Simple Instrumentation for the Inductive Detection of Superconductivity

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A circuit is described which can be used to detect the superconductive transitions of several elements used as thermometric fixed points. The circuit is found to perform as well as much more elaborate mutual inductance bridges previously used for this research. Details for construction and operation of the circuit are given.

Recent work at the National Bureau of Standards has shown that several elements exhibit very sharp and reproducible superconducting transitions. Samples of these elements have been incorporated into a device called SRM 767 used to define fixed points on a temperature scale. The superconducting transitions are readily observed as a change in mutual inductance of a pair of coils surrounding the sample. Normally we display the transition on an X-Y recorder (see Fig. 1), where the vertical axis is driven by the output of a phase-sensitive detector which monitors the offset of a mutual inductance bridge circuit. The bridge is a Hartshorn circuit, consisting of two shielded transformers, a 50 mH standard mutual inductance, a resistive balance network, and a voltage divider for the inductive balance. In this article we wish to describe a bridge circuit which yields identical results, but is much easier and less expensive to build. Since the aim of either circuit is simply the detection of the superconductive transitions, it is clearly advantageous to use the simpler circuit. Use of SRM 767 and this circuit will permit the repeated attainment of ±1 mK reproducibility at each of five fixed point temperatures: 7.201 K (the measured value of the SRM 767 Pb transition), 3.417 K (In), 1.175 K (Al), 0.844 K (Zn), and 0.515 K (Cd).

This circuit, drawn in Fig. 2, consists of two pairs of coils: one pair is empty and the other contains one or more samples with different transition temperatures. The two primaries are driven at an audio frequency by the reference output of a phase-sensitive detector, while the two secondaries form one branch of the bridge. A change in state of one of the samples is observed as a change in output of the phase-sensitive detector N. The wiper on the 10-turn variable resistor, K, is moved rebalance the inductive voltage comp-

![Fig. 2. Circuit for the inductive detection of superconductivity. The dotted box includes the part of the circuit maintained at low temperatures. It consists of five superconductive samples mounted in a common copper primary and secondary coil pair. The ac magnetic field in this primary and another at room temperature is provided by the "Reference Output" of a phase-sensitive detector. Changes in the mutual inductance of the low temperature coils due to a superconductive transition appear as a voltage across the phase-sensitive detector N, which is located in the bridge circuit. The detector used here is a Princeton Applied Research model 412 preamplifier and a model 120 lock-in amplifier. The bridge is balanced using a 10-turn 10 kΩ Helipot (Roekman Instruments, Inc., linearity tolerance ±0.01%) and a 0.01 pF increment decade capacitor, C. The primary coils are 400 turns of 38 AWC copper wire wound in two layers 2.5 cm long on a Bakelite former of 0.39 cm o.d. The secondary coils consist of 2000 turns of No. 46 AWC copper wire 1 cm long with an i.d. of 1.0 cm and o.d. of 1.58 cm. One such primary and secondary is supplied as part of the SRM 767.](image-url)
A component and a variable capacitor is used to rebalance the quadrature voltage component.

Calibration of another thermometer using an SRM767 device is accomplished by the following technique. Generally the bridge is balanced several millikelvins away from a given superconductive transition. The temperature of the cryostat is then varied so that the appropriate sample passes completely through its transition. The cryostat is then stabilized at the center of the transition (defined as \( T_c \)) while calibration of other thermometers at this particular fixed point is completed. Before going to the next fixed point both components of the signal are rebalanced since the superconductive transition produces both inductive and resistive changes in the bridge circuit. The resistive balance (accomplished by the variable capacitor) is not very critical, so that compensation of this component to better than 10% is not needed.\(^6\)

The circuit may be operated under a wide range of conditions. For example, the room-temperature coils need not be identical to the coils surrounding the superconductors, as the Heopit can easily compensate for large differences in mutual inductance. The shape of the transition curves and \( T_c \) values for the five elements in SRM767 are not affected when the frequency of the applied magnetic field is varied from 4 to 4000 Hz. We have also found that the \( T_c \) of the samples shift less than 0.1 mK when the peak-to-peak amplitude of the magnetic field in the primary coil is increased to 100 mG.\(^7\) As a matter of standardizing our measurement technique, we have generally used a 50 mG peak-to-peak field at a frequency of 270 Hz. This particular choice of circuit parameters produces approximately 0.1 \( \mu \)V inductive voltage change in the secondary when one sample passes completely through a transition. For a detection time constant of 0.3 sec on the phase-sensitive detector, the signal-to-noise on a recorder output is about 10 to 1. A recorder output is not necessary for the measurement; very often we identify \( T_c \) as \( \frac{1}{2} \) full scale deflection of the meter output of the phase-sensitive detector.

Transition curves were taken for all the samples in SRM767 using a Hartshorn bridge and then the circuit described in this article. In every case when the two \( X-Y \) recordings for each sample were superimposed, the curves were found to be identical within the noise. We consider this as satisfactory evidence that there are no distortions or other problems with this simple circuit and we conclude that it can be used with complete confidence for the inductive detection of superconductive fixed points.

Certain components of the bridge circuit were identified by brand name. They were cited as examples and are not necessarily optimum or recommended for the measurements discussed in this paper.

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\(^2\) This device consists of a copper mounting stud, samples of Pb, In, Al, Zn, and Cd, and a coil set. It may be obtained from the Office of Standard Reference Materials at a cost of $250.00.

\(^3\) See, for example, W. D. Gregory, Phys. Rev. 165, 556 (1968).


\(^5\) For example, a thermometer employing the temperature-dependent magnetic susceptibility of a paramagnetic salt. In this laboratory, the two constants which arise in the conventional mutual inductance-temperature relation due to the susceptibility of a single-crystal sphere of cerous magnesium nitrate were obtained by least-square-fitting the data to the transition temperatures of Al, Zn, and Cd as given in Ref. 1.

\(^6\) Though the bridge is extremely easy to build and operate for fixed point devices, analysis of the circuit is complicated; and in general, the two voltage components are not uniquely proportional to the resistive and capacitive settings. For the circuit parameters used here, however, mathematical analysis of the circuit shows that, to approximately 10%, the inductive change in the coil is balanced by the setting on the potentiometer, and that the change in the imaginary part of the mutual inductance is balanced by the capacitor setting.

\(^7\) The peak-to-peak current in the primary circuit may be measured by monitoring the differential voltage across the 1 k\( \Omega \) resistor shown in Fig. 2. The peak-to-peak magnetic field may be calculated using the coil constant of the primary coil in the SRM 767 unit (H/I = 180 G/A). The coil constant was obtained by:

(1) calculation, (2) dc measurements of \( H \) and \( I \), and (3) ac measurements of \( H \) and \( I \) up to 40 Hz.