Digitally programmable ratio transformer bridge*

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(Received 20 June 1975)

We describe a digitally programmable impedance bridge, used here for low-temperature resistance thermometry, and a compatible digital programming and data logging interface. The bridge employs a commercial programmable ratio transformer to achieve high resolution with minimum circuit complexity. We measure the ratio of the resistances of a carbon thermometer and a fixed reference resistor, both near 2 K, with a resolution limited by Johnson noise in the resistors. The bridge circuit described here is suitable for a variety of programmable or self-balancing impedance measurements.

INTRODUCTION

The increasing popularity of digital data logging and processing has created a growing need for digitally programmable instruments. To automate a measurement of the surface tension of ^{4}He as a function of temperature near the lambda transition,[1] we designed a high-resolution programmable ac resistance bridge for carbon resistance thermometry. The use of a commercially available programmable ratio transformer simplifies the circuitry over that of previously described programmable bridges.[2,3] We also describe a digital data logging interface which programs the bridge to make measurements at fixed thermometer resistance intervals as our experimental cell temperature drifts. Other digital interfaces could adapt this instrument for a variety of programmable or self-balancing applications. The ratio transformer bridge is suitable for measuring capacitance as well as resistance.

THE BRIDGE

A basic ratio transformer bridge circuit[4] is shown in Fig. 1. The bridge is in balance when the ratio of the impedances Z_1/Z_2 is equal to the ratio of the voltages e_1/e_2. The ratio transformer serves as an inductive voltage divider; it is a low-impedance source of a voltage which is an accurate fraction of the input. In the programmable ratio transformer used here,[5] the division ratio is selected by relays.

The ratio transformer bridge is suitable for measuring ratios of impedances of various circuit elements. In our case, the impedances Z_1 and Z_2 are a carbon resistance thermometer and a fixed reference resistor, both at liquid helium temperature. Since these dissipative bridge elements are cold, they contribute much less Johnson noise than if they were at room temperature.[6]

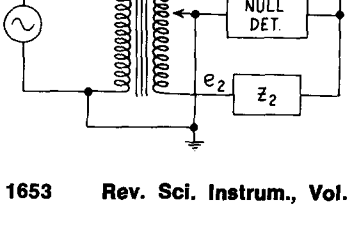

FIG. 1. Basic ratio transformer bridge circuit. The bridge is balanced when the voltage ratio e_1/e_2 equals the impedance ratio Z_1/Z_2.

In this simple bridge circuit, the measured resistances include all contact and lead resistances. In our application, these are small with respect to the 60 kΩ thermometer and 100 kΩ reference resistances. If true four-terminal resistance measurements are required, a programmable ratio transformer can be incorporated into a more complicated circuit.[2,4,7]

We note that stray capacitance is not as troublesome in the ratio transformer bridge as it is in a standard Wheatstone bridge. Capacitance to ground on either side of the measured resistances does not produce an unbalance signal. The quadrature signal introduced by capacitances across the resistors is balanced by small variable capacitors across these bridge arms. It is desirable to use shielded cable for the preamplifier input lead to minimize stray capacitances across the resistors.

NULL DETECTOR

A block diagram of the bridge and null detector is shown in Fig. 2. The bridge is driven at 385 Hz by a Wien bridge sine wave oscillator. This operating frequency is high enough to reduce amplifier $1/f$ noise and is far from frequencies of power line pickup in the ratio transformer. In other bridges we have used odd multiples of 30 Hz synthesized from the power line frequency using a phase-locked loop. Such a technique might be preferable here due to the greater frequency stability and reduction of the distracting effects of power line pickup on an oscilloscope display. The balancing of capacitive bridge components is more critical at this frequency than at a lower one, but the narrow range of thermometer resistances encountered in our application minimizes this problem.

To estimate the maximum resolution of this bridge, we consider the noise sources at the null detector input. The Johnson noise in the two resistive bridge arms is an unavoidable noise source. The source resistance R_s in which Johnson noise is generated is the parallel combination of the thermometer and reference resistances. The greatest output resistance of the ratio transformer is 50 Ω, so its Johnson noise is negligible even though the transformer is at room temperature. The preamplifier contributes additional input noise, which we divide into a voltage noise e_n and a current noise i_n, where e_n^2 and i_n^2 are each measured per unit bandwidth at the operating frequency. Summing these three noise contributions, we obtain the total input noise E_n in a bandwidth B,

$$E_n=[B(4kTR_s+e_n^2+i_n^2R_s^2)]^{\frac{1}{2}},$$

where k is Boltzmann's constant, and T is the absolute temperature of the resistors comprising R_s. The amplifier contributes the least noise relative to the Johnson noise when R_s equals e_n/i_n.

With a 60 kΩ thermometer resistor and a 100 kΩ reference resistor, R_s is 38 kΩ. Since these resistors are at a temperature of 2 K, the Johnson noise in R_s is 2.0 nV–(Hz)$^{\frac{1}{2}}$. For the input preamplifier we have chosen an ultralow-noise field effect transistor[8] with a voltage noise e_n of 1.5 nV/(Hz)$^{\frac{1}{2}}$ at the operating frequency. This is about an order of magnitude below the voltage noise of commercial FET-input operational amplifiers. The current noise of our FET is unknown, but assuming a value of 5 fA/(Hz)$^{\frac{1}{2}}$ typical of FET-input operational amplifiers, the current noise does not contribute significantly to the total noise. It is not practical to optimize the source resistance with a transformer; limited primary inductance and high capacitance restrict the application of transformers to lower source impedances. Little can be gained in our application by optimizing the source resistance, since a noise-free amplifier would reduce the input noise by only 1.9 dB.

After the FET preamplifier, the unbalance signal is further amplified and filtered by two stages of bandpass active filtering.[9] This extensive filtering is necessary to reduce signals at 60 Hz and its harmonics, primarily inductively coupled into the ratio transformer. The filtered signal is amplified in a saturating amplifier to simplify balancing the bridge without frequent adjustment of the gain control. Phase-sensitive detection is provided by an analog multiplier,[10] the output of which is low-pass filtered and monitored on a panel meter or chart recorder. This signal is also tested by a comparator to determine whether the bridge is above or below balance. The comparator output is coupled to the data logger through an optical isolator to prevent introducing switching spikes into the analog circuitry. Heater driving circuitry, not shown in the diagram, provides temperature regulating capability.

PERFORMANCE

Using a fixed metal film resistor at 2 K in place of the thermometer, the bridge performance is consistent with our noise estimates. With a 60 kΩ thermometer R_t, a 100 kΩ reference resistor R_r, a thermometer power dissipation of 5×10^{-10} W, and a single stage low-pass filter with a time constant of 1 sec, the rms noise corresponds to about 0.02 Ω. This implies an input noise of 4 nV/(Hz)$^{\frac{1}{2}}$, which is probably within measurement error of the expected input noise of 2.5 nV/(Hz)$^{\frac{1}{2}}$.

When a carbon resistance thermometer was used in the bridge, we observed an additional noise, proportional to the bridge excitation, of about three times the electronic noise. We did not determine whether this was due to excess noise in the carbon resistor or residual temperature fluctuations.

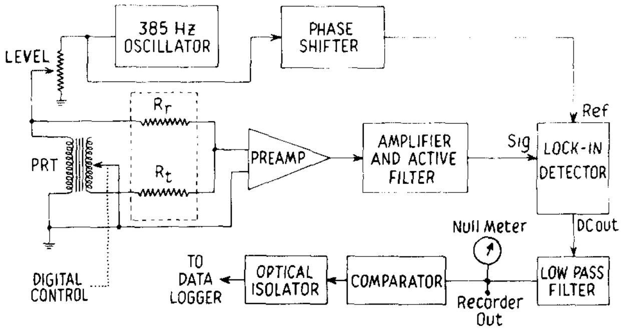

FIG. 2. Programmable resistance bridge and null detector. Components in the dotted enclosure are mounted on the experimental cell. The programmable ratio transformer PRT is controlled by a digital interface.

The ratio transformer produces electrical transients when the relays switch. These caused no difficulties in our experiment, and we did not investigate their nature or how they might be suppressed.

DIGITAL INTERFACE

The digital interface used to program the bridge depends on the specific application. In our case, we cause the temperature of our experimental cell to drift and record the cell thermometer resistance and the binary-coded decimal (BCD) outputs of several digital meters at a series of equally spaced resistances. A block diagram of our interface is shown in Fig. 3. Up to 15 digits of data may be recorded; speed is limited to about 10 points per minute by the settling time of the null detector after the ratio transformer switches.

The bridge setting is determined by the outputs of a chain of six bidirectional BCD counters. For the initial data point, the counters are preset from thumbwheel switches. When the cell temperature reaches the programmed balance point, the comparator output changes state, and a pulse is generated to start the logging of data. The digital voltmeters reading the raw experimental data are signaled to hold their readings until they can be recorded. The data, consisting of these voltmeter readings and the counter outputs which program the ratio transformer, are now present in BCD form at the inputs of four 16-bit multiplexers. A minus sign, decimal point, and final carriage return are coded at the multiplexer inputs using some of the unused four-bit codes. A counter is started which selects each BCD digit in succession and passes it to the output.

The BCD codes are converted to the standard seven-bit ASCII character codes at the multiplexer output. For the BCD digits this merely requires supplying three constant bits; for the other characters the conversion is slightly more complicated. The characters are passed one by one to a Texas Instruments model 720 data terminal, which has parallel inputs for ASCII data. A keyboard strobe indicates when each character is to be read in. The data are printed by the terminal and may be sent on-line to a computer or recorded on digital cassette tape for later analysis.

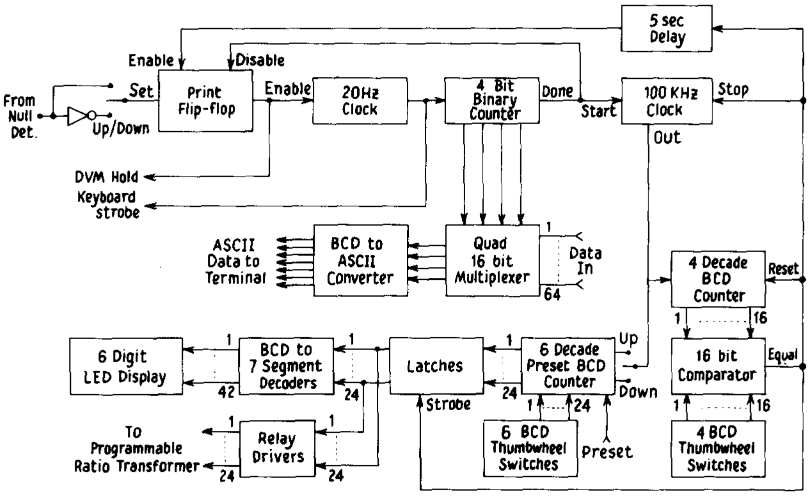

FIG. 3. Digital interface for programming the bridge and logging data automatically.

After the numbers have been passed to the terminal, the ratio transformer setting is incremented by allowing two BCD counter chains to count a 100 kHz clock. The four-decade increment counter starts at zero and counts until it reaches the value set by the increment thumbwheel switches. A digital comparator senses the equality and shuts off the clock. This same clock signal is counted by the main ratio transformer control counter, so its count is increased or reduced by the correct amount. Latches at the main counter outputs hold the old count until the updated count is available. After a 5 sec delay to let the null detector settle, the zero-crossing detector is enabled for the next data point. The main counter outputs are decoded and fed to seven-segment LED displays, which indicate the ratio transformer setting.

The data logger is implemented using standard 7400 series TTL integrated circuits. The ratio transformer relays are driven from a 24 V high-current power supply using Texas Instruments SN75454 peripheral drivers. Use of a wire-wrap board[11] allowed rapid construction and easy troubleshooting. Flat 26-conductor cable with crimp-on connectors was used for digital connections to and from the board. Total parts cost for the digital interface, including the wire-wrap board and suitable power supplies, is less than $500.

ADDITIONAL APPLICATIONS

Our digital interface successfully automated a tedious job. Unfortunately, we soon made several changes in the experimental procedure; additional steps which could not be handled by this simple interface were performed manually. The use of hard-wired logic made modification of the unit difficult. With a more versatile computer-based interface planned for the future, changes in procedure could be accommodated with changes in programming. In addition, much of the present multiplexing and serializing could be eliminated, and data acquisition rates could be increased.

The programmable ratio transformer bridge is also suitable for self-balancing applications. The chain of bidirectional counters could count a clock frequency which might be constant or related to the magnitude of the unbalance signal. Programmed control of bridge gain and filter time constant could reduce balancing time.

The programmable ratio transformer bridge can, of course, be used to measure resistances in applications other than low-temperature thermometry. This type of bridge is also useful for measuring capacitance.

ACKNOWLEDGMENTS

We are grateful to J. W. Chapman for advice on several aspects of the digital data logger and thank James Peters for constructing the digital circuitry.

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[*] Work supported in part by the National Science Foundation.

[1] J. H. Magerlein, Ph.D. thesis (University of Michigan, 1975).

[2] P. C. F. Wolfendale, J. Phys. E **2**, 659 (1969).

[3] R. L. Chase, Rev. Sci. Instrum. **42**, 319 (1971).

[4] For a discussion of ac bridge techniques see, for example, B. M. Oliver and J. M. Cage, *Electronic Measurements and Instrumentation* (McGraw–Hill, New York, 1971), Chap. 9.

[5] A variety of programmable ratio transformers with different resolutions and a choice of binary or BCD coding are produced by Singer Instrumentation, 3211 South La Cienega Blvd., Los Angeles, CA 90016. We used a model PRTD-60012, which has BCD coding and six-digit resolution.

[6] Ratio transformer bridges with both resistors at helium temperature have been used, for example, by G. Ahlers, Phys. Rev. **171**, 275 (1968) and G. G. Ihas and F. Pobell, Phys. Rev. A **9**, 1278 (1974).

[7] A. C. Anderson, Rev. Sci. Instrum. **44**, 1475 (1973).

[8] Type C413N from Teledyne Crystalonics, 147 Sherman St., Cambridge, MA 02140. We used the simple circuit from the transistor data sheet. Several high-transconductance switching FETs were also found to have quite low voltage noise. We measured a voltage noise of about 2 nV/(Hz)$^{1/2}$ for the Motorola type 2N4860.

[9] The bandpass filters are built from universal active filter type FS-60 from Kinetic Technology Inc., 3393 De La Cruz Blvd., Santa Clara, CA 95950. A similar product is now available from Burr–Brown Research Corp., International Airport Industrial Park, Tucson, AZ 85734.

[10] G. I. Rochlin, Rev. Sci. Instrum. **41**, 73 (1970).

[11] Type 8136-PG21-60 from Augat Inc., 33 Perry Ave., Attleboro, MA 02703.