# LOW FREQUENCY PHASE SHIFT MEASUREMENT TECHNIQUES

81

APPLICATION NOTE

HEWLETT hp PACKARD

*ACKNOWLEDGEMENT*

*Application Note 81 combines contributions from many members of the Hewlett-Packard Loveland Division R & D staff, especially from Don Wick. Don holds a BSEE from Southern Methodist University (1960). He is applications engineer for audio-video instrumentation.*



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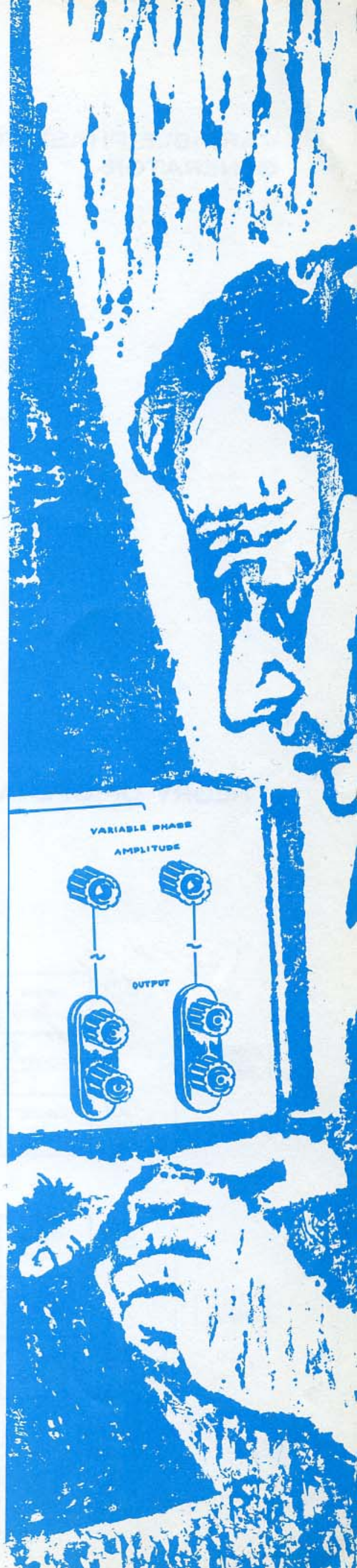



## INTRODUCTION

Low frequency phase shift measurements are valuable in many applications: check-out of medical and geophysical equipment, servo-mechanism analysis, in-process control testing, and as forcing functions for real time analogs of mechanical systems.

Oscillators used for phase shift measurements provide a second output waveform that can be phase shifted in known amounts with respect to the oscillators reference output. Recently introduced—the Hewlett-Packard Model 203A Variable Phase Function Generator—has been developed for phase shift applications. It is a low frequency oscillator with two outputs, one can be phase-shifted continuously through a full 360° range with respect to the other.

This application note describes in detail various Low Frequency Phase Shift Measuring Techniques for Servo System Testing, Phase Shift Measurements of Components, Hysteresis Curve Plotting, Multiple Phase Generation, Bow Tie Phase Shift Measurement Techniques and others made practical with the Hewlett-Packard 203A Function Generator.

## VARIABLE PHASE FUNCTION GENERATOR

Although intended primarily for low frequency work, the HP 203A has a 12,000,000 to 1 frequency range extending from 60 kHz down to 0.005 Hz with options down to as low as 0.00005 Hz, (5 hours for one cycle). In addition to sine wave outputs, the 203A generator has separate square wave outputs on both the reference and variable phase channels. All four output signals, which have maximum amplitudes of 30 V peak-to-peak, are supplied simultaneously and all have individual 40 dB attenuators. Output signals are exceptionally clean—the rms total of all harmonic distortion, hum, and noise on the sine wave signals is $>64$ dB below the fundamental (or $<0.06\%$ of the fundamental). The excellent waveform purity is maintained throughout the entire frequency range of the instrument. The Function Generator is well suited as a source of sine waves for critical tests of audio as well as sub-audio equipment.

The square wave tops are flat. Rise and fall times are $<0.2\mu s$ with $<5\%$ overshoot. Square waves of this quality are well suited for transient response testing of high-grade audio and other low frequency equipment.

Frequency accuracy of the new oscillator is better than $\pm 1\%$ at all frequencies and the instrument may be quickly calibrated to power line frequencies operating within a 60 to 1000 Hz frequency range.

## THEORY OF OPERATION

The oscillator in the 203A uses beat frequency techniques which usually are not suitable for low frequency operation because of frequency locking between the two oscillators. The 203A utilizes frequency division and mixing which eliminates any possibility of synchronization between the fixed and variable oscillators.

The fixed frequency oscillator is a crystal operating at 4.995 MHz. It is divided by a factor of 9 in a special divider and used as a 555 kHz fixed reference frequency. The Variable Frequency oscillator is a simple L-C type operating over the range of 495 kHz to 550 kHz. When mixed with the 555 kHz reference frequency, an output frequency in the range of 5 kHz (555 kHz minus 550 kHz) to 60 kHz (555 kHz minus 495 kHz) is generated. This is the top frequency band.

To derive the next band, the 4.9995 MHz crystal frequency is mixed with the variable frequency oscillator giving a band of frequencies from 5.490 MHz (4.995 MHz +495 kHz) to 5.545 MHz (4.995 MHz +550 kHz). These frequencies are then divided by 10 with a resultant range of 549 kHz to 554.5 kHz. When mixed with the 495 to 550 kHz variable frequency oscillator, the second band of frequencies from 500 Hz (555 kHz minus 554.5 kHz) to 6 kHz (555 kHz minus 549 kHz) is generated. By repeating this mixing-dividing-mixing operation, extremely low frequencies can be generated. The standard 203A has a lower limit of 0.005 Hz but two lower ranges of 0.0005 Hz and 0.00005 Hz can be obtained by simply adding two more mixer-divider circuit boards.

The output from the final mixer is filtered and amplified to provide the proper output level and impedance. A square wave output is provided by a Schmitt trigger operating from the normal sine wave output.

One of the features of the 203A is the variable phase output which is derived by phase shifting the 555 kHz reference frequency before mixing. The phase shifter thus operates at a fixed frequency and amplitude simplifying the design of the phase shifter and providing constant phase shift with varying frequency. The phase shifter is a goniometer consisting of two stator windings and a rotor. Two 555 kHz signals 90° apart are supplied to the stator windings thus generating a rotating magnetic field much like a two phase synchro. The rotor winding is mechanically coupled to the front panel phase dial and the phase of its output voltage is dependent on the relative position of the rotor to the two stator windings. This output signal, whose phase is different from the 555 kHz reference frequency, is then mixed with the variable frequency signal to create an output signal whose phase can be varied with respect to the reference output. Similar amplifiers and Schmitt triggers generate sine and square wave phase shifted outputs.

Linear operation of oscillators and mixers along with proper filtering, insures extremely low distortion (—64 dB) sine waves. Leveling circuitry in the amplifiers provide flat (±1%) frequency response and operation of the phase shifter at a fixed frequency eliminates any frequency dependent problems usually associated with phase shifters.

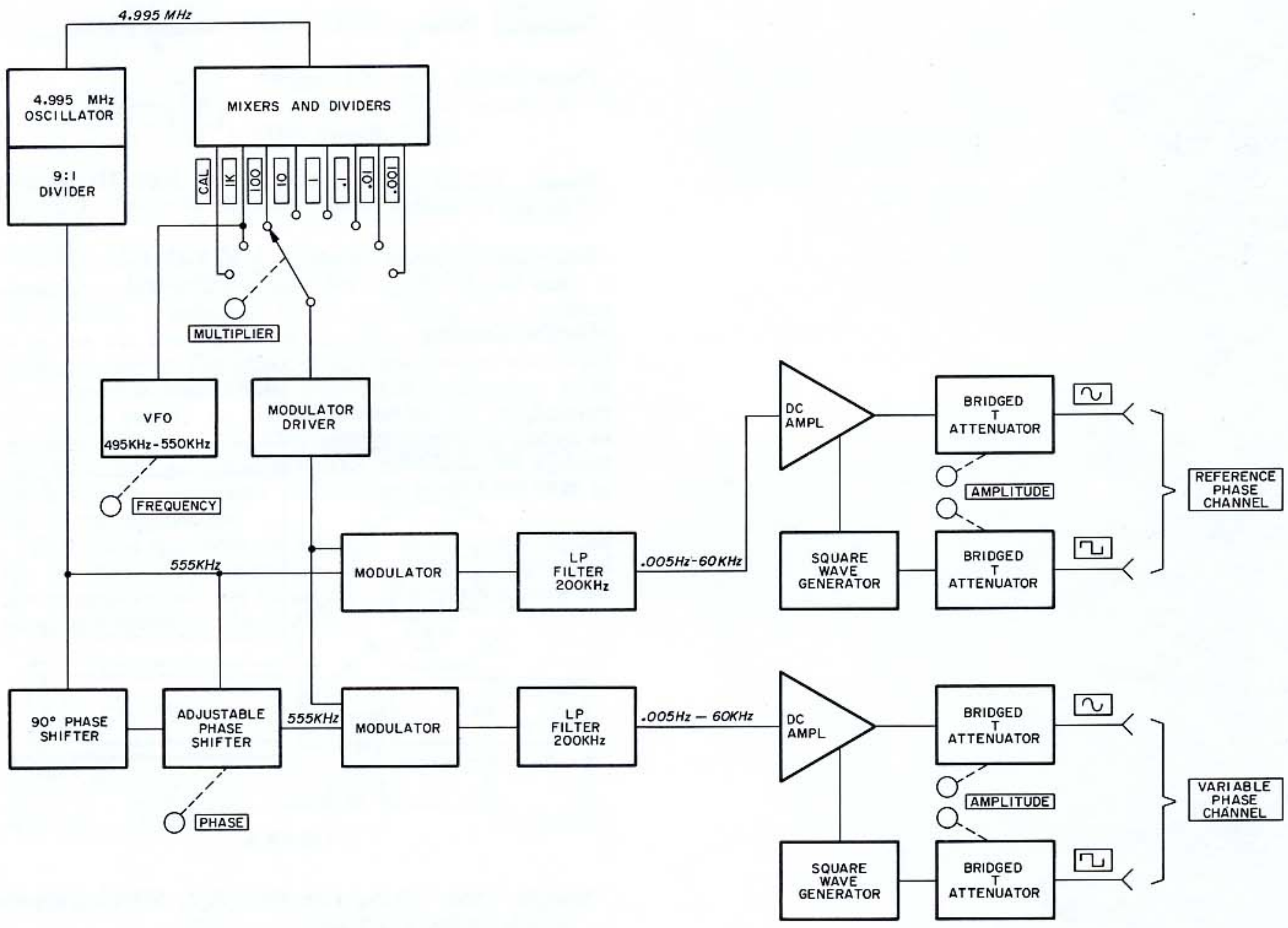



Figure 1. 203A Block Diagram

## 203A SPECIFICATIONS

**Frequency Range:** 0.005 Hz to 60 kHz in seven decade ranges.*

**Dial Accuracy:** ±1% of reading.

**Frequency Stability:** Within ±1% including warmup, drift and line voltage variations of ±10%.

**Output Waveforms:** Sine and square waves are available simultaneously. All outputs have common chassis terminal.

**Maximum Output Voltage:** 30 volts peak-to-peak open circuit for sinusoidal and square waveforms.

**Output Power:** 5 volts into 600 ohms (40 mw); 40 dB continuously adjustable attenuation on all outputs.

**Output Impedance:** 600 ohms.

**Output System:** Direct coupled output is isolated from ground and may be operated floating up to 500 Vdc.

**Distortion:** Total harmonic distortion, hum and noise >64 dB below fundamental (<.06%) at full output.

**Square Wave Response:** Rise and Fall Time: <200 nsec
Overshoot: <5% at Full output.

**Frequency Response:** ±1% referenced to 1 kHz.

**Phase Range:** 0 to 360 degrees.
Accuracy: ±5° sine wave
±10° square wave

**Power:** 115 or 230 v ±10%, 50 to 1000 Hz, approximately 25 watts.

**Dimensions:** Cabinet mount, 5 1/4" high x 16 3/4" wide and 11 1/2" deep (133 x 425 x 286 mm).

**Outline Drawing:**

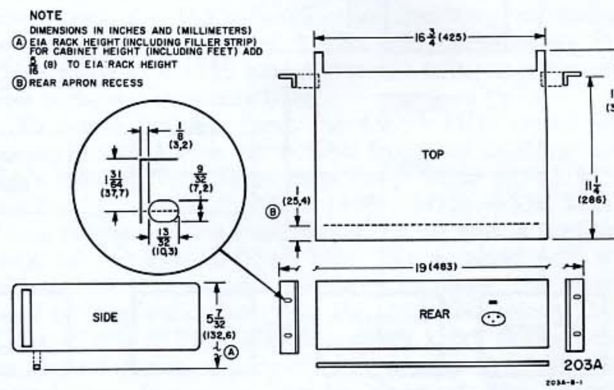



Figure 2.

**Weight:** Net: 19 lbs, 4 oz. (8,66 kg); Shipping approximately 28 lbs. (12,5 kg).

*Two lower ranges of 0.0005 Hz (option: 01) and 0.00005 Hz (option: 02) are available on special order.

## SERVO SYSTEM TESTING

The calibrated phase dial and low distortion sine wave capability makes servo measurements simple. Measuring phase shift involves comparing the output of the device under test to the output from the variable phase channel of the 203A and adjusting the phase dial until a phase null is reached. The phase angle is read directly from the 203A phase dial.

To accurately determine gain and loss in the servo system, an HP 350D attenuator set can be used as an attenuation standard since the attenuators in the 203A are uncalibrated. This attenuator is designed to match a 600Ω system and must be terminated properly for correct attenuation. Once phase and amplitude information has been gathered using these measurement techniques, the characteristics of the servo system can be plotted. A plot of phase vs.amplitude on the complex plane is a Nyquist Diagram. The plot of log amplitude vs. log frequency is a Bode Diagram. The plot of log amplitude vs. phase gives the familiar Nichols Diagram.[2]

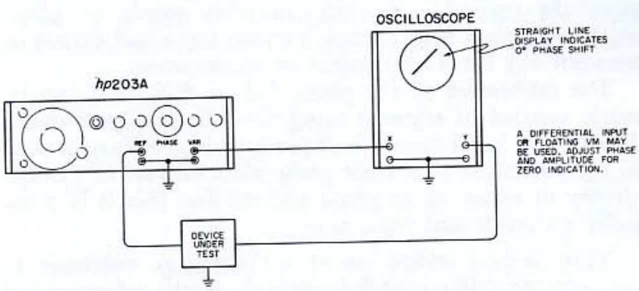



Figure 3. Setup to Measure Phase Shift of Components

At extremely low frequencies, the repetition rate of the signal is so low that a continuous display on the scope is not possible. A technique for circumventing this problem is to use the low frequency signal to modulate a higher frequency carrier. The effect of this modulation, when used in conjunction with a long persistence oscilloscope, is to fill in the pattern on the scope making the modulation envelope easily readable. This type of pattern is known as the Bow Tie presentation.[3] The new Hewlett-Packard 141A variable persistence oscilloscope is an ideal unit to use in this application.

To develop the proper X and Y axis oscilloscope signals for the Bow Tie presentation, some form of suppressed carrier modulation must be used. Figure 5 and 6 show the setup and details of the modulator.

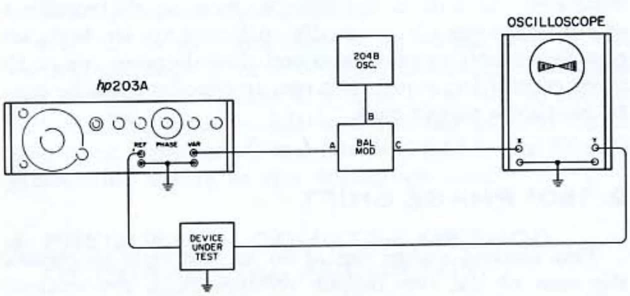
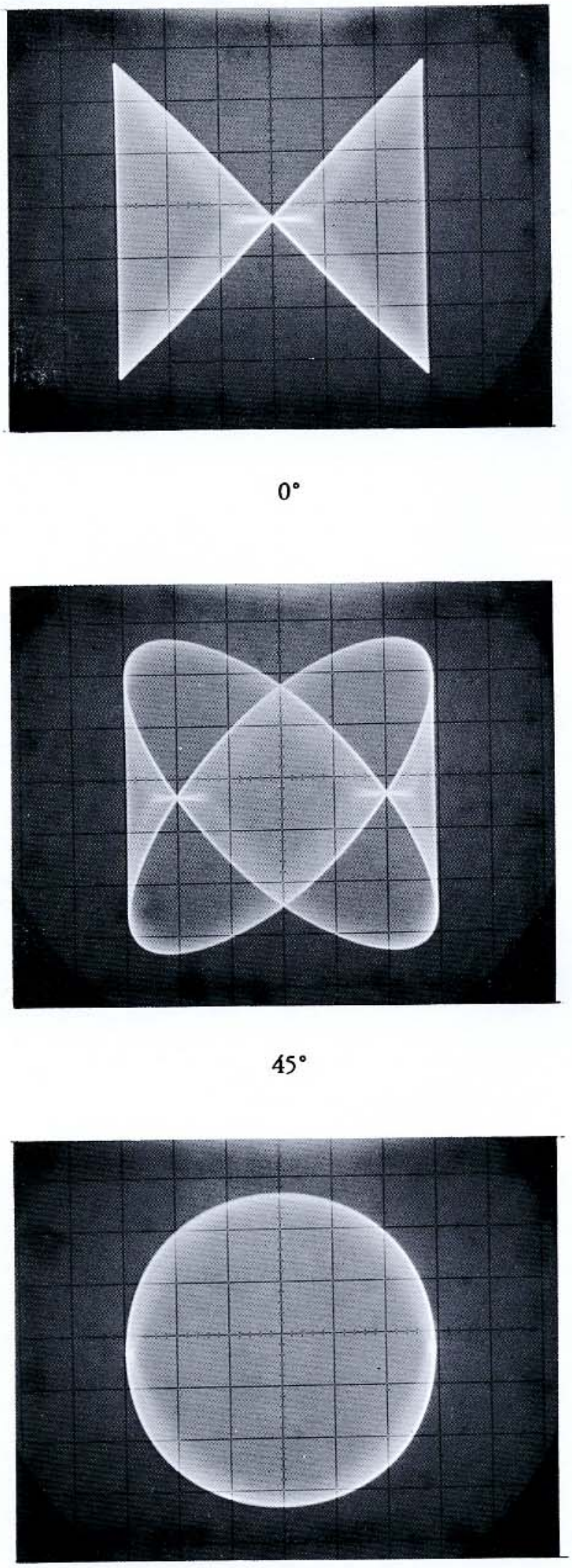



Figure 4. Setup to Measure Phase Shift Using Bow Tie Method



0°

45°

90°

Figure 5. Phase Shift Patterns Using Bow Tie Method

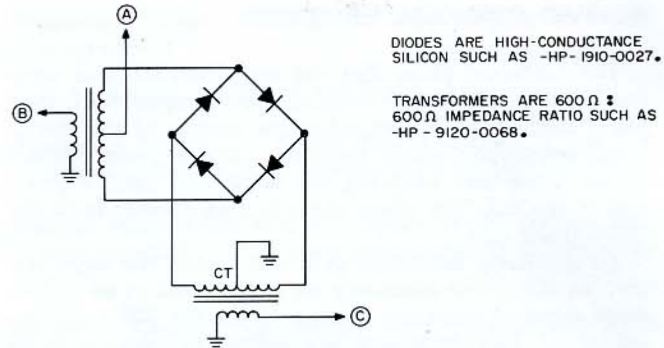



Figure 6. Details of Balanced Modulator

Since the usual method of measuring phase shift is a substitution technique, it is often necessary to know the calibration of the phase shifter, particularly at cardinal points such as 0°, 90°, 180°, and 270°. The substitution techniques requires the operator to set the phase standard dial for a phase null or 0° phase shift on an oscilloscope or meter. 0° phase is generally used because it is an easily physically realizable quantity; in other words, 0° phase shift is simply a short circuit between input and output or between any other two points of measurement.

The calibration of the phase dial on the 203A can be easily verified or adjusted using the following procedures. Notice that in all cases a null point or zero voltage is used as the indication of correct phase shift because of its sensitivity to variations in phase and the fact that it is physically realizable and repeatable.

This method makes use of a floating ac voltmeter to measure the differential voltage between the reference and variable phase outputs. When the relative phase shift between these two outputs is 0°, and the amplitudes are equal, they will exactly buck each other creating a null.

## 1. 0° PHASE SHIFT

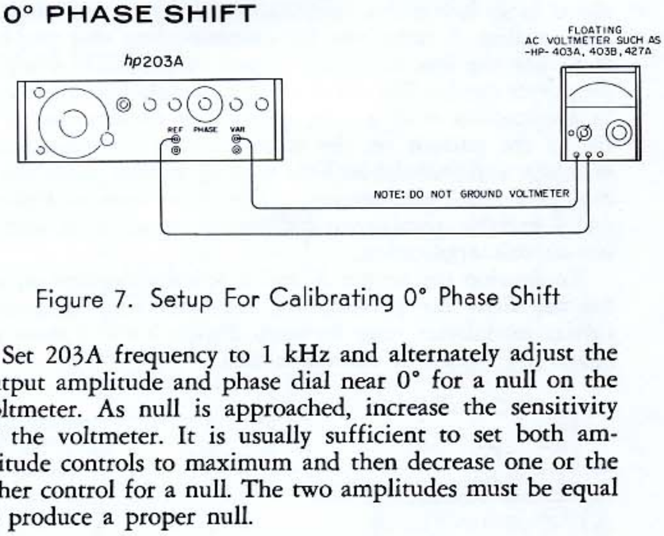



Figure 7. Setup For Calibrating 0° Phase Shift

Set 203A frequency to 1 kHz and alternately adjust the output amplitude and phase dial near 0° for a null on the voltmeter. As null is approached, increase the sensitivity of the voltmeter. It is usually sufficient to set both amplitude controls to maximum and then decrease one or the other control for a null. The two amplitudes must be equal to produce a proper null.

## 2. 180° PHASE SHIFT

This method makes use of an ac voltmeter to measure the sum of the two output voltages from the reference and variable phase outputs. When these two signals are 180° out of phase and equal amplitude, they will add in opposition to produce a voltage null.

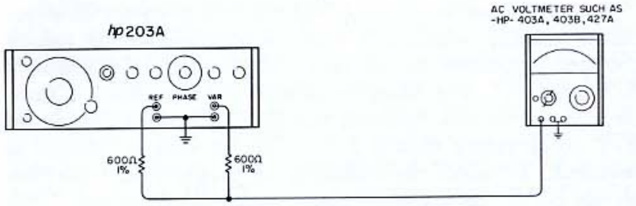



Figure 8. Setup For Measuring 180° Phase Shift

Set 203A frequency to 1 kHz and alternately adjust the output amplitude and phase dial near 180° for null on the voltmeter. Adjusting only one amplitude control as described in the previous section for 0° phase shift is suitable.

### 3. 90° AND 270° PHASE SHIFT

This method is more involved as it requires a balanced modulator to mix the two identical frequency outputs differing in phase by 90° to a zero frequency or dc output. Mathematically it can be shown that the balanced modulator has a zero output when and only when the phase difference between the two input signals is exactly 90°. [4]

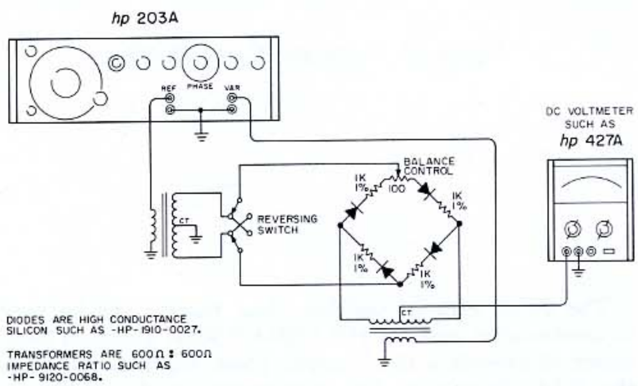



Figure 9. Setup For Calibrating 90° and 270° Phase Shift

Referring to figure 9, set the 203A frequency to 1 kHz, both amplitudes to maximum and the dial to 90° or 270°. Adjust the phase dial for a zero reading on the dc voltmeter. Switch the reversing switch to the opposite polarity and note the dc voltage offset. Adjust the balance control to reduce the dc voltage to one-half its original value. Reset the dc voltage to zero using the phase dial. Change the reversing switch to the opposite polarity and again note the dc offset. Continue adjusting the balance control and phase dial until no dc offset is present when the reversing switch is changed. Usually one careful adjustment will sufficiently balance the modulator.

After the balance procedure is completed, zero dc voltage will indicate 90° or 270° phase difference. The amplitude controls should have very little effect on the zero indication. This same modulator circuit can be used for the suppressed carrier modulation as described in the Bow Tie presentation earlier in this application note.

### 4. FREQUENCY COUNTER METHOD OF PHASE DIAL ACCURACY

A frequency counter with a time interval function such as the HP 5233L with the capability of counting a 1 MHz standard frequency in the time interval mode of operation can be used to give a direct phase angle readout in degrees and tenths of degrees at one frequency. It is possible to make time interval phase angle measurements at any frequency provided the exact frequency is known and the proper calculations are made.

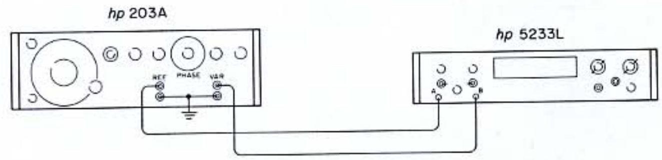



Figure 10. Phase Dial Calibration With Time Interval Counter.

Set counter to measure period with a time base of 1 μs (1 MHz). Adjust the 203A frequency near 278 Hz for a period reading of exactly 3600. Set counter to time interval function with a time base of 1 μs (1 MHz). The counter reading will be the phase shift in degrees and tenths of degrees, ie. 2205 is 220.5° of phase shift. With the phase dial at 0°, the reading may be either 0 or 3600. Care should be exercised when adjusting the start and stop counter to minimize phase error.

These methods are typical of some of the techniques used to calculate the phase dial to better than its specified accuracy of 5°. Since the phase shifter operates at a fixed frequency, there is no phase variations with frequency due to the phase shifter. However, there will be some phase error with frequency to the extent that the output amplifiers and attenuators may not be identical. Additional phase error may be introduced in the square wave output since zero crossing detection is used to generate the output square wave.

Occasionally a balanced-to-ground output is desired from the 203A. This can be provided by setting the phase dial to 180° and using the reference and variable phase output terminals as the two-wire balanced output. The output impedance in this case will be approximately 1200 ohms.

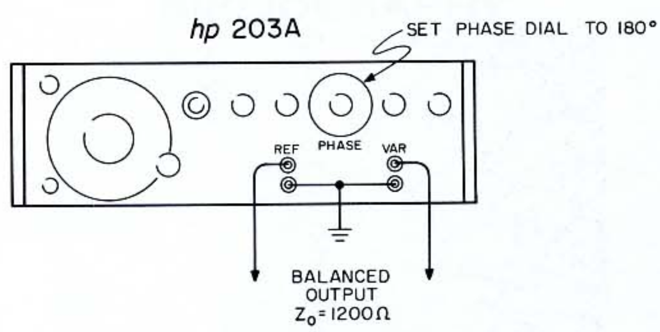



Figure 11. Balanced Output.

To insure an exact 180° phase setting and exactly equal amplitudes, follow the technique described earlier to calibrate the 180° phase dial setting. One amplitude control should be set to give a single-ended output of half the desired balanced output voltage and the other amplitude control adjusted to a null as indicated on the ac voltmeter when setting the phase dial.

## HYSTERESIS CURVE PLOTTING

Hysteresis curve plotting and recording on an X-Y recorder usually requires a waveform translator to reduce the test frequency to the range of commercially available X-Y plotters.[5] The Moseley Model 101 Waveform Translator performs this function but since it is operating in an X-Y mode rather than a Y-T mode, an external trigger is required. To allow the translator to properly scan the hysteresis curve, the variable phase square wave in the 203A can be used as a manual scan control. The reference phase output is used as the driving function for the measurement and is, of course, limited to 60 kHz. The smoothness of the recorded trace will depend on the operator's care in turning the phase dial. Further information is presented in HP's Application Note 108, *Hysteresis Curve Plotting.*

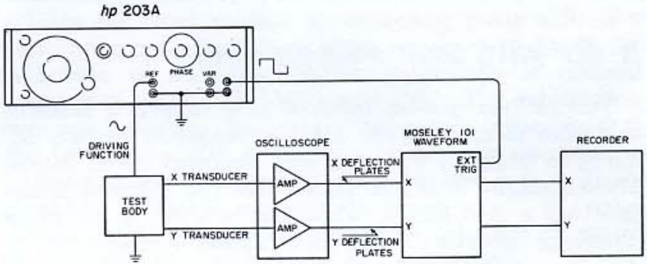



Figure 12 Hysteresis Curve Plotting.

## MULTIPLE PHASE OUTPUTS

The 203A with its variable phase outputs can be used in combination with an HP 3300A/3302A Function Generator to provide a third output phase which is locked to the 203A's frequency. The instruments may be set, for example, to deliver 3 outputs with a 120° phase difference between each of the outputs.

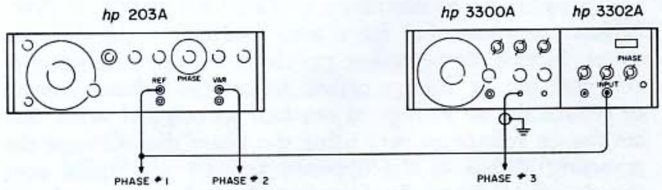



Figure 13 Multiple-Phase Generation.

The frequency of the 3300A and the 203A must be identical and the 3302A Trigger/Phase Lock Plug-In operated in phase lock mode. The position of phase#3 with respect to phase #1 is set by the phase dial on the 3302A Plug-In. The position of phase #2 with respect to phase #1 is set by the phase dial on the 203A. Refer to the 3300A/3302A operating manuals for further information.

The 203A is conservatively designed using premium components and ample negative feedback to insure stability with time and temperature. As with all Hewlett-Packard instruments, it is designed to operate over an ambient temperature range of 0° to 55° with a maximum relative humidity of 95% at 40°C.

## TYPICAL PERFORMANCE DATA

Additional performance data above that which is specified is presented here. It is generally understood that maximum stability of frequency and amplitude will occur in a relatively stable environment such as will be found in the average laboratory. Short term frequency stability is typically 2 parts in $10^4$ over a period of a minute while long term stability over a period of a working day is typically 5 parts in $10^4$. The 203A requires two hours to properly warm up and frequency will drift about 0.1% during this time.

The phase shift will typically remain within 2° over the entire frequency range and better than 1° over one decade. Phase shift stability is typically better than 1° per day.

The output amplitude drift will typically be less than 1% while the output dc component stability will typically be less than 200 mV per day. Short term amplitude stability is typically within 1 part in $10^4$.[6]

*Complete information on the 203A and other Hewlett-Packard equipment discussed in this application note is available from your nearest HP field office.*

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