup for Making Swept-Frequency Group Delay Measurements
Using a 20-kHz Modulation Frequency

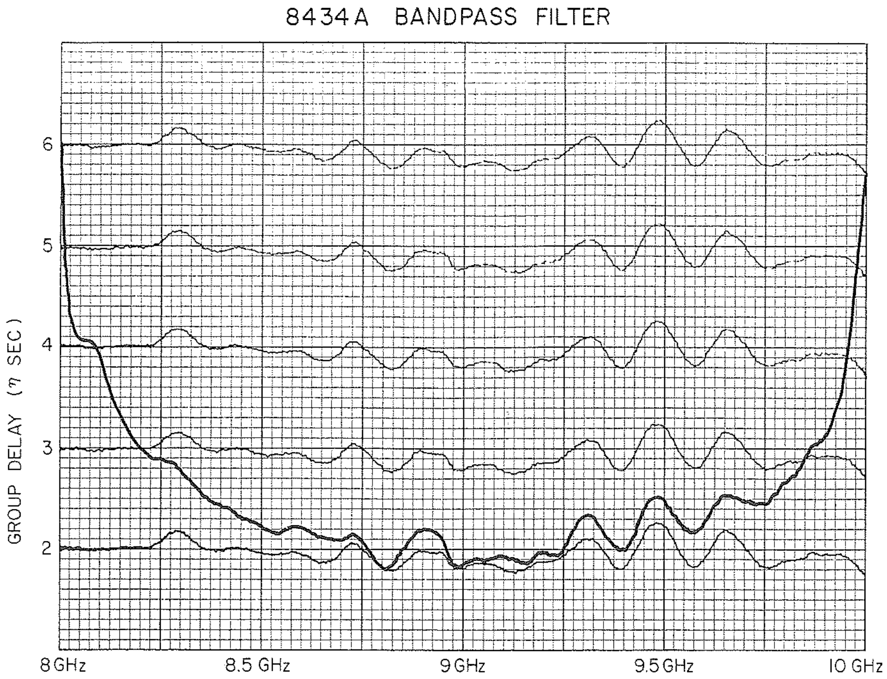


Figure 5. Group Delay of HP 8434A Bandpass Filter

f. Adjust the attenuation in the 355D Variable Attenuator so that Channels A and B read within 10 dB of each other on the 8405A Vector Voltmeter.

NOTE

> Phase accuracy of the 8405A is best when signal levels are approximately the same. If the test device has greater than 10 dB of gain or attenuation the 355D should be adjusted so that the difference in signal levels at Channels A and B is a minimum before and after calibration.

g. Calibrate X-Y recorder sweep width using sweep oscillator manual sweep, and calibrate phase resolution using the 8405A PHASE ZERO and METER OFFSET switch.

h. Use sweep oscillator to drive X-Y recorder and draw calibration grid lines for different settings of PHASE ZERO. (When the test device is inserted after calibration, group delay will be indicated by a more negative phase shift.)

i. Insert test device and make swept-frequency group delay measurement.

2. The recommended test procedure using a 20-kHz modulation frequency is as follows:

a. Remove the top cover of the 8405A and remove circuit boards A3, A4, and A10 so that the RF circuitry is disabled.

b. Set up equipment as shown in Figure 4 and turn on all instruments.

c. Adjust 204B for a 20-kHz modulation frequency and set power supply for proper mixer bias level.

d. Adjust 355D attenuator for desired incident signal level on test device and adjust 465A amplifier so that the Channel A and B of the vector voltmeter have about the same reading.

NOTE

> The detector diode, oscilloscope probe and amplifier act as a high impedance detector so that the device under test will not be loaded and thus causing a change in its characteristics.

e. Set sweeper for fast sweep and observe group delay on scope.

f. Figures 6, 7, and 8 show a typical oscilloscope display of group delay. The amplitude characteristics are also displayed by connecting the amplitude recorder output of the vector voltmeter to the oscilloscope.

ACCURACY CONSIDERATIONS:

Possible sources of error and means by which they can be minimized are:

1. Modulation Frequency.

Since the calibration factor is determined by the modulation frequency, it is important to know the modulation frequency quite accurately. A counter can effectively eliminate this source of error.

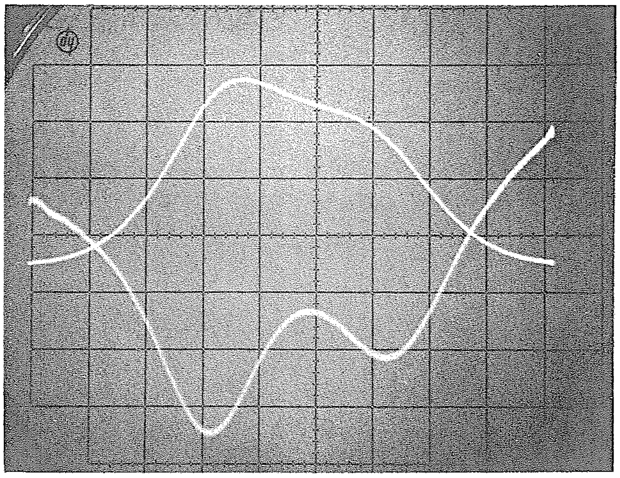


Figure 6. Top Trace: Amplitude Response of IF Passband of FM Receiver. Bottom Trace: Group Delay. Note that filter in receiver is out of alignment.

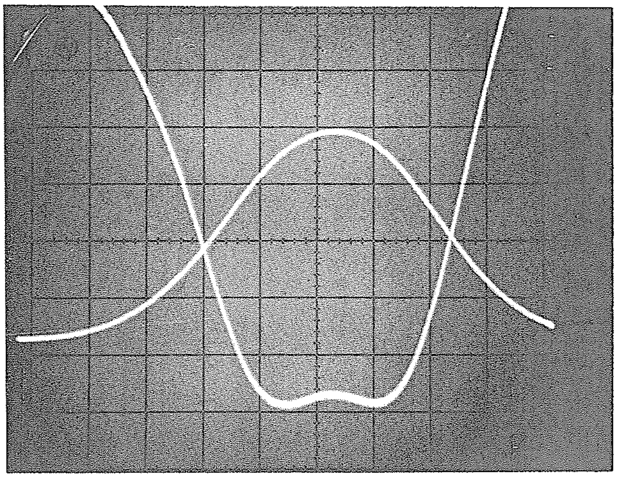


Figure 7. Same as Figure 6 but filter is adjusted for optimum amplitude response, although phase, or group delay, is still slightly nonlinear.

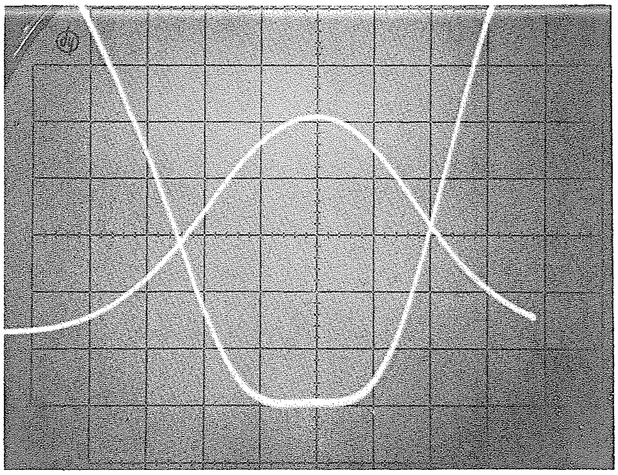


Figure 8. Same as Figure 6 and 7 with IF strip properly adjusted for flat group delay over passband.

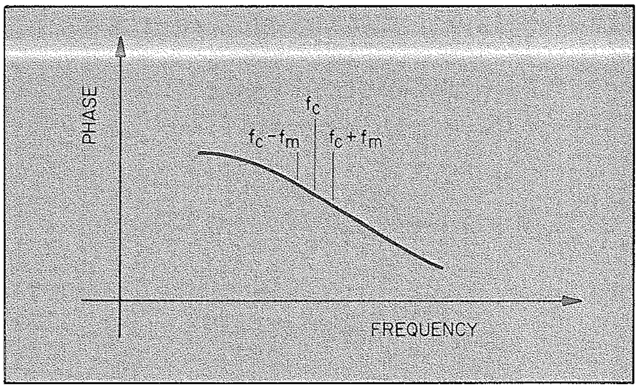


Figure 9. Relative Positions of Carrier and Sidebands of Modulation Signal
(f_c = carrier frequency;
f_m = modulation frequency)

2. Mismatch.

Since neither the source nor the crystal detectors are exactly 50 ohms, an error from mismatch ambiguities will result. This error is minimized by the use of a low SWR 10-dB pad following the PIN modulator. Leveling the sweep oscillator will also improve the source match.

3. Separation of Sidebands.

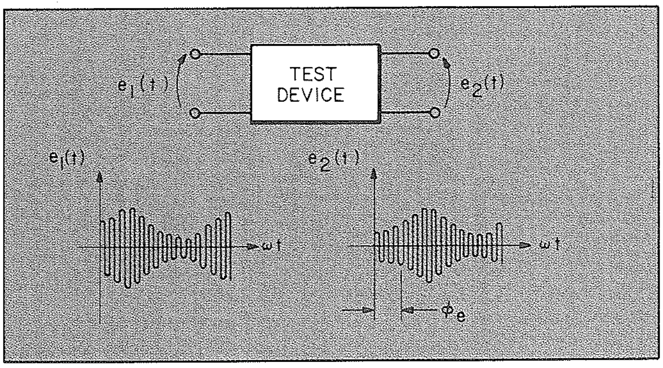
The separation of the sidebands that make up the modulation envelope is a measure of the smallest bandwidth within which fluctuations in group delay can still be measured. The smaller the modulation frequency the closer the sidebands will be to the carrier frequency (see Figure 9). By selecting a low modulation frequency which will still give the necessary resolution, this error can normally be neglected.

4. Distortion of Modulation Envelope.

If the detected envelope is distorted, then a small error in the measurement of phase shift will result. By observing the 8405A 20-kHz IF outputs on an oscilloscope and adjusting the modulation amplitude for a true sine wave, this source of error can effectively be eliminated. If a HP 8403A Modulator is used to drive the PIN Modulator, a low distortion envelope with greater amplitude can be obtained.

APPENDIX

Derivation of formula for group delay:



$$e_1(t) = E_1(1 + M \sin \omega_m t) \sin \omega_c t$$

where

M = modulation index

ω_m = modulation frequency

ω_c = carrier frequency

$$e_1(t) = E_1 \sin \omega_c t + \frac{ME_1}{2} \cos (\omega_c - \omega_m)t$$

$$- \frac{ME_1}{2} \cos (\omega_c + \omega_m)t \quad .$$

Assume constant group delay (t_d) from ($\omega_c - \omega_m$) to ($\omega_c + \omega_m$)

then

$$e_2(t) = E_2 \sin (\omega_c t + \omega_c t_d)$$

$$+ \frac{ME_2}{2} \cos [(\omega_c - \omega_m)t + (\omega_c - \omega_m)t_d]$$

$$- \frac{ME_2}{2} \cos [(\omega_c + \omega_m)t + (\omega_c + \omega_m)t_d]$$

$$e_2(t) = E_2 \sin \omega_c(t + t_d)$$

$$+ \frac{ME_2}{2} \cos [\omega_c(t + t_d) - \omega_m(t + t_d)]$$

$$- \frac{ME_2}{2} \cos [\omega_c(t + t_d) + \omega_m(t + t_d)]$$

$$e_2(t) = E_2[1 + M \sin \omega_m(t + t_d)] \sin \omega_c(t + t_d)$$

$$e_2(t) = E_2[1 + M \sin (\omega_m t + \omega_m t_d)] \sin (\omega_c t + \omega_c t_d)$$

Therefore

$$\theta_e = \omega_m t_d$$

$$t_d = \frac{\theta_e}{\omega_m}$$

or

$$t_d = \frac{\phi_e}{360° \times f_m}$$

where

t_d = group delay in seconds

ϕ_e = modulation envelope phase shift in degrees

f_m = modulation frequency in Hz .

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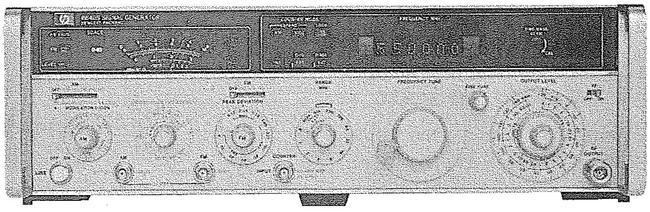
APPLICATION NOTE 171-1

Measurements with SIGNAL GENERATORS

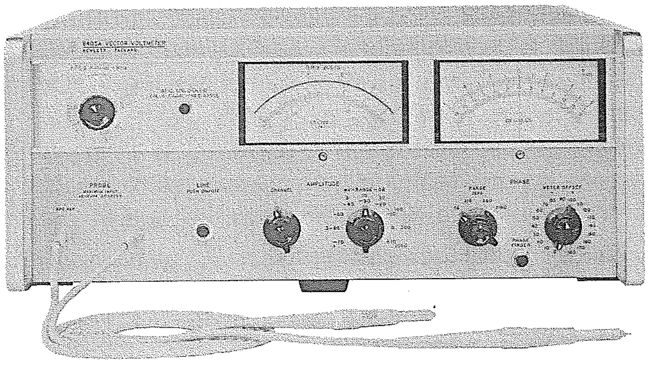
HEWLETT PACKARD

Crystal Testing

WITH THE HP 8640A/B AND HP 8405A



8640B Signal Generator



8405A Vector Voltmeter

The HP 8640A and 8640B are signal generators which cover the frequency range of 450 kHz to 550 MHz and can be extended to 1100 MHz with a frequency doubler. These generators provide AM, FM and pulse modulation. The 8640A has a mechanical dial, the 8640B has a built-in counter and phase lock synchronizer. The synchronizer phase locks the RF output frequency to the crystal time base used in the counter. Output level range of the 8640B is +19 dBm to −145 dBm (2 volts to 0.013 μ volts). The high stability and low residual FM make the 8640A/B ideal for this measurement.

The 8405A Vector Voltmeter is a two-channel (A and B), tuned voltmeter/phasemeter with a 1 kHz bandwidth. Its frequency range extends from 1 MHz to 1000 MHz. The 8405A has >90 dB dynamic range. Voltages from less than 100 μ volts to 1 volt can be measured with the 8405A. Phase (the phase difference between channels A and B) can be measured over 360° with 0.1° resolution. Four phase scales are available: ±180°, ±60°, ±18°, and ±6°. A meter offset selectable in precise 10° increments makes it possible to get 0.1° resolution throughout the 360° phase measurement range.

The 8405A uses phase-locked coherent sampling to translate the incoming RF signals in channels A and B to 20 kHz IF signals that retain the same amplitude and phase relationship as the original RF input signals. Phase lock is automatic at any frequency, only coarse tuning covering octave or greater spans is needed to phase lock.

For more information, call your local HP Sales Office or East (201) 265-5000 • Midwest (312) 677-0400 • South (404) 436-6181 • West (213) 877-1282. Or, write: Hewlett-Packard, 1501 Page Mill Road, Palo Alto, California 94304. In Europe, Post Office Box 85, CH-1217 Meyrin 2, Geneva, Switzerland. In Japan, Yokogawa-Hewlett-Packard, 1-59-1, Yoyogi, Shibuya-Ku, Tokyo, 151.

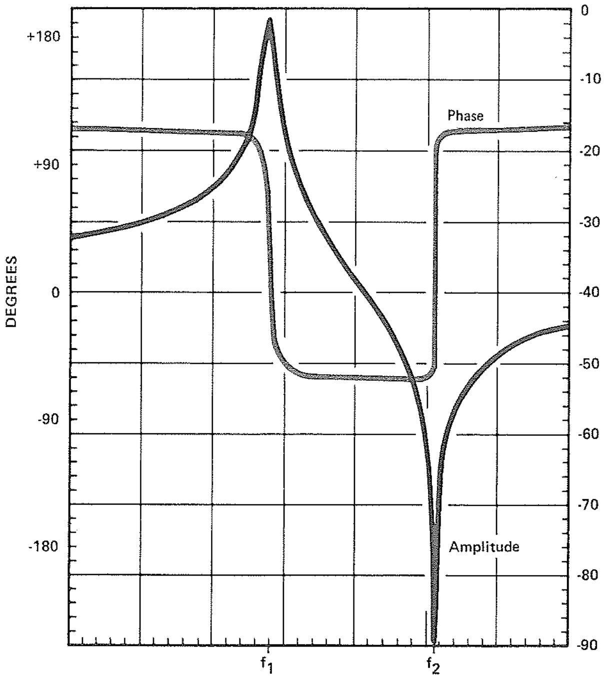


Figure 1. Amplitude and Phase Characteristics of a Typical Crystal.

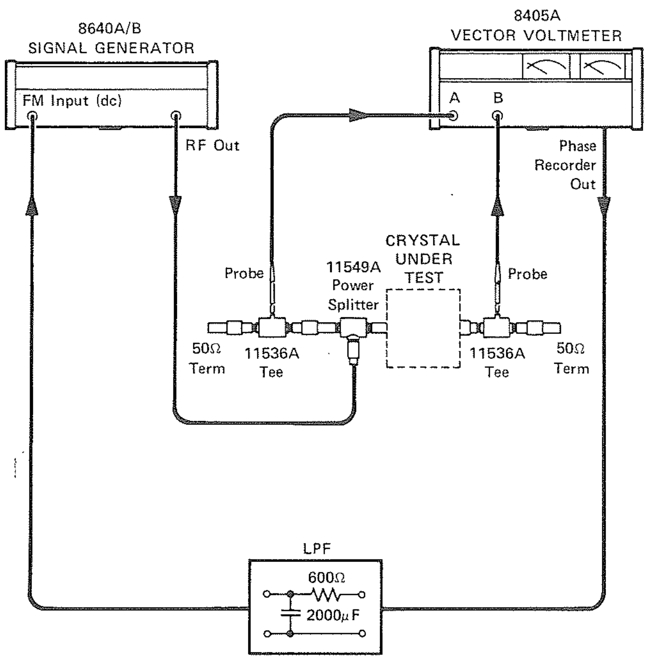


Figure 2. Crystal Series Resonance Testing with the 8640A/B and 8405.

This application note describes a procedure to measure the crystal resonant frequency. Resonant frequency is defined as the frequency at which the crystal phase goes through zero degrees. A typical crystal has two such frequencies as shown in Figure 1. One frequency corresponds to series resonance (i.e., crystal impedance is minimum and therefore loss in the crystal is minimum) and the other frequency corresponds to parallel resonance (i.e., crystal impedance is infinite and loss due to reflection is maximum). After measuring the resonant frequencies, a procedure is outlined to measure the rest of the amplitude and phase characteristics.

Objectives:

1. Measure zero-phase crossing corresponding to series resonance.
2. Measure zero-phase crossing corresponding to parallel resonance.
3. Make a complete amplitude and phase characterization versus frequency.

Equipment Needed: The 8640A and counter or 8640B signal generator, 8405A vector voltmeter, 11507A accessory kit for the 8405A, an inverter amplifier and a low pass filter.

Test Description

The block diagram shown in Figure 2 can be considered as a frequency lock loop where the 8640A/B is locked to the zero-phase frequency of the crystal under test. Initially, channels A and B are equal in phase, that is, the phase meter reads zero degrees, and the 8405A is tuned to the input frequency in channel A. After the crystal to be tested is inserted in the setup, it introduces some phase shift depending on its phase versus frequency response. However, at the crystal resonant frequency, phase shift through the crystal is zero and channels A and B are equal in phase again.

The phase recorder output is a dc voltage proportional to the phase meter reading (phase difference between channels A and B). It is an error signal that shifts the 8640A/B frequency up or down depending on polarity. The low pass filter shown in the block diagram acts as a lag network (RC time constant typically is 0.1 - 0.5 second) which eliminates loop oscillation and reduces loop bandwidth.

Once the lock condition is achieved, the feedback loop reduces frequency disturbances in the system by a factor related to open loop gain*. For example, the 8640A/B Fine Tuning control tuning range is reduced; we can see this by turning it from one end to the other. Large frequency disturbances, however, can not be re-

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*The loop action reduces frequency disturbances at series resonance by $\frac{1}{1 + 1/2\, K_1 K_2 K_3}$

where K_1 = the slope of phase vs frequency response of the crystal (degree/Hz).

K_2 = 8405A phase meter range sensitivity, (volts/degree: 0.25/6°, 0.25/18°, 0.25/60°, 0.25/180°).

K_3 = 8640A/B FM sensitivity (Hz/volt).

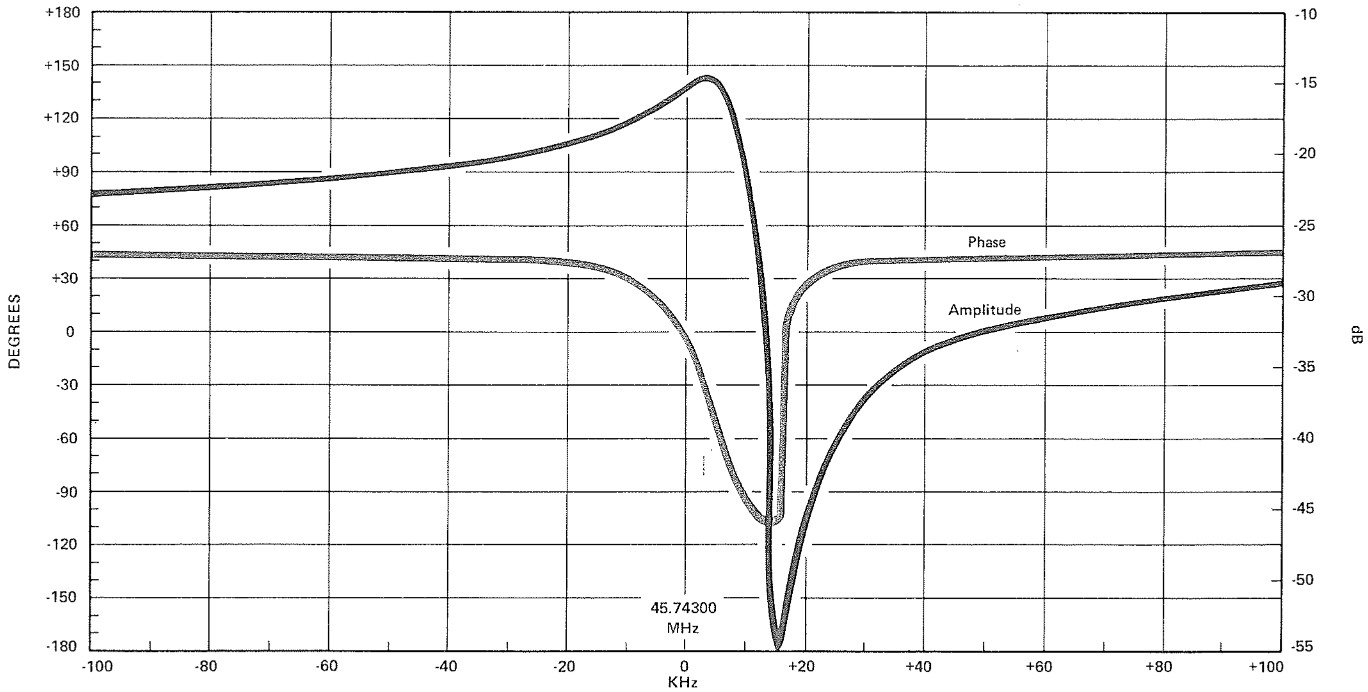

Figure 3. Complete Amplitude and Phase Characteristics of 47.5 MHz Crystal. Note the two zero-phase crossings.

duced sufficiently so lock breaks.

Measuring the zero-phase crossing at series and parallel resonances is easy and straightforward. The response shown in Figure 3 is for a 47.5 MHz crystal. Note the steep amplitude and phase characteristics. For series resonance, we simply tune the 8640A/B for maximum or near maximum indication on the 8405A amplitude meter. For parallel resonance, an inverter amplifier must be inserted in the feedback loop. However, since the crystal amplitude response at parallel resonance is at or near minimum, it might be difficult to pinpoint the parallel resonance point of a crystal whose parallel resonance response is 70 dB or greater because the zero-phase point will be obscured by the noise in the 8405A test channel.

Procedure

We will establish the series resonant frequency first and then proceed to characterize the crystal (amplitude and phase) around series resonance. We will repeat the same procedure at parallel resonance.

Set the 8640A/B and 8405A as shown in Figure 2. Select the 8640A/B frequency range which covers the crystal frequency and set the signal generator as follows:

Peak Deviation: Maximum allowable
FM slide switch: Ext. dc
FM Vernier: Maximum CCW
Lock (8640B): Off

1. With the crystal under test removed, establish the phase meter null, that is, zero the 8405A phase with the range switch in ±6° range. Return the range switch to the ±180° position after nulling the meter.
2. Insert the crystal and tune the 8640A/B to see an indication on the amplitude meter. Peak the amplitude meter using the 8640A/B fine tune control.
3. Slowly turn the FM vernier maximum clockwise and observe the 8405A meter—it should be at or near zero degrees. Since the loop has a slow response time (governed by the low pass filter's time constant), the FM vernier should be turned at a slow rate. This precaution is recommended to avoid transients which the loop may not track and would result in breaking lock.
4. To get the best phase resolution, reduce the phase range to the ±6° position. Fine tune the 8640A/B to center the phase meter at zero.
5. Read the frequency displayed by the 8640B, or the external counter if the 8640A is used. This is the series resonant frequency of the crystal. Return to the ±180° position.

Starting from the zero-phase crossing just established, we can tune the 8640A/B down (to the left of resonance) to characterize the crystal in amplitude and phase. Simply tune the 8640A/B downward and observe the amplitude and phase meters. Do not tune so far

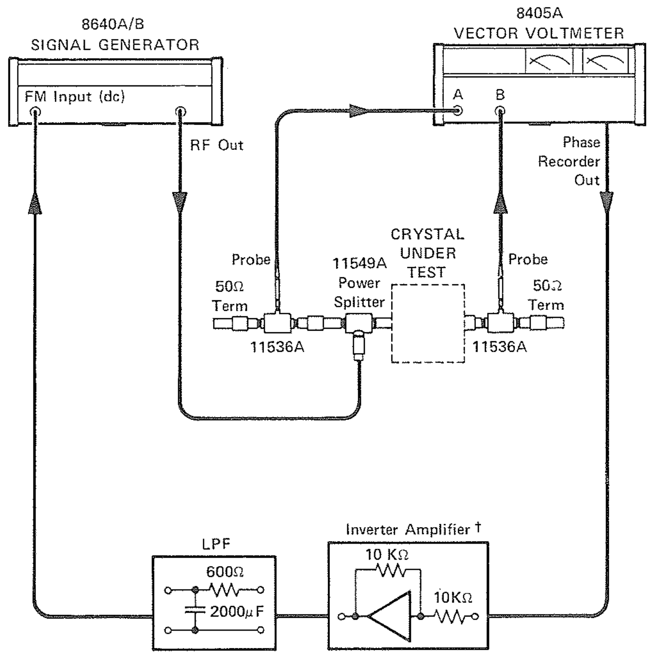

Figure 4. Crystal Parallel Resonance (Feedback loop uses inverter stage).

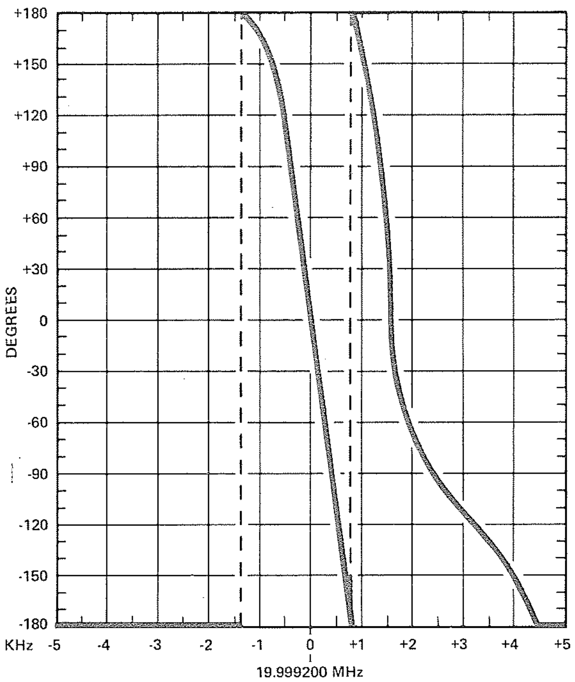

Figure 5. Phase Response of a 20 MHz Bandpass Filter.

that you lose lock. If lock breaks, re-establish zero crossing.

Again, come back to the zero-crossing frequency and tune the 8640A/B up (to the right of zero-crossing). Observe the amplitude and phase meters. As you approach the parallel resonance frequency, the amplitude response decreases rapidly and, at some point, the phase response changes slope and the meter swings from the negative end to the positive end of its range.

At this point, turn the FM vernier fully counter clockwise and insert an inverter stage in the feedback loop as shown in Figure 4. This stage is needed to provide the correct dc polarity for the FM input of the 8640A/B. Reduce peak deviation two or three ranges. Tune the 8640A/B and observe the frequency which gives minimum amplitude response. Turn the FM vernier fully clockwise, the phase meter should be at or near zero degrees. Fine tune to bring the 8405A phase meter to zero degrees. The frequency displayed by the counter is the parallel resonance frequency. Tune the 8640A/B up to characterize the amplitude and phase of the crystal in this region. Again, care should be taken when measuring the zero-phase crossing at parallel resonance because of a low signal-to-noise ratio in the test channel and a sharp phase versus frequency slope.

Measurement Considerations

This measurement system has three sources of error which affect frequency accuracy:

1. Counter accuracy.
2. The 8405A zero-phase adjust.
3. The physical length of the device under test*.

Assuming the physical length of the device under test is negligible at resonance, the frequency accuracy is equal to:

$$\text{Counter accuracy} + \text{zero phase adjust x } \frac{\Delta F^{**}}{\Delta\phi}$$

If physical length of the device under test is not negligible, a phase shift could occur due to the electrical length of the device (we assume the device resonates at the center plane of its physical configuration). To estimate this error, we can measure the device physical length, convert it to electrical length at resonance and convert the electrical length to phase shift. Then multiply by $\frac{\Delta F}{\Delta\phi}$ to find the error in Hz.

In summary, this measurement system represents an economical way of testing crystals, crystal filters, crystal oscillators and other frequency selective circuits. Figure 5 shows phase characteristics of a two-crystal 20 MHz filter. Note the two zero crossings and the phase reversals at ±180°.

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*The effects of physical length are discussed in HP AN 91, "How vector measurements expand design capabilities".

$^{**}\frac{\Delta F}{\Delta\phi}$ is equal to the inverse of phase versus frequency slope.

†LM301AH, National Semiconductor.