Design and Performance Evaluation of the NIST Digital Impedance Bridge

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Abstract An impedance bridge that compares two-terminal standard inductors to characterized resistors is described. A dual-channel digitally synthesized source and sampling digital multimeter are used to generate and measure relevant bridge signals. A linear interpolation algorithm is used to autocalibrate the bridge to a 1 nF air-dielectric capacitor. An intercomparison of the new bridge with existing measurement standards in the low audio frequency range for inductors from 1 mH to 10 H will be reported.

I. Introduction

This paper describes an automatic impedance bridge that is comprised mostly of commercially available instruments to automatically compare a standard ac resistor to a test inductor. The bridge is similar to the one described by Field in 1990 [1]. It is quite simple, requiring only a tuned detector and a controller in addition to the digital generator and sampling digital multimeter (DMM). The bridge is a refinement of the one described in [2], with special attention being paid in this paper to the characterization of the standard impedances and to the investigation of the sources of error.

II. Hardware

A simplified schematic of the digital impedance bridge is shown in Fig. 1. The bridge consists of seven standard ac resistors from 100 Ω to 100 kΩ, the most suitable of which is then compared to the test inductor. For simplicity, Fig. 1 shows only one of the standard resistors, along with its associated parasitic components.

The bridge is supplied with test signals V_R and V_V by a commercially available dual-channel signal generator. The generator must have amplitude stability of about 10 ppm/hour, amplitude resolution corresponding to at least 12 bits, and phase resolution of about 0.001 degrees. In order to supplement the generator's amplitude resolution, the bridge incorporates programmable power amplifiers A_1 and A_2, which increase amplitude resolution from 12 bits to approximately 20 bits.

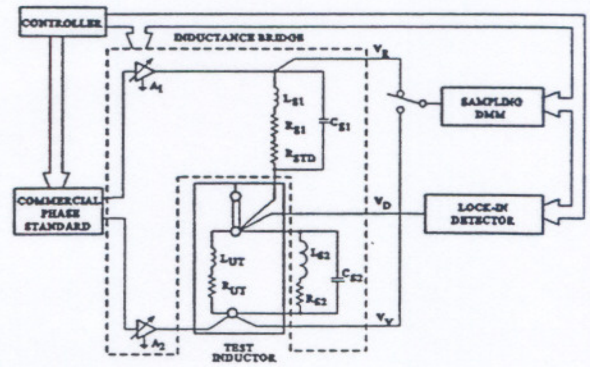

Figure 1. Impedance bridge simplified diagram.

The sampling DMM quantizes signals V_R and V_V with 16-bit resolution using an equivalent-time sampling method that results in effective sampling intervals of as low as 10 nanoseconds. Subsequent analysis of the sampled data is used to extract the test signals' amplitude ratio and phase relationships; therefore, the DMM's ac voltage measurement linearity is much more critical than its absolute accuracy. Although not shown in Fig. 1, the DMM is also used to perform in-situ, 4-terminal dc resistance measurements of the seven standard ac resistors.

III. Measurement Technique

Referring to Fig. 1, the bridge operates by comparing a known standard ac resistor to the two terminal inductor under test, shown as L_{ut}, along with its associated series resistance, R_{ut}. The test inductor can also be modeled as an inductance and equivalent parallel resistance, whichever model is more appropriate. The signal generator is adjusted to produce a null signal, V_D, using an autobalancing algorithm, to be detailed in the final paper. When operating at a null, the ratio of the unknown total impedance, termed collectively as Z_{UT}, to the standard impedance, termed collectively as Z_{STD}, is proportional to the ratio of the two voltages by:

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[1] *Electricity Division, Electronics and Electrical Engineering Laboratory, Technology Administration, U.S. Department of Commerce. Official contribution of the National Institute of Standards and Technology; not subject to copyright in the United States.*

$$\frac{V_V}{V_R} = \frac{Z_{UT}}{Z_{STD}}, \text{ or } Z_{UT} = \frac{Z_{STD} V_V}{V_R}. \qquad (1)$$

The sampling DMM is used to measure the ratio of V_R to V_V and the phase angle between them using a 4-parameter sine fit algorithm as described in [3]. The L_{UT} and R_{UT} values are then computed by extracting the L_{S2}, R_{S2}, and C_{S2} open-circuit residual impedances.

IV. Autocalibration Procedure

Even with careful attention to minimizing lead and stray impedances linked to the standard and test impedances, it became necessary to develop a means to measure the residual strays present in the bridge. A linear interpolation procedure was developed for this purpose.

As stated earlier, the dc resistance components of the seven standard impedances are measured in-situ to a one-sigma uncertainty of approximately 5 ppm using the sampling DMM. The DMM is routinely calibrated at these cardinal resistance values, since the accuracy to which these values are known directly affects bridge accuracy. The remaining L_{S1}, R_{S1}, C_{S1}, L_{S2}, R_{S2}, and C_{S2} values are calculated by solving the matrix equation

$$Y_M = \Delta V\, x, \quad \text{thus}$$

$$x = [\, \Delta V^T\, \Delta V \,]^{-1}\, \Delta V^T\, Y_M\,, \qquad (2)$$

where:

ΔV = a 2n x 6 sensitivity matrix computed by estimating the system's V_V to V_R ratio and phase sensitivity to small changes in the equivalent circuit's individual element values, over n different frequencies, using reasonable initial estimates of circuit element values,

Y_M = a 2n-element vector containing measurements of the V_V to V_R ratio and phase information over the same n frequencies, and

x = an error coefficient vector that indicates how well the model agrees with the observed bridge balance measurements.

The above process is then used to adjust the model's R, L, and C estimates until the coefficient vector, x, is sufficiently small. It is important to note that in the above procedure, the test inductor of Fig. 1 is replaced with a known 1 nF gas dielectric capacitor. This substitution has the effect of increasing the bridge's sensitivity to the open-circuit impedance over the n frequencies and allows for better convergence of the interpolation algorithm. Further details of this approach will be given in the final paper.

V. Test Results

The results of an intercomparison of the digital impedance bridge with the present standard (Maxwell Wien bridge) at 1 kHz are given in the table below. Details of the intercomparison for frequencies throughout the audio range will be given in the final paper.

1 mH	10 mH	100 mH	1 H	10 H
11	12	46	32	109

Difference (in ppm) between 1 kHz measurements using the new digital impedance bridge and the Maxwell Wien bridge.

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References

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