CLARKE-HESS COMMUNICATION RESEARCH CORPORATION
clarke-hess.com

MODEL 5002

PHASE VERIFICATION BRIDGE SET

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WARRANTY

All *CLARKE-HESS* instruments are warranted against defects in materials and workmanship. This warranty applies for one year from the date of delivery of the instruments. The *CLARKE-HESS Communication Research Corp.* will repair or replace instruments that prove to be defective during the warranty period. For such repair or replacement the instrument must be returned to *CLARKE-HESS* and, in our opinion, the instrument must not have been subjected to unreasonable usage or to internal reworking. No other warranty is expressed or implied.

CLARKE-HESS assumes no liability for secondary damages or charges.

CLAIM FOR DAMAGE IN SHIPMENT

The instrument should be thoroughly inspected immediately upon original delivery to purchaser. All material in the container should be checked against the enclosed packing list. The manufacturer will not be responsible for shortages against the packing sheet unless notified immediately. If the instrument is damaged in any way, a claim should be filed with the carrier immediately.

I BASIC ASSEMBLIES

1.1 INTRODUCTION

The Model 5002 Phase Verification Bridge set comprises passive devices that are used in conjunction with Model 5500-2 Phase Standard and an output null indicator such as a true rms voltmeter, an oscilloscope or a wave analyzer to verify that the Phase Standard is continuing to operate within its specified phase accuracy limits. Each bridge has two input terminals for the two output terminals of the Phase Standard and an output terminal to which the null indicator is connected. An impedance (a resistor or a capacitor) is connected between each input terminal and the output terminal.

1.2 BASIC ASSEMBLY AND SPECIFICATIONS

The Model 5002 Phase Verification Bridge Set comprises:

(1) A set of four phase verification bridges.

(2) A set of three inter-connecting coaxial cables.

(3) An Instruction Manual

(4) A set of data comparing the particular Bridge Set to the master Bridge set.

The four Phase Verification Bridges have the following form..

(1) 5002A. A one-to-one resistive bridge.
Nominal loading of 50kΩ at its two inputs at balance. Usable from 1Hz to 50kHz. Inherent phase error less than ±1m° to 1kHz and ±2m° to 50kHz.

(2) 5002B. A one-to-one capacitive bridge.
Nominal loading of 900pF at its two inputs at balance. Usable from lkHz to 200kHz. Inherent phase error less that ±2m° from 1kHz to 50kHz and less than ±8m° to 200kHz. (May be used below lkHz if special precautions are observed)

(3) 5002C. A ten-to-one capacitive bridge.
Nominal loading of 900pF and 90pF at its two inputs at balance. Usable from lkHz to 200kHz. Inherent phase difference from the Standard C Bridge between 5kHz and 50kHz is less than ±2m° and less than ±8m° to 200kHz.

(4) 5002D. A hundred-to-one capacitive bridge.
Nominal loading of 1000pF and l0pF at its two inputs at balance. Usable from lkHz to 200kHz. Inherent phase difference from the Standard D Bridge between 5kHz and 50Hz is less than ±2m° and less than ±8m° to 200kHz.

1.3 OUTPUT INDICATOR

As an output indicator the bridges require some sort of signal indicator. This indicator may be an oscilloscope, an true rms voltmeter or a wave analyzer. For automated performance and numerical results the choice should be an IEEE-488 equipped, true rms ac voltmeter. (The voltmeter bandwidth should be at least three times the highest frequency to be measured.)

If one wishes to use the Phase Bridges to investigate small output voltages from the Phase Standard then the output voltmeter needs to have a low "noise floor" or voltmeter noise will obscure the bridge output. (A low noise amplifier with a gain or 10 or 100 between the bridge output and voltmeter may be useful in such cases.)

Since the bridge outputs are dealt with on a relative basis, the absolute accuracy of the indicator voltmeter is normally not significant.

1.4 PHYSICAL CONSTRUCTION

Figure1 illustrates the physical construction of one of the four bridges.

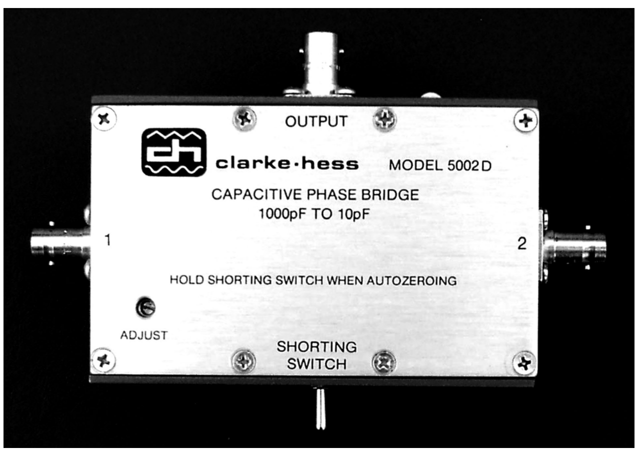

Figure 1. Capacitive Phase Verification Bridge

The Bridge has two BNC input terminals labeled #1 and #2. It has a single BNC output terminal. It has a momentary shorting switch and a screw diver AMPLITUDE adjustment.

II OPERATION

2-1 INTRODUCTION

A four arm bridge has a single generator, and at least two arms are adjusted to produce the minimum output. With the Phase Standard, two outputs exist with an adjustable phase shift between them. This means that two arms are sufficient for the bridge. The bridge can be balanced by adjusting the relative amplitude of the two generators and the phase angle between them. **If the two impedance arms of the bridge have identical phase angles, the bridge will balance when the phase angle between the two bridge inputs is exactly 180°**, and each input amplitude divided by the magnitude of the impedance connected to its input has the same value. All of the bridges are designed and constructed so that the two impedances have identical phase angles over a broad range of frequencies.

Since, in general, the two adjustments are independent, the amplitude balance can be made and then the phase balance. In practice, the amplitude gradations available from the Phase Standard, even though they are often as small as 1mV, are not sufficient to allow an accurate amplitude balance. To solve this problem, each bridge includes an AMPLITUDE vernier which permits the adjustment of the amplitude between the amplitude settings of the Phase Standard. Since the trimmer is of the same impedance type as the main arm of the bridge, it adjusts the amplitude without causing phase shifts. The difference between the phase indication on the Phase Standard at balance and 180° is the phase error in the Standard plus any small error in the bridges. Usually an offset of 180° is entered into the Phase Standard and the phase indication at balance becomes the phase error.

2-2 BASIC CONNECTIONS

Figure 2 illustrates the basic interconnection of the Phase Standard, the Bridge, and a bridge output indicating device, a Voltmeter in this case.

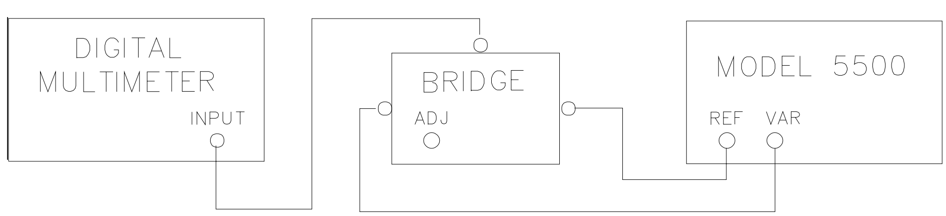

Figure 2. Interconnection of a Phase Standard, Bridge, and a Voltmeter.

When used as directed, the Bridges provide phase readings, in millidegrees (m°) around the 180.000° point of the Phase Angle Standard. Since the angles in the Phase Standard are all generated digitally, their relative agreement is within 1.37 m° (which is the least significant bit of the phase generation circuitry). Checking the 180° point absolutely is sufficient to show the proper operation of the Phase Standard at all other angles.

Since the impedances of the two arms of the bridge have been matched to have identical phase angles, it follows that when they are driven by signals that are exactly 180.000° out of phase, the fundamental portions of the signals from the two arms cancel. The residual signal will be harmonic or noise terms from the two signals that do not cancel. As will be shown in the Theory of Operation section of this manual the effects of this residual signal may be largely removed allowing one to experimentally reproduce the theoretical phase in vs. phase out plot very closely for a great many combinations of frequency and amplitude, including cases where the Bridge output has apparently vanished into the noise background.

2-3 SAMPLE MEASUREMENT

INITIAL SET-UP

The Phase Standard REFERENCE output is connected to the #1 input of the Bridge with a 30 cm (1 ft) coaxial cable. The VARIABLE output is connected to the #2 input of the Bridge with a similar cable. The OUTPUT of the Bridge is connected to the voltmeter with a convenient length of cable. (At higher frequencies, the cable capacitance will cause the absolute values of the output voltage to vary with cable length, but should not cause the computed phase errors to vary.)

To make a measurement with a 1-to-1 bridge at 1kHz with 50V levels, proceed as follows.

a.) Set the Phase Standard FREQUENCY to 1000Hz.

b.) Set the Phase Standard PHASE to 0.000° and the OFFSET to 180.000°.

c.) Set both the REFERENCE and the VARIABLE outputs to 50.00V

d.) Hold the SHORTING SWITCH on the Bridge to either side and AUTOZERO the Phase Standard several times.

e.) Use the adjustment screw driver to vary the ADJUST control until the Voltmeter reading goes through a minimum. - If this adjustment is not possible at 1kHz something is probably wrong either with the equipment, the interconnection, or the procedure. At high frequencies it is possible that one of the Phase Standard outputs must be varied slightly away from the 1-to-1 condition to allow the amplitude minimum adjustment to be made.

f.) Note the Voltmeter reading then repeat step d.. several times. On the second and subsequent AUTOZERO operations the Voltmeter reading should be essentially same. When operating at higher frequencies there may be some difference between readings. Stop the operation on the reading which occurs most frequently.

BALANCING THE BRIDGE

Vary the Phase Standard PHASE, using the INCREMENTING keys, to determine the lowest minimum value. The final value of phase is the Phase error.

When an rms voltmeter is used as a null detector, its internal noise (and sometimes the minimum amplitude before the display is forced to zero) prevent an accurate determination of the null position. This problem can be overcome by setting the offset at 180°, balancing the bridge as well as possible, entering a large negative angle into the Phase Standard and recording the rms output voltage, entering the same magnitude angle, only positive, into the Phase Standard and recording the rms output voltage and then utilizing the following formula.

$$\textbf{Phase error} = \theta\, [V_{neg} - V_{pos}] / [V_{neg} + V_{pos}] \qquad (1)$$

where θ is the magnitude of the large angle in degrees, V_{neg} is the rms output for the negative angular deviation and V_{pos} is the rms output for the positive angular deviation. The Phase error is in degrees and has a resolution of a fraction of a millidegree.

Thus if a negative 0.100° phase deviation yields a voltage of 41.334mV and a positive 0.100° deviation yields a voltage of 40.325mV, the phase error is1.23m°. In this case, the Voltmeter minimum voltage should occur at phase settings of 1 or 2m°.

2-4 COMPUTER OPERATION

If the rms Voltmeter used as the null detector has an IEEE-488 interface, then it may be connected along with the interface of the Model 5500-2 to a bus controller. National Instruments supplies many of these controllers along with the necessary software to implement them on a standard computer. A simple program to measure the phase error of the Model 5500-2 after the manual set up has been completed deviates the phase angle of Phase Standard by -θ, measures the reading of the voltmeter, deviates the phase angle of the Phase Standard by θ, measures the reading of the voltmeter, and calculates Equation 1.
With the one-to-one bridges (5002A and 5002B) it is not too critical to hold the shorting switch when AUTOZEROING. In addition, if Equation 1 is used to determine the phase error and θ is selected to be large (greater than 2 or 3 °), the rms Voltmeter readings are not affected by the fact that the bridge is not perfectly balanced in amplitude during set-up. Consequently, the Phase error at a number of different amplitude and frequency settings may be made without any manual adjustments of the bridge. The user should verify these assumptions in a particular-set up by first nulling the bridge in amplitude and AUTOZEROING with the shorting switch pressed prior to calculating the Phase error. The user should then offset the amplitude balance slightly and AUTOZERO without depressing the shorting switch prior to calculating the Phase error. The readings should agree within 1 to 2 m°.

Unfortunately this procedure does not work as well for the 10:1 and the 100:1 bridges.

2-5 ABSOLUTE PHASE MEASUREMENTS

If one determines the Phase error with either of the 1-to-1 Bridges then reverses the cables between the Phase Standard and the Bridge and determines the Phase error again (without AUTOZEROING), the results may be combined to produce an absolute phase error for both the Phase Standard and for the Phase Bridge.

In particular, if the Phase errors from the two measurements are added algebraically and divided by two then the result is the Phase error for the Phase Standard. If the Phase errors from the two measurements are subtracted algebraically and divided by two then the result is the Phase error for the Phase Bridge.

Thus, even if a Phase Bridge has a built-in phase error, it may still be used to provide an accurate phase measurement of a Phase Standard.

2-6 SUGGESTED PHASE MEASUREMENTS

The suggested tests for the Model 5500-2 are included in Section III of its instruction manual.

III BRIDGE CALIBRATION

3-1 INTRODUCTION

This section describes the methods used to verify that the Model 5002 Phase Verification Bridge set is operating within its specified limits. The 5002A and the 5002B bridges are shown to be self calibrating, while the 5002C and the 5002D bridges can be calibrated by comparing them with standard bridges.

3-2 CALIBRATION OF 1:1 BRIDGES

When the magnitude of the impedances in the two arms of the bridge are equal, the calibration of the bridge is very straight forward and can be done at the same time the Phase error in the Phase Standard is being determined. This is accomplished by first determining the phase error as described above and then, without adjusting anything, interchanging the two input cables to the bridge and determining the phase error a second time. As can be easily shown, **the sum of the two Phase errors divided by 2 is the error in the Phase Standard and the difference of the two Phase errors divided by 2 is the error in the bridge.** If there is no bridge error, both Phase errors are the same and equal to the Phase Standard error. If there is no Phase Standard error, the phase errors are equal and opposite in sign and track the bridge as its position is reversed.

3-3 CALIBRATION OF 10:1 AND 100:1 BRIDGES

When the magnitude of the impedances of the two arms of the bridge are not equal, the bridge is calibrated by the comparison method. In this case, the bridge to be calibrated and a Standard Bridge having the same ratio of the impedance magnitude of both arms as the bridge under test, are connected in parallel to the same Phase Standard. That is, a "tee" is placed on each output of the Phase Standard and the two equal length cables connected to each "tee" are connected to the corresponding inputs of each bridge. Each bridge has its own rms voltmeter connected to its output. Both bridges are nulled and the Phase Standard is deviated to obtain the Phase Error of both bridges simultaneously. Since the Phase Standard component of both errors is the same, the difference of the two errors is the error of the bridge under test relative to the Standard Bridge.

3-4 STANDARD BRIDGES

A Standard Bridge is a bridge that is known to have the same phase angle for the impedances in both of its arms. When such a bridge is used with the Phase Standard, the entire phase error away from 180° is due to the Phase Standard. When such a bridge is constructed, it can be used as a standard to calibrate other bridges as discussed in the preceding paragraph.

Clarke-Hess has constructed its Standard Bridge, in the same fashion that it constructs all of its unequal amplitude bridges.

The Clarke-Hess approach is to obtain a large number of low dissipation, high quality multi-layer ceramic capacitors and match them for phase angle at a number of frequencies between 100Hz and 200kHz. Two 900pF capacitors matched in such a fashion are used in the arms of the Model 5002B bridge. Eleven 900pF phase angle matched capacitors are used in the arms of the Model 5002C bridge. Ten are placed in series to form the 90pF arm while a single one is used for the 900pF arm. Twenty 100pF phase angle matched capacitors are used in the arms of the Model 5002D bridge. Ten are placed in series to form the 10pF arm while ten are placed in parallel to form the 1000pF arm.

The capacitors are matched in a test jig which resembles a 1:1 capacitor bridge. A reference capacitor is placed in one arm and the capacitor under test is placed in the other arm. The Phase error is recorded at all frequencies of interest. Keeping the same reference capacitor, the procedure is repeated for a second capacitor, and so on. Capacitors with the same set of phase errors for the differing frequencies are matched. The fact that the loss and the dissipation factor of these capacitors is low, keeps the Phase error terms low and thus makes the matching reasonably straight forward.

Confidence in this procedure has grown over the years as the number of bridges produced, using capacitors from different manufacturers, all resulted in bridges which were essentially identical to the in-house reference bridge set, S/N 71. In particular, typical agreement was within 1m° from 100Hz to 50kHz and within 4m° to 200kHz. Bridges constructed in this fashion do indeed provided an intrinsic standard for measuring errors in phase angle.

Resistance Bridges

Capacitor Bridges become very high impedances at low frequencies (below 100Hz) and are subject to phase errors because of parallel resistance loss. Consequently, for low frequency phase measurements, bridges with resistive arms are superior. Because of unequal stray capacitance across the two resistors, the phase error in such a bridge increases with increasing frequency. (Low loss stray capacitance has no effect on the angle of a capacitor bridge). To make such a bridge essentially perfect, in the 1:1 case, a variable capacitor, in the form of a wire bent over the resistor with the lower amount of stray capacitance, is adjusted until the bridge has no error at 50kHz as determined by the bridge reversal method. With this adjustment, similar bridge reversal measurements at other frequencies always indicate that the bridge produces very little phase error. Very little error is also indicated when the 1:1 resistive bridge, Model 5002A, is compared with the Model 5002B capacitive bridge.

IV CALIBRATION DATA

4-1 INTRODUCTION

This section contains the comparison data between the Model 5002 Phase Verification Bridge Set accompanying this manual and the Standard Bridge set (S/N 71) at Clarke-Hess. The user can verify these data for the 5002A and 5002B by the bridge reversal method discussed in Section III