Errata

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APPLICATION NOTE 164-3

NEW TECHNIQUES FOR ANALYZING PHASE LOCK LOOPS

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CONTENTS

Phase lock loops (PLL's) have recently gained in popularity for a wide range of applications. However, because of several basic PLL properties they have been difficult to analyze.

This application note illustrates a number of new techniques for analyzing phase lock loops (PLL's) made possible by the phase modulation capability of the HP 8660A/C Synthesized Signal Generator. Block diagrams of various methods for analyzing PLL's and examples of typical results are included.

PHASE LOCK LOOP OPERATION

Although there are almost infinite variations in loop design, an elementary loop consisting of a phase detector, low-pass filter, and voltage-controlled oscillator (VCO) illustrates PLL operation and indicates the types of difficulties PLL analysis presents (see Figure 1).

In a PLL the phase detector compares the input signal phase with that of the VCO and generates a voltage that is proportional to the difference in phase of its inputs. The phase error voltage is passed through the low-pass filter which suppresses noise and any high frequency signal components and helps determine loop dynamic performance. The VCO is controlled by this filtered error voltage, and the output from the VCO is then compared with the incoming signal at the phase detector. The loop operates in such a way that the VCO and input signal are locked together.

PRESENT METHODS OF ANALYZING PLL's

PLL analysis has posed problems for the design engineer because of several basic properties of PLL's:

1. After the input phase detector, all signals are based on phase error and not the input signal itself.

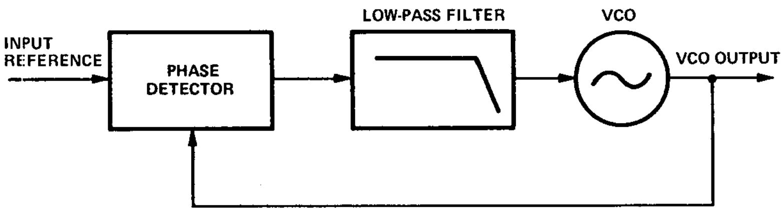

Figure 1. Simple PLL Block Diagram.

2. The phase detector must have two input signals to operate. This necessitates that the loop be closed or a second signal be input to the phase detector.
3. Since frequency is the derivative of phase, the phase of the VCO is proportional to the integral of the filtered error voltage so the loop has an integrated rather than a linear feedback function.
4. Because loop components such as the phase detector are often non-linear, input signals with varying peak phase deviation cause varying loop responses.

Several different techniques are presently used to analyze PLL's. One technique is to frequency modulate the input signal and monitor the resulting voltage into the VCO. This technique is extremely useful when the PLL is being used as a frequency demodulator, but for other applications it is necessary to assume that the VCO has constant gain that is independent of modulation rate or signal amplitude. Since the modulation index in FM is dependent on modulation rate, when FM is used phase deviations can become large enough to cause the loop to operate in non-linear regions.

Other techniques involve inserting signals into the loop and analyzing the resulting response. This method must be used with care since the circuitry for injecting the test signal can alter loop performance. Techniques that involve analyzing each element separately are valuable when diagnosing faulty loop operation but loop interactions can be difficult to predict accurately.

The use of phase modulation does not reduce the value of these techniques but does offer unique capabilities that greatly enhance a design engineer's ability to easily and effectively analyze PLL.

VALUABLE 8660A/C CAPABILITIES

The 8660A/C makes PLL analysis easier and more accurate. Because of the 8660's wide frequency coverage and crystal stability, even narrow bandwidth PLL's with center frequencies from 1 to 2600 MHz can be analyzed without drift problems. The 8660's output is frequency coherent with its reference (output frequency is a direct multiple of the reference) which has definite advantages when a phase demodulation system is desirable.

Phase modulation is very desirable when analyzing PLL's because a constant peak phase deviation is maintained independent of the modulation frequency. With either the 86634A or 86635A Modulation Sections and either the 86602B Option 002 or 86603A Option 002 RF Sections, the 8660A/C provides high performance phase modulation capability. The 86634A modulation plug-in allows modulation at rates from dc to 10 MHz, while the 86635A modulation plug-in allows FM as well as phase modulation at rates from dc to 1 MHz.

A calibrated signal level, such as the 8660 offers, is very desirable when testing a PLL whose frequency response is dependent on input amplitude.

PLL MEASUREMENTS POSSIBLE WITH THE 8660A/C

Using the 8660 with phase modulation it is possible to determine many loop characteristics. Three major characteristics readily evaluated are:

1. Closed loop frequency response*—both amplitude and phase.
2. Closed loop transient response for step changes in phase.
3. Phase detector linearity and gain.

A section outlining test methods used to obtain each of these characteristics is included.

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* In this application note the term "frequency response" denotes VCO peak phase deviation variation with modulation rate.

Closed Loop Frequency Response

There are several methods available which use phase modulation to obtain PLL frequency response information. The choice of which method to use will necessarily depend on the PLL to be tested, the information desired, and the equipment available. Several methods will be covered in detail in the following pages.

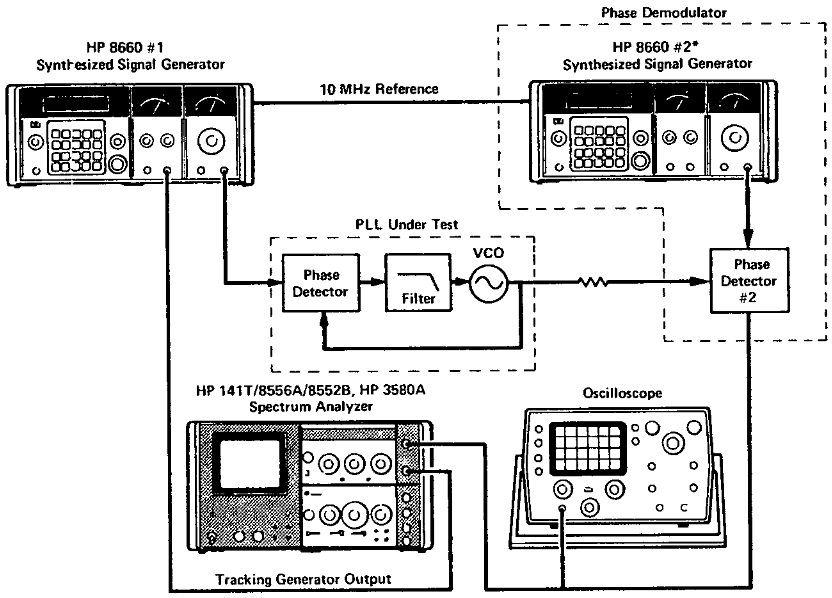
Summary of PLL Frequency Response Test Methods

Technique	Major Equipment Required	Possible Test Rates	Comments
Low Frequency Spectrum Analyzer	2 HP 8660 Synthesized Signal Generators* 1 Phase Detector (Example HP 10514A Mixer) 1 Oscilloscope (Example HP 1700B) 1 Low Frequency Spectrum Analyzer (HP 3580A, HP 141T/8556A/8552B)	5 Hz to 300 kHz	Swept Display of amplitude response. Almost instantaneous display — ideal for visualizing response while making loop adjustments. Good noise rejection.
Gain-Phase Meter	2 HP 8660 Synthesized Signal Generators* 1 Phase Detector (Example: HP 10514A Mixer) 1 Oscilloscope (Example: HP 1700B) 1 HP 3575A Gain-Phase Meter 1 Test Oscillator (Example: HP 651B)	1 Hz to 10 MHz	Phase as well as amplitude information.
RF Spectrum Analyzer	1 HP 8660 Synthesized Signal Generator 1 RF Spectrum Analyzer (Example: HP 141T/8553A/8552B 1 Test Oscillator (Example: HP 651B)	Resolution of spectrum analyzer to 10 MHz.	Minimal equipment requirement. Visual display of amplitude response.

*** One of the 8660's could be replaced with an 8640 Signal Generator. See Appendix.**

USING A LOW FREQUENCY SPECTRUM ANALYZER

The system illustrated in Figure 2 can be used to obtain a swept display of PLL amplitude versus frequency response. This makes it extremely valuable for monitoring the PLL frequency response while making adjustments on the loop. It can be effectively used to analyze PLL's at rates from 5 Hz to 300 kHz depending on which spectrum analyzer is used.



* HP 8660 #2 can be replaced with an HP 8640A/B Signal Generator. See Appendix.

Figure 2. PLL Analysis Setup Using a Low Frequency Spectrum Analyzer.

Operation

In this test setup the spectrum analyzer's tracking generator output is used to phase modulate 8660 #1 at rates from as low as 5 Hz to some frequency higher than the PLL bandwidth. The modulated RF output from this 8660 is applied to the input of the PLL under test. This causes a phase error to which the loop attempts to respond by modulating the VCO. 8660 #2 and phase detector #2 act as a phase demodulator. The VCO output is demodulated and the frequency response on a linear frequency scale is displayed on the spectrum analyzer (see Figure 3).

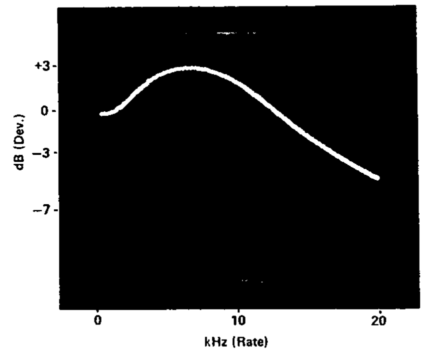


Figure 3. PLL Frequency Response Obtained Using the Test Setup Shown in Figure 2.

Measurement Procedure

1. With the modulation off in both 8660's connect the equipment as shown in Figure 2. Both 8660's must be connected to the same frequency reference to ensure frequency coherence. The resistor shown in Figure 2 is necessary to ensure that the VCO and PLL phase detector operation is not affected by connection of the test circuit.
2. Set 8660 #1 to the input frequency of the PLL and 8660 #2 to the corresponding VCO frequency. The phase relationship between 8660 #2 and the VCO must be adjusted so that phase detector #2 operates in its most linear region. This is accomplished by stepping 8660 #2 up 1 Hz in frequency (2 Hz for RF frequencies above 1.3 GHz) and quickly stepping it back again while monitoring the output of phase detector #2. This results in a momentary sweep of the phase detector's phase/amplitude characteristic. By repeating this process several times it is possible to operate in the middle of phase detector #2's operating range. This point is reached when the dc output from phase detector #2 corresponds to that of the center of the phase detector's range.*
3. Turn on the phase modulation on 8660 #1 and adjust deviation low enough to ensure that both the PLL under test and the phase detector demodulator are operating in their linear regions. For a mixer such as the HP 10514A (dc to 500 MHz) this is less than 30 degrees peak. If the loop under test has significant peaking, use a small deviation to ensure that gain compression does not occur. Remember, if the VCO output frequency is a multiple of the input frequency, the VCO deviation may also be multiplied thus requiring reduced input deviation to maintain linear operation.
4. Adjust the spectrum analyzer for a convenient display.
5. Many PLL's are sensitive to input amplitude variations so it may be desirable to test the PLL at various input amplitudes (see Figure 4).

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* It may be necessary to repeat this procedure periodically to maintain the proper phase relationship between the VCO and 8660 #2 because of phase drift (typically less than a few degrees per minute) between the 8660's.

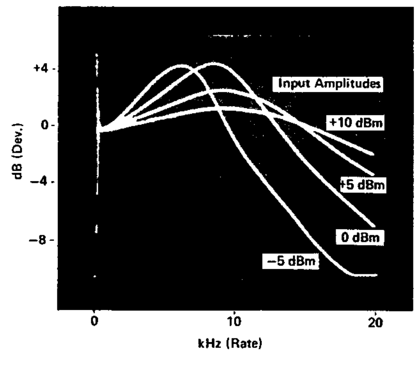
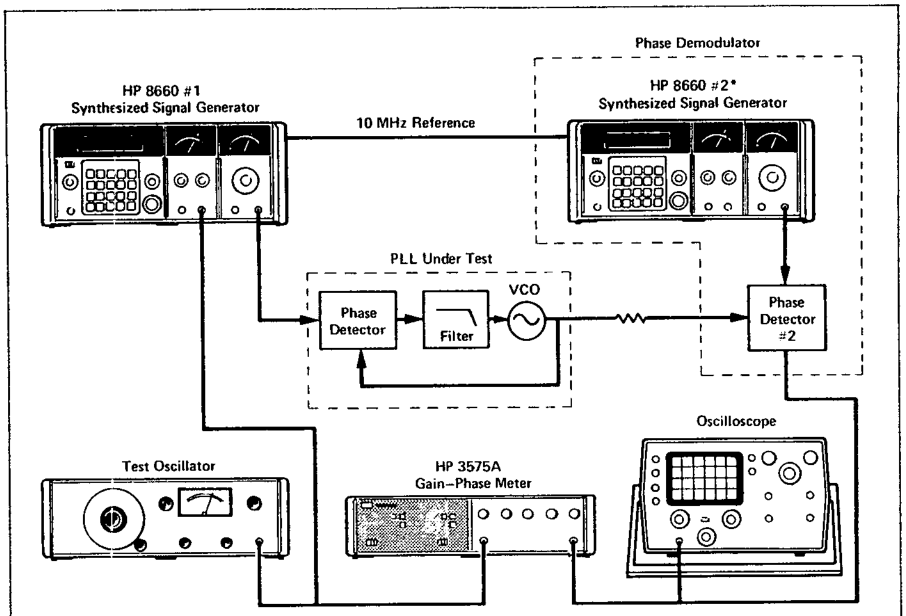


Figure 4. Variation of Frequency Response With Input Amplitude Obtained Using Test Setup Shown in Figure 2.



* HP 8660 #2 can be replaced with an HP 8640A/B Signal Generator. See Appendix.

Figure 5. PLL Analysis Setup Using a Gain-Phase Meter.

USING A GAIN-PHASE METER

Using a gain-phase meter it is easy to obtain phase as well as amplitude response information about the PLL under test. The test setup is very similar to that using a low frequency spectrum analyzer except that an audio oscillator and gain-phase meter replace the spectrum analyzer (see Figure 5).

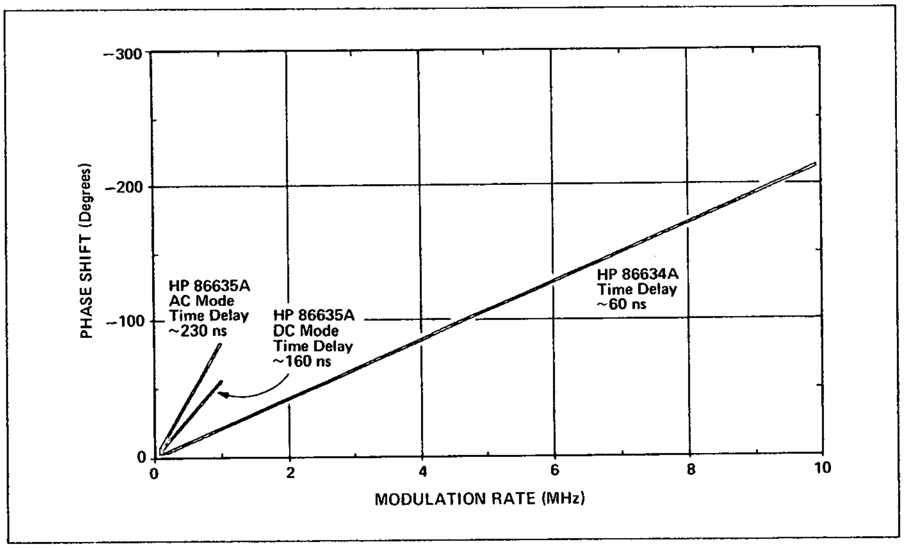


Figure 6. Typical Phase Shift of 8660 ϕM Measured from Modulation Section Input to RF Section Output.

Operation

This test setup is very similar in operation to the system using a low frequency spectrum analyzer except that this test setup yields phase as well as amplitude information.

Using a Gain-Phase Meter allows measurements to be made at rates from 1 Hz to 10 MHz. The phase information that results is the difference between the modulation at the input of 8660 #1 and at the output of the PLL. At low frequencies the phase shift due to the 8660 is extremely small and increases as it approaches the modulation section bandwidth. This phase shift at high rates due to the 8660 can be accounted for by first taking calibration readings with the PLL out of the circuit and then subtracting these readings from those taken with the PLL in the circuit.

The digital display of the HP 3575A Gain-Phase Meter makes it convenient to rapidly make a point-by-point plot. For a swept phase amplitude display an XY plotter could be used with the HP 3575A or a network analyzer such as the Model 8601A/8407A or Model 3040A could be used.

Since the filtering previously provided by the spectrum analyzer's IF filter is not available with the HP 3575A Gain-Phase Meter, more attention must be given to measurement system signal-to-noise ratio. Power-line interference can significantly affect both amplitude and phase measurements if steps are not taken to reduce it (such as using a common power line receptacle, using short interconnecting cables, etc.).

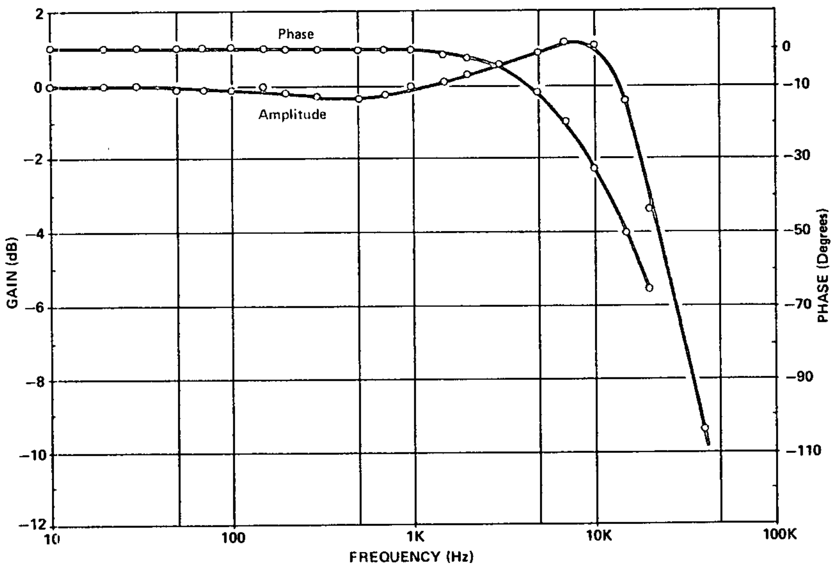


Figure 7. Complete Bode Plot of PLL Obtained Using the Test Setup Shown in Figure 5.

Measurement Procedure

The procedure for this setup is similar to that using a low frequency spectrum analyzer (page 6) with one minor exception. For certain phase detectors such as mixers it is possible to operate on a positive or negative slope which results in a 180° phase difference. This condition is indicated by an extra 180° phase shift. This shift can be eliminated by repeating the step-up, step-down process as necessary or by inverting the gain-phase meter phase reference switch.

USING AN RF SPECTRUM ANALYZER

This method of obtaining frequency response is extremely useful because few instruments are required and the test setup is extremely simple (see Figure 8). This method can be used to test loop frequency response at rates up to 10 MHz and is limited at low frequencies only by the resolution of the spectrum analyzer.

Operation

In this setup the 8660 is phase modulated using a test oscillator and the PLL frequency response is displayed by the level of the first sideband as the modulation rate is varied.

This technique is possible because in phase modulation the level of the sidebands is independent of the modulation rate. Also for small modulation deviations (i.e., less than 30°) the amplitude of the first sideband is almost directly proportional to the phase deviation. Thus the first sideband amplitude essentially tracks the closed loop frequency response.

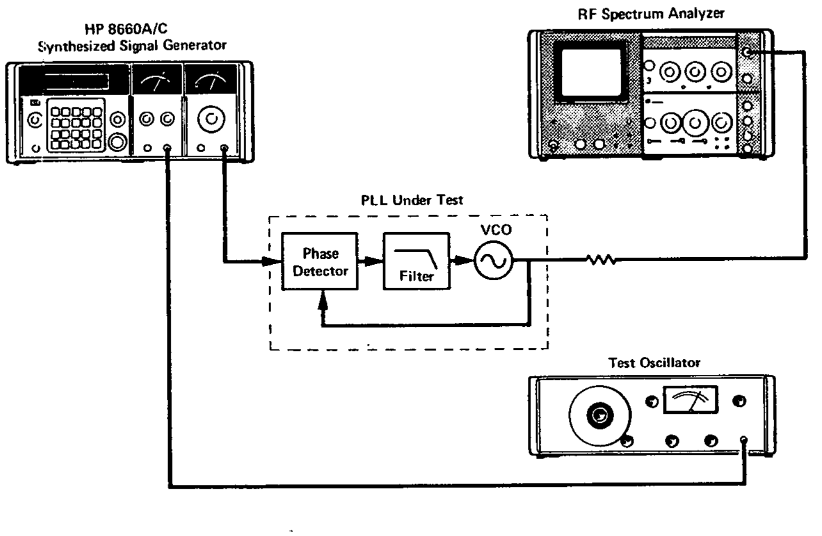


Figure 8. PLL Analysis Setup Using An RF Spectrum Analyzer.

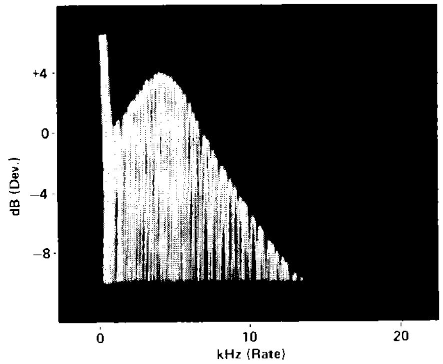


Figure 9. PLL Frequency Response Obtained Using the Test Setup Shown in Figure 8.

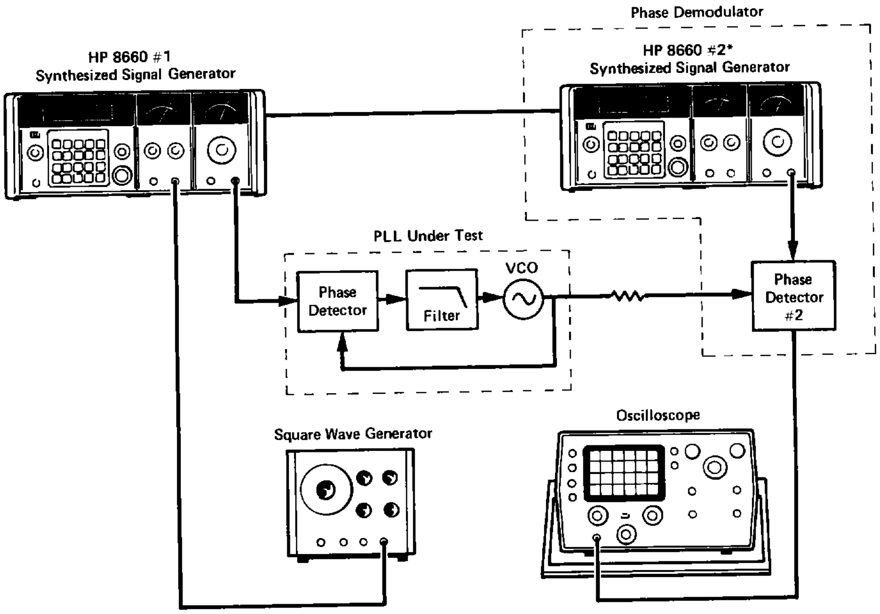
Measurement Procedure

1. With the 8660 phase modulation on and adjusted for a deviation of less than 30°, adjust the spectrum analyzer to the appropriate scan width and resolution. Tune the analyzer such that the carrier is on the left edge of the display. Since the first sideband carries the frequency response information, adjust the spectrum analyzer's IF attenuation so that this sideband is conveniently positioned vertically on the display.
2. If the spectrum analyzer has variable persistence, turn it to maximum and slowly vary the audio oscillator frequency. The resulting display is the PLL frequency response (see Figure 9). If variable persistence is not available, the sideband level could be manually recorded.

In many applications it is desirable to measure a phase lock loop's response to transients in order to determine such parameters as rise time, overshoot, damping factor, etc. The test setup shown in Figure 10 can be used to obtain PLL response for step changes in phase. With calibrated phase modulation the size of the phase steps can accurately be controlled to ensure operation in the linear region of the PLL under test and of phase detector #2.

Operation

In this test setup 8660 #1 is phase modulated with a square wave which causes the RF output to switch back and forth between two discrete phases. The VCO output is then demodulated and the resulting response to step changes in phase is displayed on the oscilloscope (see Figure 11).



* HP 8660 #2 can be replaced with an HP 8640A/B Signal Generator. See Appendix.

Figure 10. PLL Transient Analysis Test Setup.

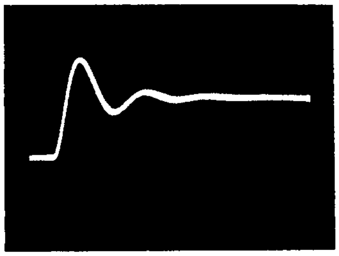


Figure 11. PLL Response to Step Changes in Phase Obtained Using the Test Setup Shown in Figure 10.

Measurement Procedure

1. Connect the equipment as shown in Figure 10. Connect both 8660's to the same frequency standard so that they are frequency coherent.
2. With the modulation off, step 8660 #2 up and back down 1 or 2 Hz until phase detector #2 is operating in the center of its range. This procedure is described in more detail in the section on using a low frequency spectrum analyzer to obtain PLL frequency response, page 6.
3. Turn on 8660 #1 phase modulation with the modulation input in the external dc position. Set the phase deviation small enough to insure linear operation of the PLL and phase detector #2. Then observe the PLL transient response on the oscilloscope.*

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* The 86634A and 86635A display the peak phase deviation resulting from the negative portion of the input waveform. Any dc offset affects meter readings.

Phase Detector Characterization

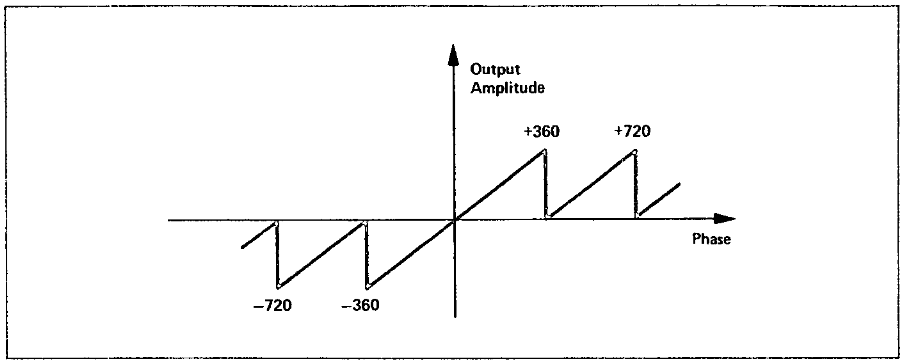

Figure 12. Typical Phase-Frequency Detector Phase/Amplitude Characteristic.

A major element in every PLL and often a difficult one to actually evaluate is the phase detector. Frequently phase detectors can be characterized by offsetting two synthesizers a few hundred hertz, thus sweeping through the phase detector's phase/amplitude characteristic. Although adequate for some phase detectors this method has two serious problems. First, it is often impossible to look at a small section of the phase detector curve in greater detail. Second, and more important, certain types of phase detectors cannot be evaluated at critical points—particularly the popular phase-frequency detectors of the type shown in Figure 12. With this type of detector it is difficult to determine the actual crossover characteristic without phase modulation.

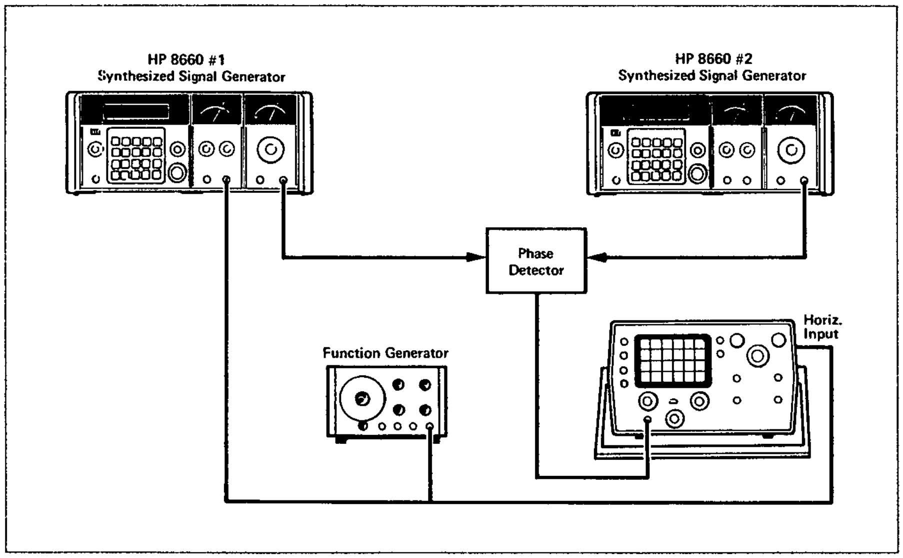

Figure 13. Phase Detector Characterization Test Setup.

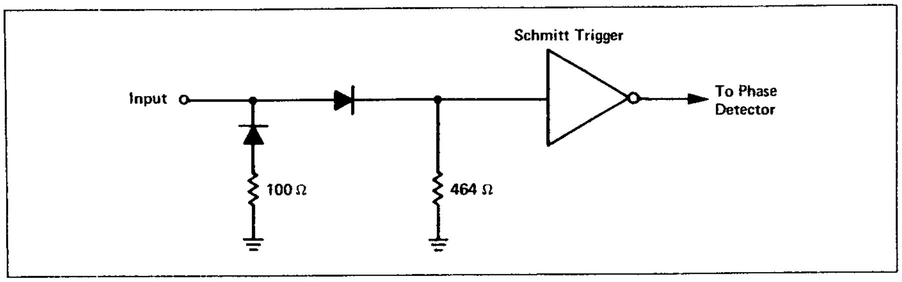

Figure 14. Schmitt Trigger Input Shaper Circuit for TTL Inputs.

Operation

By using the test setup shown in Figure 13 and phase modulating 8660 #1 with either a triangle wave or sine wave, it is possible to linearly display an amplitude vs. phase curve. The resulting waveform on the oscilloscope is the phase detector response over a selected portion of its characteristic.

Measurement Procedure

1. With the equipment connected as shown, set both 8660's to the same frequency, turn the modulation off, and step 8660 #2 up and back down again until the dc voltage out of the phase detector is reached for that portion of the phase detector characteristic to be analyzed. For phase-frequency detectors such as those shown in Figure 12, it will be necessary to step 8660 #2 down first and then back up in order to analyze the region to the left of the crossover point. This procedure is described in more detail in the section on using a low frequency spectrum analyzer to obtain PLL frequency response, page 6.
2. If a digital phase detector is tested, a circuit similar to that in Figure 14 could be used to convert the 8660 sine wave to digital pulses.
3. With the modulation on, the oscilloscope displays the phase detector characteristic over the region of the input deviation.* Resolution can be increased by reducing the peak input deviation and increasing the oscilloscope sensitivity.

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* The 86634A and 86635A meters display the peak phase deviation resulting from the negative portion of the input waveform.

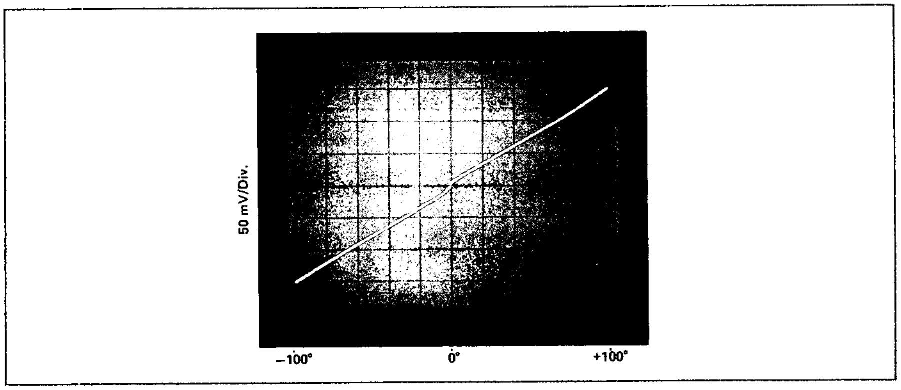

Figure 15. Phase-Frequency Detector Phase/Amplitude Characteristic Obtained Using the Test Setup Shown in Figure 12.

Calibrated phase modulation from an 8660 Synthesized Signal Generator opens a new dimension in Phase Lock Loop analysis. As has been shown, phase modulation provides an easy, accurate way to characterize closed loop phase lock loops and phase detectors.

The test setups used in this Application Note were chosen to provide the reader with a clear understanding of the areas of usefulness of phase modulation in PLL analysis. As such they can be easily modified to suit a wide variety of PLL's and can accommodate limited substitution of other test equipment, depending upon the reader's accessibility to the instrument types called out in this discussion. (See Appendix which follows.)

For more information on the uses of phase modulation refer to AN 164-4 "Digital Phase Modulation (PSK) and wideband FM using the 8660A/C Synthesized Signal Generator."

Appendix

It is possible to substitute an 8640A/B Signal Generator* for 8660 #2 in many of the test procedures previously described by using a double balanced mixer such as the HP 10514A as a phase detector and the FM input to phase lock the 8640 Signal Generator (see Figure 16). This arrangement distorts low-frequency loop readings, can significantly alter transient response measurements, and is slightly less convenient than using two synthesizers; but this method can be quite adequate for testing loops with bandwidths of a few kilohertz or more.

Operation

This arrangement is a phase lock loop itself. The double balanced mixer is acting as a phase detector. As the 8640 tends to drift away from the VCO output frequency an error voltage is generated in the mixer that drives the 8640 frequency back to that of the VCO thus maintaining the 8640 output phase locked to that of the VCO.

Measurement Procedure

1. Connect the equipment as shown and set the 8640 Signal Generator FM mode to dc, the FM vernier fully clockwise, the FM peak deviation to the widest permissible, and turn the counter lock **off** if using an 8640B.
2. Adjust the 8640 Signal Generator to exactly the same frequency as the VCO and use the fine tune to adjust the mixer output to zero volts dc.
3. Adjust the FM range selector to the smallest setting that allows lock and convenient measurements. While reducing the FM deviation range setting adjust the fine tune to maintain the mixer output at zero volts dc. Reducing the FM

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* Many RF signal generators with dc coupled FM could also be used.

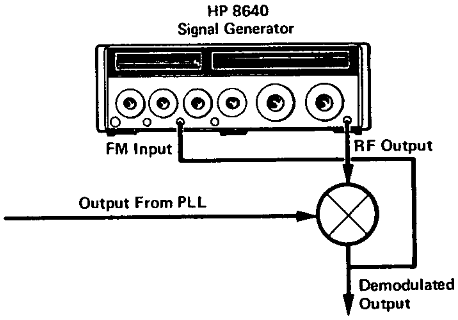

Figure 16. Setup using an 8640 Signal Generator to replace 8660 #2.

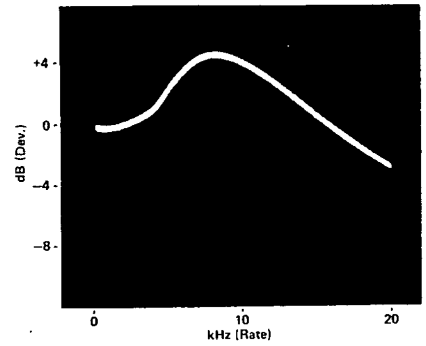

Figure 17. PLL Frequency Response Display Using An 8640 Signal Generator and Mixer as the Demodulator. Compare with Figure 3.

deviation setting reduces loop bandwidth thus reducing measurement distortion. Periodically the fine tune must be adjusted to compensate for system phase drift and to maintain the mixer in its linear range.

4. The 8660 phase modulation can now be turned on and measurements taken.

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