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A sensitive temperature measuring system

Larry Dean Morris

A SENSITIVE TEMPERATURE MEASURING SYSTEM

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LARRY DEAN MORRIS, 1949-

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ABSTRACT

A sensitive temperature measuring system, providing an analog output proportional to sensor temperature, has been designed for use in the wall temperature control system of a cloud simulation chamber. A platinum resistance element is the sensor, and a precision wirewound resistor is the reference in a bridge circuit which uses four low cost operational amplifiers arranged to provide two precision 1000 Hz current sources. Problems with an initial bridge amplifier design were corrected in the final design by the use of a low Q bandpass amplifier for the bridge signal followed by a phase detector and an output low pass filter which reduces noise and allows fine adjustment of overall gain. Although a completed system was never built and calibrated, the breadboarded final design features r.m.s. output noise equivalent to 0.2 m°C, and drift over a period of several hours reducible to less than 3 m°C. System non-linearity is a maximum of 0.6% when the instrument is calibrated over a 10°C range, and full scale accuracy is limited only by oscillator stability to about 4%. The cost of the system is sufficiently low that the system could be used wherever control or monitoring applications require a continuous signal proportional to sensor temperature difference from a reference value.

ACKNOWLEDGEMENT

The work reported here would not have been possible without the assistance of the laboratory personnel of the Cloud Physics department. That assistance is gratefully acknowledged. Special thanks goes to Dr. Gordon Carlson for his willingness to jump into the middle of an unfamiliar project and see it to a successful conclusion. The typing and proofreading skills of Frances Morris have proved to be invaluable, as has the gentle yet persistent encouragement of Susan Sundeen. Without the latter, this paper might never have been written.

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I. INTRODUCTION

Recent developments in thermometry enable present electronic thermometer systems to provide a direct digital readout of temperature with a resolution of 0.0001°C or less. Even though this represents a terrific advance over the manually balanced bridge, it still does not posess the combination of speed, accuracy, and versatility required of the temperature instrumentation in the cloud simulation chamber under construction at the University of Missouri-Rolla.

More for the care devoted to its instrumentation than for any other single reason, the cloud simulation chamber being built is of unique design. As shown in Figure 1, it is a ten-sided cylinder about 24 inches high and 18 inches in diameter. The outside walls are machined from 3-inch aluminum and the inside walls are 1/4-inch thick aluminum plate which has been anodized black to minimize light reflection. There are two or three observation ports in the sides and holes in the top and bottom for changing the atmosphere or varying its pressure. Overall control of the simulation chamber will be provided by a special purpose computer programmed to, among other things, change the chamber pressure in synchronization with wall temperature changes so that adiabatic conditions may be sustained.

For reasons which will be outlined later, the sensor for the temperature instrumentation system was chosen to be a platinum resistance element. The remainder of this

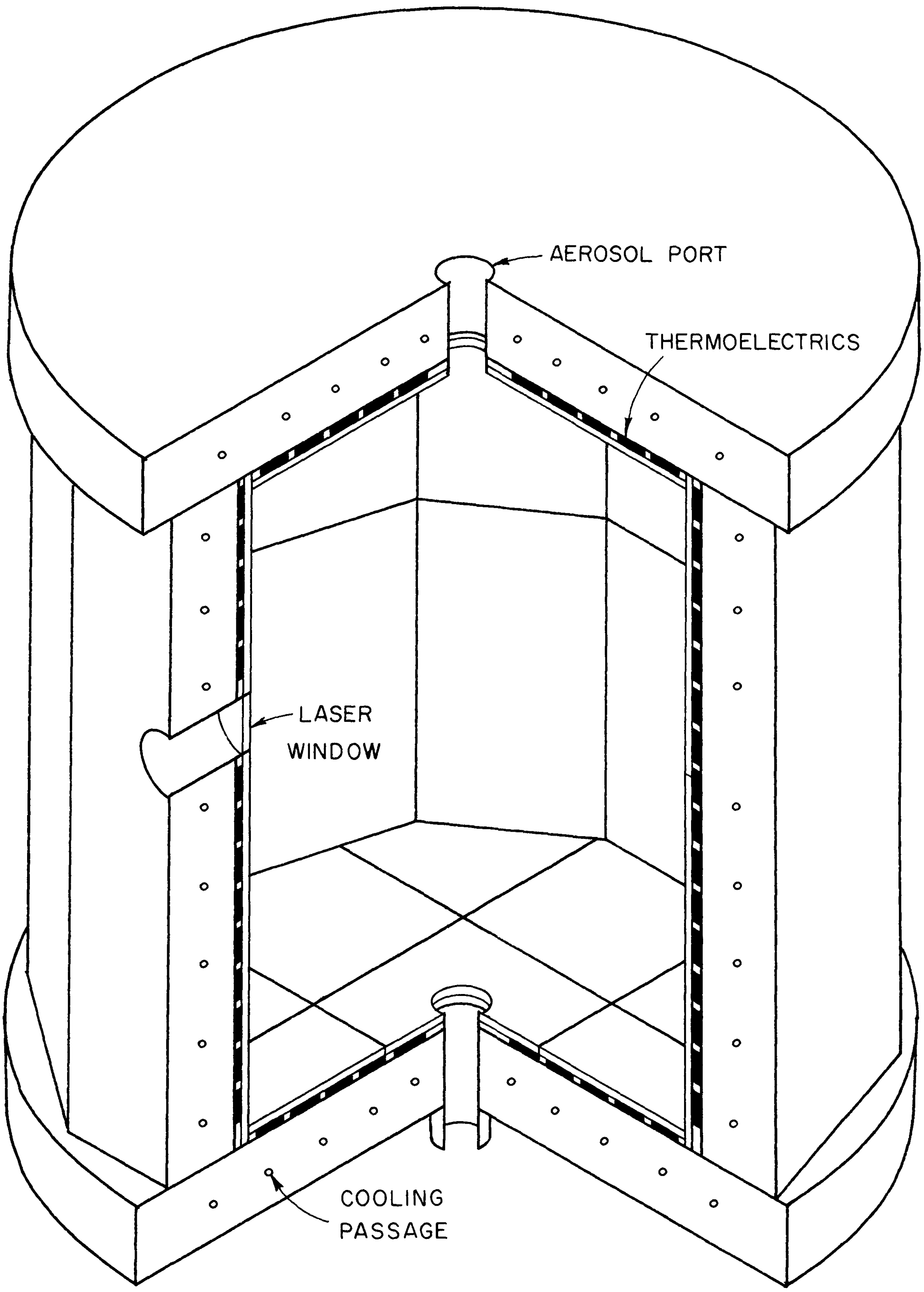

Figure 1. Cutaway View of Cloud Simulation Chamber

paper is concerned with the development of a sensitive temperature measuring system using such a sensor, and providing the necessary wall temperature signal to the cloud chamber control system. A review of the literature establishes background for a description of the general design of the new device. This is followed by a look at the specific requirements which provide a basis for the discussion of the details of the thermometer circuit. A complete description of the final design is followed by conclusions and recommendations for further improvements.

II. REVIEW OF THE LITERATURE

The "invention" of platinum resistance thermometry has been credited to Callender, who, in 1887, published a paper describing the construction of a platinum resistance thermometer element.[1] At the same time, Callender postulated for his element a relation between resistance and temperature that has remained essentially unchallenged to this day.

Originally, resistance measurements were made using a Wheatstone bridge. Shortly after the introduction of the platinum thermometer element, Callender and Griffiths modified the Wheatstone bridge to compensate for the resistance of the leads.[2] There was essentially no change from this method of measurement until about the time of World War I, when the four-terminal resistance element became popular. At that time, Smith described two forms of what has become known as the Thompson or Kelvin double bridge which are especially suited for use with platinum resistance thermometry.[3] Four operations are required to obtain a resistance reading with a bridge of the Smith type. Three of these consist of adjusting the resistance in the thermometer leads.

In 1941, Mueller described a simple variation of the Smith bridge which is presently in standard use.[4] This variation is an adaptation of the Wheatstone bridge so that four-terminal resistances may be measured. Only two operations are required to obtain a resistance measurement with the Mueller bridge.

In recent years, various efforts have been made to automate bridges so that only one operation is required to obtain a measurement. One commercially successful design has been described by Kusters and MacMartin.[5] It employs a self-balancing direct current comparator as the main component of a current comparator bridge. Balance of the bridge is accomplished by adjusting the number of turns on a transformer. As an additional feature, the bridge provides for direct reading of the self-heating of the resistance thermometer.

A bridge configuration in which operational amplifiers supply the currents to the reference and sensor elements has been described by Kirby.[6] It is reviewed in some detail in Section IV, as it is used as the starting point of the present design.

III. DESCRIPTION OF THE PROBLEM

In order to give the reader some conception of the overall cloud chamber design and how it contributes to the requirements placed on the temperature instrumentation in particular, this section begins with a description of the internal construction and the normal operating mode of the chamber. That is followed by descriptions of the physical and electrical environments in which the chamber is found.

A. CLOUD CHAMBER DESIGN

As was mentioned in the introduction, the inside walls of the chamber are 1/4-inch aluminum plate which has been anodized black. Behind these plates are thermoelectric units responsible for the primary temperature control of the chamber. The thermoelectric units are computer programmed to give a temperature versus time relation similar to that experienced by a parcel of air in an updraft in a warm cumulus cloud. It is beyond the scope of this paper to describe that relation in any detail.

Normally every effort will be made to run the chamber so as to maintain adiabatic conditions. This means that there can be no transfer of heat to or from the chamber walls. Since the walls will be cooled by the thermoelectric units, the gas must also be cooled to maintain zero temperature difference between the gas and the chamber walls. This cooling will be done by controlling the chamber pressure.

The gas in the chamber will be humid air with a closely controlled and continuously monitored condensation nuclei size distribution. The composition of the nuclei will depend on the particular experiment being conducted, but may be corrosive. Therefore, the wall temperature sensor must be relatively inert. This requirement is nicely met by a platinum resistance element.

Since the average heat transfer must remain zero, and small temperature gradients exist across the chamber inside surface, it is desirable that the thermometer system indicate an average surface temperature rather than the temperature of a specific point on the chamber wall. This can be done any of several ways: one sensor could be used which covers a large portion of the wall area, several sensors could be mounted and wired to give an average temperature measurement, or several independent sensors could be multiplexed and an average temperature computed from the multiplexed thermometer output. In any event, because of the desire to have little or no heat input to the chamber, the total sensor power dissipation must be held to less than 5 milliwatts. This figure is based on experience with other instrumentation in other cloud chambers.[7]

B. PHYSICAL AND ELECTRICAL ENVIRONMENT

The cloud simulation chamber and its associated temperature control, air humidification, aerosol generation, instrumentation, and computing apparatus will take up several hundred square feet in the corner of a large basement room when chamber construction is completed. It is planned that the temperature and pressure instrumentation systems will share a cabinet located some three feet from the simulation chamber base. Thus the leads to the sensors will be four to six feet long and some consideration must be given to possible noise pickup.

Air temperature in the room is controlled by steam radiators and three window air conditioners to an average daily variation on the order of 5°C. This does, of course, play some part in determining the kind of compensation required to eliminate the effects of ambient temperature changes in the wall thermometer system. The presence of a large volume temperature bath controlled to 0.002°C is also a factor of some importance here in that part or all of the system could be immersed in that bath if necessary.

Extensive wiring has been done in the simulation chamber room so that both A.C. and D.C. power is available in a variety of voltages. Unfortunately, these supplies are not of good (noise-free) quality. If it were necessary, it would not be out of the question to run the temperature instrumentation from internal batteries of either the rechargeable or throw-away type. The electrical environment is complicated by the presence of radio frequency noise. This has a variety of sources: the numerous solenoids and electrically operated valves associated with other cloud chambers in the building, proportional temperature controllers, the pressure measuring system, and a laser, to name a few. In some instances, these noise sources have presented problems before and ways have been found to reduce their effects. This is especially true in the case of the laser, which is now customarily covered by a copper screen.

An effort has been made here to detail the operating environment of the temperature measuring system. Before the actual system design is considered, some specific values are assigned to the electrical specifications of the device. In order to assure that meaningful data can be obtained with the necessary degree of accuracy, the temperature measuring system must be capable of holding an absolute calibration to within 0.05°C for a period of several hours. It must have total noise and drift less than 0.005°C over the operating period of 100 seconds, and accumulated systematic errors must be less than 0.1% over a range of at least 1°C.

IV. THE SOLUTION TO THE PROBLEM

The development of a circuit which can accurately measure small temperature changes about a calibrated reference point is now discussed. First, there is a discussion of some of the problems associated with choosing and mounting a sensor. Second, there is a review of the construction and operation of the resistance measuring circuitry developed by the National Research Council of Canada and reported by Kirby. This is followed by a description of the initial approach taken to solve the temperature measurement problem under consideration and a discussion of the differences between the resulting circuitry and that reported by Kirby. The preliminary results are reported and the problems that suggest further development are outlined. The final design of the measurement circuit and its initialization and calibration are then discussed in some detail.

A. THE SENSOR

The choice of sensor for the simulation chamber thermometer system was among thermoelectric, resistance, and semiconductor elements. In spite of the highly developed technology in the Cloud Physics laboratory in the use of thermocouples, those devices were not used due to their extremely low signal level, the high-stability reference bath required, and the difficulty associated with obtaining a mean surface temperature with point-type sensors. Semiconductor elements were ruled out for similar reasons, even though their signal level is a hundredfold greater than that obtained from a thermocouple when driven by a source which meets the 5 milliwatts input power requirement. Carbon resistance elements are physically too bulky and electrically too noisy and nonlinear for this application. The best combination of potentially high output, speed of response, linearity, stability, repeatability, inertness, and variety of possible geometries seems to be held by platinum resistance elements.

Commercial platinum resistance elements having almost any desired combination of nominal resistance and package size are available. Much of the developmental work reported here was done with a low-cost element measuring 0.1" square and 0.05" thick having a nominal value of 100 ohms resistance at room temperatures and a temperature coefficient of about 0.4 ohms/°C.

The actual instrumentation could be accomplished with sensors of the above mentioned type mounted over a large area and wired in a series-parallel configuration which maintains the nominal resistance value. Alternatively, a single platinum wire of a few mils diameter could be affixed to the chamber surface in a pattern that would assure an average surface temperature indication. The difficulties associated with the latter method include problems with calibration and the required strain-free mounting. It is beyond the scope of this paper to discuss in any detail the problems with mounting and calibrating a platinum temperature sensor. They have been well documented in the literature.[8]

In view of the above characteristics and requirements, the sensor considered is assumed to be a platinum resistance element having an ice-point resistance of 100 ohms. It is also assumed that it meets all the requirements for purity and strain-free mounting necessary to conform to the current definition of the International Practical Temperature Scale.[4]

B. THE BRIDGE

Kirby reports a bridge design, shown in Figure 2, that is especially suited for use in an electronic temperature instrumentation system.[6] It uses four operational amplifiers, each with its own isolated power supply, arranged to provide two current sources. One source maintains a current through a four-terminal reference resistor (R), and the other supplies current to the sensor (S).

The detector is connected directly between the potential leads of the sensor and reference. A grounded centertap is necessary at the detector input to define the amplifiers' output voltages with respect to their inputs, but it also guarantees there will be no common mode signal at the detector input. Additionally this ground connection provides a symmetry in the circuit which helps to make leakage currents between the power supply commons, or between those commons and the A.C. line, cancel.

Since an A.C. drive signal and an A.C. detector are

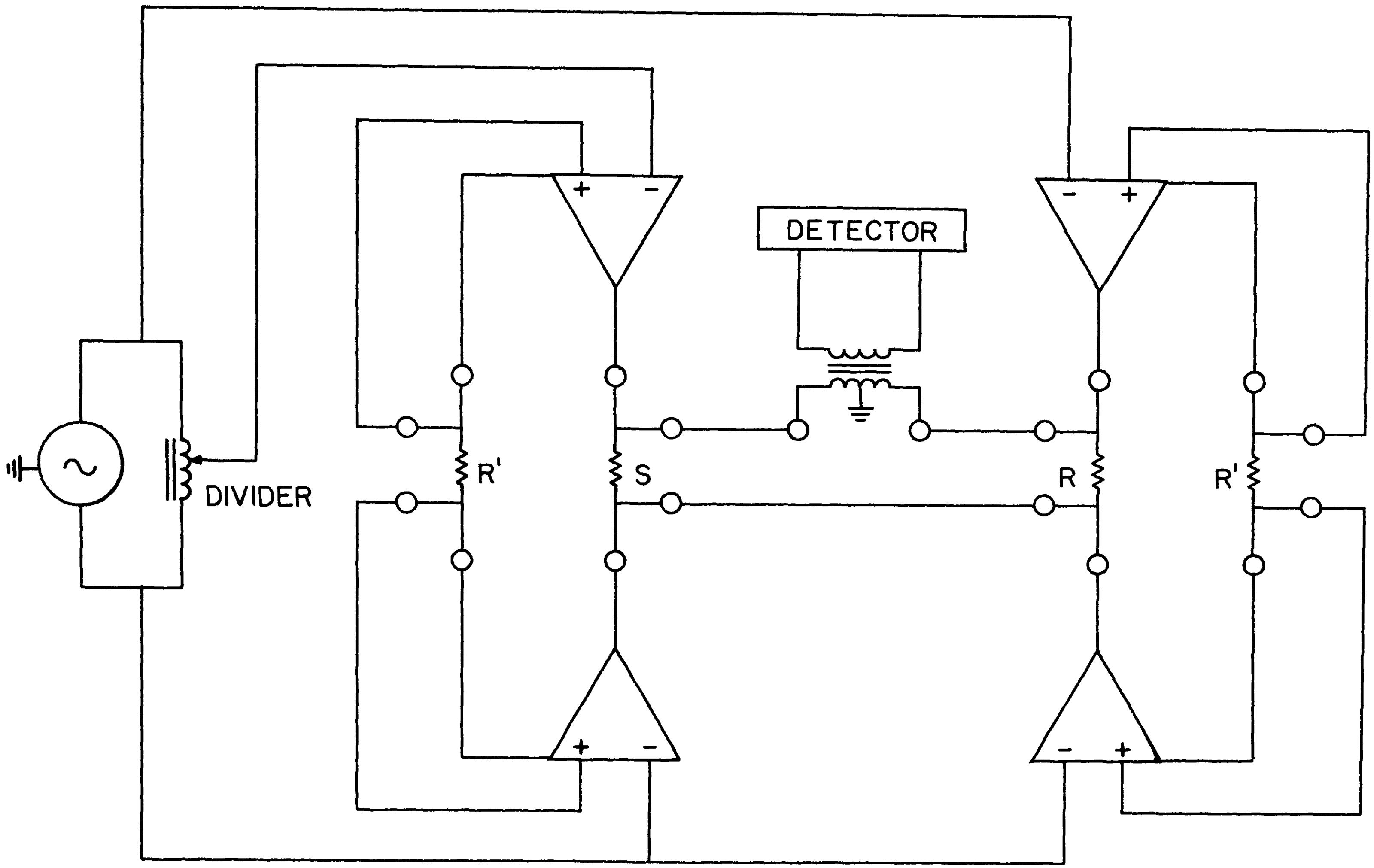

Figure 2. Operational Amplifier Bridge

used, the contribution to the detector input from D.C. offsets and thermoelectric potentials is completely ignored. Consequently, low-cost operational amplifiers, which meet only a requirement for negligible equivalent input noise in the passband of the detector amplifier, may be used in the circuit.

The divider in Kirby's bridge is a 7-decade auto-transformer. In normal operation, the ratio of S to R is found from the divider setting after adjusting the divider until the detector indicates bridge balance. This is similar to the procedure involved in reading a resistance with most bridge methods. Unfortunately, it is not especially suited to automatic operation or to applications such as simulation chamber instrumentation where a continuous time varying signal representative of temperature must be measured.

C. THE DETECTOR AMPLIFIER

Since the detector input signal is approximately a linear function of temperature difference from an initial reference temperature, the detector amplifier needs only to have gain enough to increase the bridge signal to a useable level. Over a small enough temperature range around the reference, no sophistication is required in the amplifier to maintain good correspondence between amplifier output and temperature. A more detailed discussion of the errors involved in the approximation appears in the section on results and conclusions.

1. KIRBY DETECTOR

The detector reported by Kirby, shown in Figure 3, is a lock-in amplifier designed especially for use as a bridge detector. The input signal is coupled through a transformer having a turns ratio of 100:1 in order to raise its level above the amplifier input noise. Further noise reduction is accomplished by 60 Hz and 180 Hz band rejection filters. Since the amplifier is only used to indicate bridge balance, rather than provide an output proportional to input, the next stage is a limiter to assure high gain at low signal levels without undesirable saturation at high levels. Following the limiter is a phase detector which provides a D.C. output related only to the component of the input signal which is in phase with the bridge drive oscillator. A zero-center meter is driven by a filtered version of the phase detector output. Bridge balance is achieved by adjusting the divider until the meter reads zero.

Bridge drive is provided by a two-phase oscillator as shown in Figure 3. In order to reduce the effects of leakage capacitance and lead inductance, the operating frequency is kept below 150 Hz and is usually 16 Hz. Operation below that frequency is limited by phase shift in the input transformer. Since the oscillator has an output 90° out of phase with respect to the bridge drive signal, Kirby's design includes, as an additional feature, an indicator for the out-of-phase component of the input. Also provision is made for cancelling this component if the

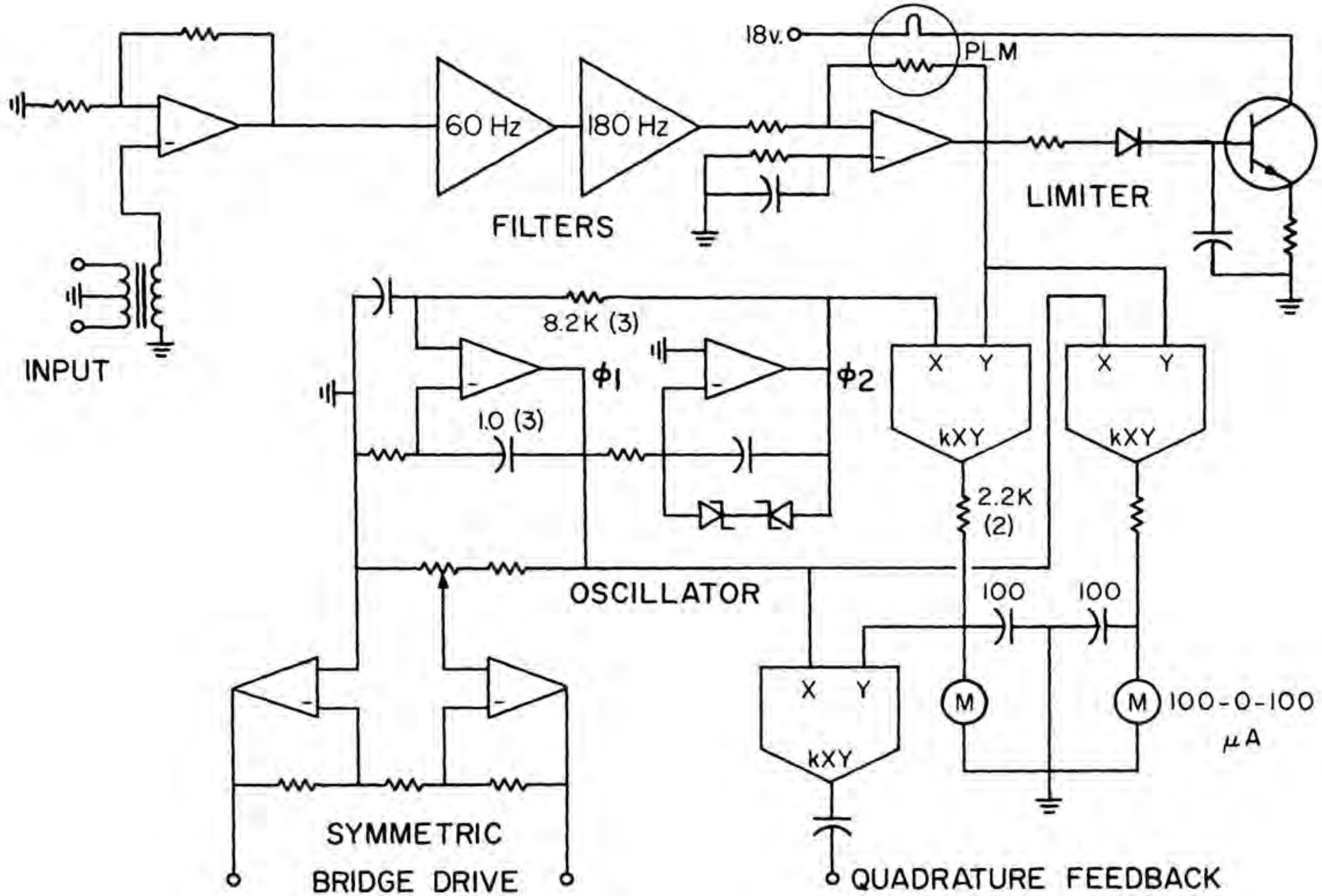

Figure 3. Kirby Bridge Detector

operator decides it is interfering with bridge balance.

2. INITIAL DETECTOR DESIGN

For the temperature measurements under discussion, Kirby's bridge circuit is used in a slightly different manner. Once the bridge is balanced at a reference temperature, the detector output can be made to correspond to a sensed change from that temperature. In fact, the signal at the detector input is very nearly a linear function of temperature and can be approximated by a linear relation over a range limited only by the acceptable temperature measurement error.

Kirby's two-phase oscillator was abandoned in favor of the simpler and more stable twin-tee design. The low frequency suggested by Kirby was found impractical for the present application due to the excessive time constant required to filter double frequency components from the multiplier output. An operating frequency near 1000 Hz was chosen: both for its spectral distance from 60 Hz and its already wide use in A.C. bridge circuits.

The use of a single phase oscillator precludes the cancellation of any out-of-phase signal components interfering with bridge balance. Considering the extreme care required to implement such cancellation without causing the detector to break into a low frequency oscillation, and considering the greater stability of the simpler oscillator, the ability of the phase detector to reject out-of-phase signal components was deemed sufficient to obviate the use of any cancellation techniques.

The initial detector amplifier design used, shown in Figure 4, differs in several important respects from that used by Kirby. As it is described by stages, working from input to output, the reasons for each of the differences will be explained. The physical construction will also be considered as it relates to the electrical characteristics, and the procedures for initialization, calibration, and use will be discussed.

Use of an input transformer to match the bridge output to the detector amplifier first stage, though desirable, proved to be impractical. The low noise unit suggested by Kirby costs $250 and a low cost substitute proved to be especially susceptible to stray 60 Hz noise pickup. Therefore a resistive divider network connected at the input of the first bandpass amplifier provides the necessary centertap to ground. A resistance value of 100 ohms was chosen as a compromise between the high resistance needed to maximize the detector input signal and the low resistance essential to minimize input noise.

The two bandpass amplifiers are identical two-pole active filters of multiple feedback design.[9] They each have a Q of 10 and a gain of 100 at the center frequency of 1000 Hz, for an overall filter gain of 10,000 and a bandwidth of 64 Hz. Broadband equivalent input noise in the low-cost operational amplifiers used in the filters is effectively eliminated by the narrow bandwidth, and the

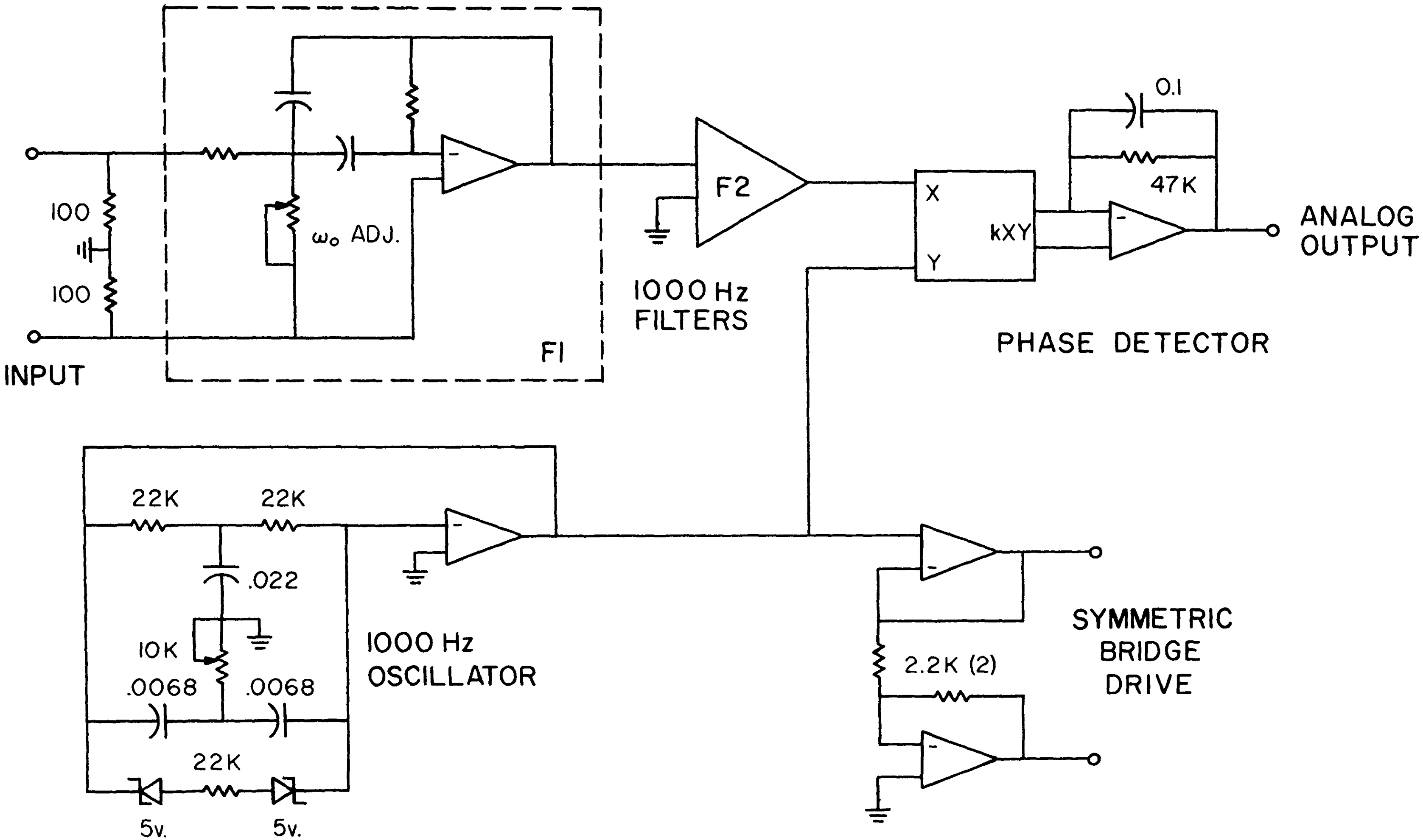

Figure 4. Initial Bridge Detector Design

high first stage gain assures that noise in succeeding stages will be well below the signal level.

The phase detection required in any good A.C. bridge detector is accomplished here with a Motorola MC1595L integrated multiplier used in the circuit recommended by Motorola. The only change is the addition of a capacitor in parallel with the feedback resistor in the current to voltage converter output stage. This capacitor is an effective low pass filter so the multiplier output is essentially free of unwanted high frequency components.

The existence of the electrical noise sources outlined in the description of the problem suggests that care must be taken in the physical layout and construction of the circuit. A majority of the noise sources are electromagnetic in nature. Therefore, steel was chosen from among the commonly available chassis materials since it has the highest permeability. A semblance of electrostatic shielding is provided by a ground plane on the component side of the bridge and amplifier circuit boards. As shown in Figure 5, the bridge and the high gain filter are mounted in separate steel miniboxes and these two boxes are mounted inside a closed steel chassis. The required power supplies are of the potted type and are mounted outside the closed chassis. Oscillator and multiplier circuits, which normally operate at high signal levels, are mounted together in a separate aluminum minibox with their own power supply.

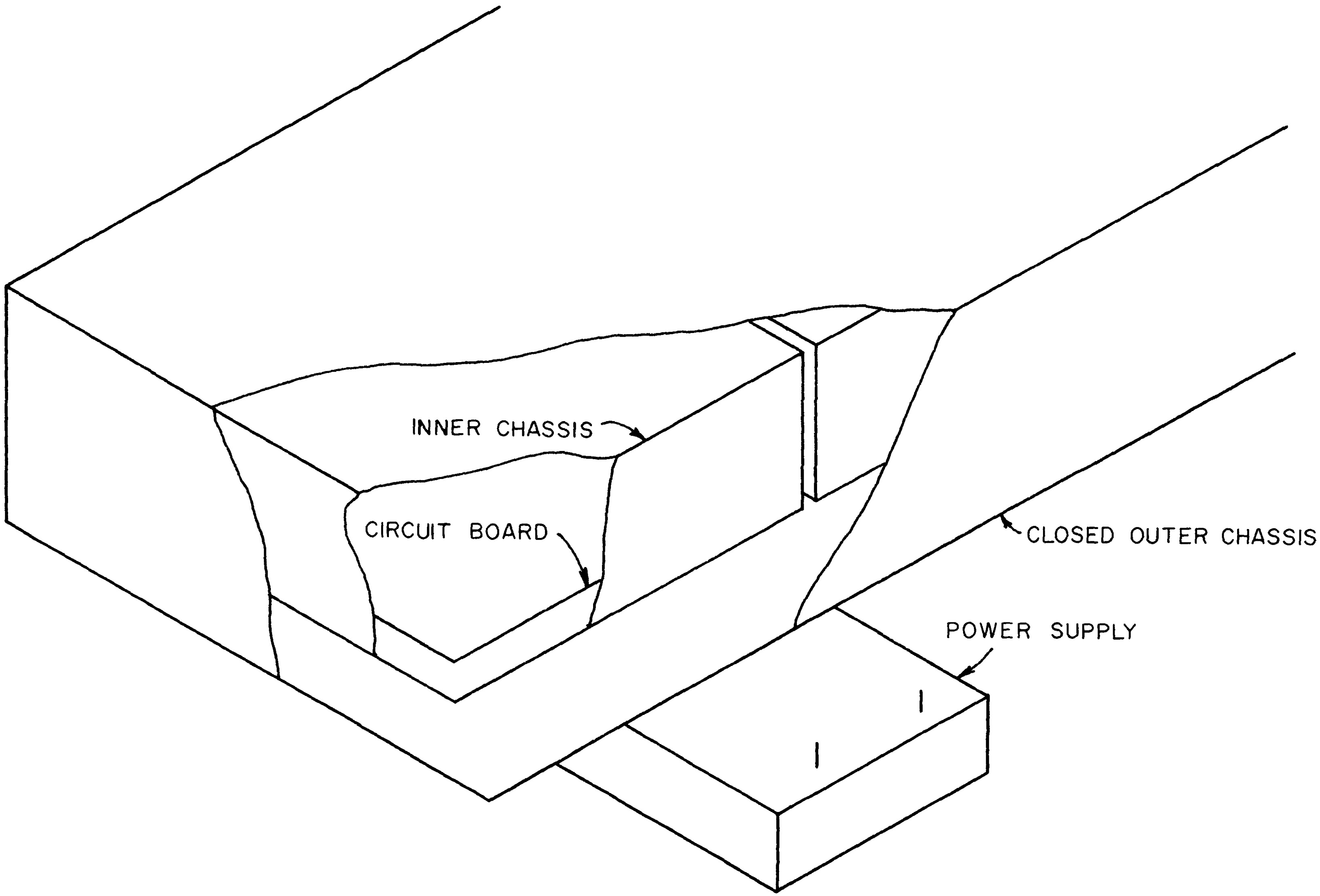

Figure 5. Cutaway View of Bridge and Amplifier Circuit Board Mounting

Several adjustments are required before the circuit is ready to operate. Once the desired oscillator frequency is set, the bandpass filters must be adjusted so they have zero phase shift at that frequency. The multiplier input and output offsets are then adjusted to zero. After these adjustments are performed, the bridge divider may be adjusted so the detector output is zero at some reference temperature, and initialization is complete.

D. PRELIMINARY RESULTS AND CONCLUSIONS

Before the results of the initial design are discussed, it should be noted that an output variation of 1.0 volt for each degree Celsius change in sensor temperature is the desired response of the circuit. Since the output may range over ±10 volts, the range of temperature which may be indicated is as many degrees. Similarly, the specifications given in the description of the problem require noise less than 5 millivolts and long term drift less than 50 millivolts.

During the tests reported here, the sensor was replaced by a 100 ohm precision wirewound resistor of large thermal mass. Every effort was made to insulate this resistor from room temperature variations in order to ensure the validity of the long term drift tests.

Introduction of 0.1 ohms in series with the "sensor" shifts the output level by 2.5 volts, indicating that the range of the instrument is about 1°C. This range limitation can be removed merely by reducing the gain in the amplifier, so the output more nearly approximates one volt/°C.

A low frequency "flicker" was observed with an oscilloscope to be about 100 millivolts peak to peak, and an overnight strip-chart recording of the output revealed a drift of about 180 millivolts over a normal range of room temperatures. Flicker in the detector output may be partly caused by short-term oscillator frequency variations, but most of the problem seems to be due to 60 Hz and random noise of a particular variety. A.C./D.C. motors, and solid state proportional controllers, relays, or manual switches which operate inductive loads, all contribute voltage impulses to the electrical environment in the Cloud Physics laboratory. By some combination of inductive and capacitive effects, these impulses are coupled into the bridge detector circuit. In the high Q filters, a 60 Hz amplitude modulated 1000 Hz output is the result of the ringing caused by the impulses. This A.M. noise is detected by the phase detector and appears as flicker at the detector output. Randomly spaced impulses produce a random output in addition to that just described. Noise effects of this sort can be reduced by a good shielding and grounding system in addition to better isolation of power supplies from the A.C. line.

Detector output drift is assumed to arise from two sources: temperature dependence of the detector characteristics, and component aging. Since any component aging effects which would appear in an overnight drift test should have been removed by the circuit warmup period of several days, attention has been given to the reduction of temperature effects in the detector.

The oscillator turns out to be responsible for most of the circuit temperature effects. Over a range of temperatures from near 0°C to about 70°C, the oscillator displays a frequency variation of 0.7%. Since the passband of the amplifier is 6.4% of the center frequency, a marked phase shift of the input signal occurs in the filters as the oscillator drifts. At bridge balance, where the drift test was made, the amplitude of signal due to resistive unbalance is zero, whereas there is about 1.1 volts r.m.s. of signal due to reactive unbalance. Oscillator drift causes the signal due to reactive unbalance to be phase shifted in the filters so the phase detector responds as though the signal were due to resistive unbalance. Hence the output drift. This effect may be reduced by increasing oscillator stability, reducing the filter Q, or both.

E. FINAL DESIGN

In the final design of the detector amplifier, shown in Figure 6, several changes have been made from the initial design in order to take advantage of things learned from the preliminary results. The input amplifier is a high pass two pole active filter followed by an active two pole bandpass filter. The first stage has a gain of 100 and a cutoff frequency of about 250 Hz, which is midway in

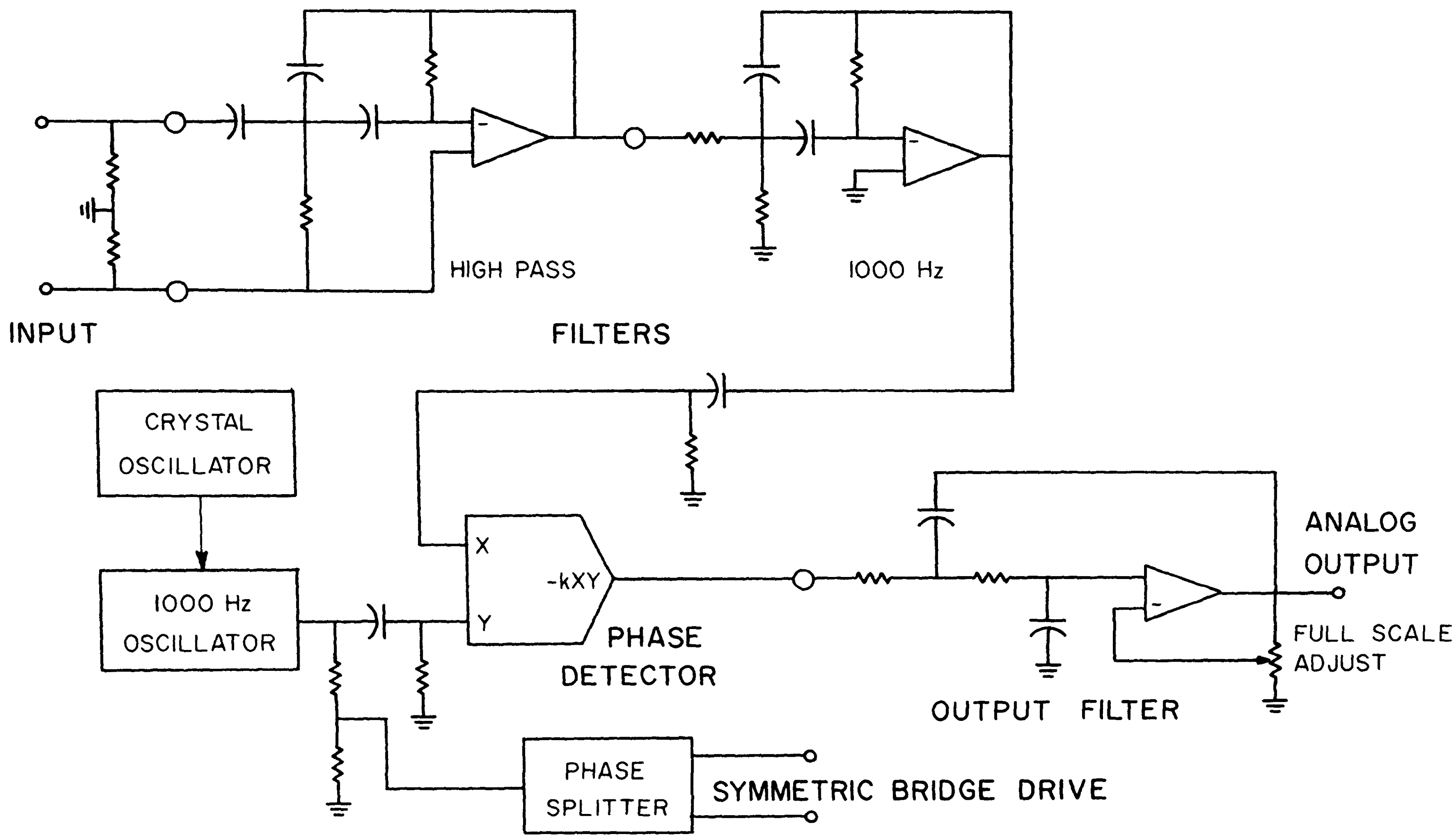

Figure 6. Final Bridge Detector Design

the spectrum between 60 Hz and 1000 Hz. The second stage has a gain of 30 and a Q of 4. Both are of multiple feedback design as before. The lower gain and Q of the second stage assure a bandpass amplifier of stable characteristics and relative insensitivity to oscillator drift.

Although the phase detector displayed a remarkable D.C. offset adjustment stability throughout the preliminary tests, its inputs have been A.C. coupled to prevent filter or oscillator output offsets from appearing in the detector output. An output filter has been added to facilitate gain adjustment and to reduce further any noise in the phase detector output. This filter has a cutoff frequency of 3.6 Hz, a gain near unity, and is of controlled source design.[9] The cutoff frequency has not been made lower for two reasons: (1) to preserve the good overall time constant of the system, and (2) to make use of readily available component values in the filter.

F. INITIALIZATION AND CALIBRATION

An oscilloscope is extremely useful for initialization of the circuit. Amplifier phase shift and phase detector offsets are easily adjusted if the bridge drive signal is used for the oscilloscope horizontal sweep. Once the phase detector offsets are adjusted according to procedures outlined in the MC1595L specification sheet, the amplifier phase shift may be easily adjusted in the following two steps. First adjust the bridge divider for minimum amplifier output signal amplitude. Then adjust the center frequency of the bandpass filter so that phase detector output is zero. Now any phase shift introduced by the amplifier is only that required to cancel the phase shift introduced by the phase detector. Experience indicates that repetition of this adjustment procedure is required only infrequently.

Full scale calibration of the instrument requires the use of two well-controlled temperature baths of known precise temperature difference. The absolute temperature of one of the baths should be known to 0.05°C. Calibration is accomplished by letting the sensor come to thermal equilibrium in one of the baths and adjusting the bridge divider until the instrument output is zero. Then the sensor is allowed to come to equilibrium in the second bath and the gain adjustment potentiometer in the output filter is adjusted to make the output voltage equal to the temperature difference between the two baths.

Several factors have prevented actual construction, calibration and use of a completed instrument, but breadboard tests indicate that the final design outlined above meets the required specifications in every respect but one. This is discussed in more detail in the following section along with additional results.

V. RESULTS AND CONCLUSIONS

Before a conclusion can be drawn regarding the effectiveness of the problem solution, several factors affecting system performance should be considered. The first part of this section describes the results obtained with the final design and investigates some of the design's known and suspected problems. The last part of this section attempts to put the present work in some sort of perspective and make some recommendations for further development of a sensitive temperature measuring system.

A. SYSTEM UNCERTAINTIES

Broadband noise in the completed system is measured at 0.2 millivolts (millidegrees C) r.m.s. Zero drift measured over a period of several hours at bridge balance is about 30 m°C, and system errors due to known nonlinearities are calculated to be less than 0.1% over any calibrated range of 4°C or less anywhere in the normally expected range of operating temperatures from -10°C to 40°C. Figure 7 shows a typical calculated error curve for the system. The maximum error increases approximately as the square of the calibrated range, so the maximum error over a 10°C calibrated range is about 27 m°C. This curve was calculated assuming the detector output voltage can be very nearly given by

$$V_o = k(R-R_c)/(R+328). \qquad (1)$$

In this relation, k is a gain constant in volts, and 328 represents the sum of the resistances of the detector input

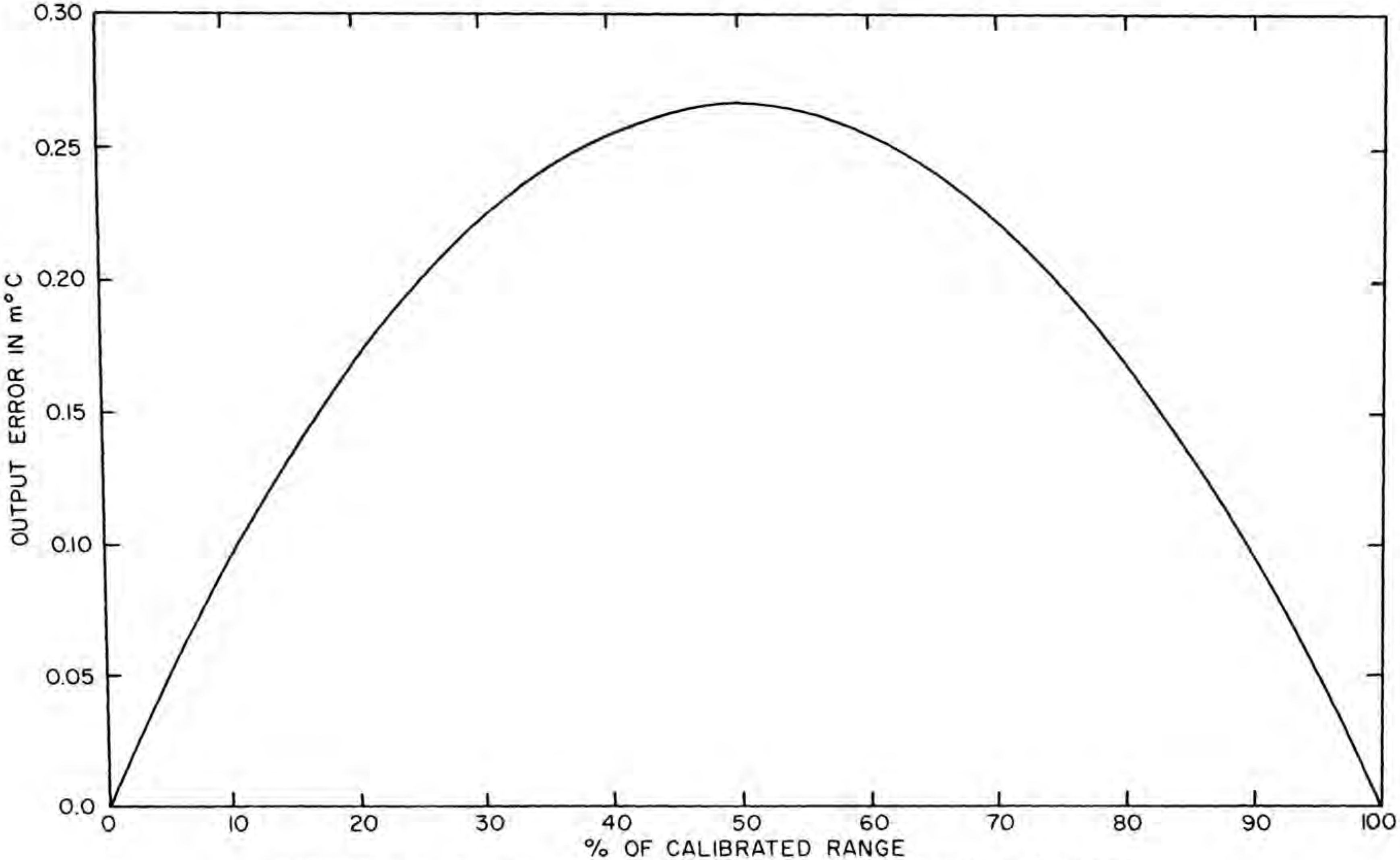

Figure 7. System Error Curve for 1°C Calibrated Range

resistors and the reference resistor. R is the sensor resistance given by a quadratic law as a function of temperature t:

$$R = R_o(1+At+Bt^2); \qquad (2)$$

where A, B are constants which are a function of the particular sensor used, and R_o is the ice-point resistance of the sensor. R_c in (1) is R evaluated at the calibration temperature $t=t_c$. By making use of (1) and (2) together, an inverse relation for t as a function of V_o may be written. Such a relation would make possible the extremely precise calculation of temperature as a function of instrument output voltage. This usually is neither necessary nor desirable, however, for good calculations may be nade using an equation for t which is quadratic in V_o, and other system uncertainties are sufficient to make any extremely precise calculation almost meaningless.

Among the other system uncertainties which require consideration are oscillator amplitude and frequency stability, reactive effects in the circuit, the self-heating and heat capacity of the platinum sensor, overall system time constant, and nonlinearities and input phase shift in the multiplier. Instrument zero drift, reported earlier in this section to be about 30 millivolts, can be reduced at least another order of magnitude by synchronizing the bridge drive oscillator to a crystal controlled source. The only remaining oscillator problem, then, is amplitude stability. In order to maintain the full-scale calibration to 0.1%, the oscillator amplitude must be stable to better than 0.05% because of the amplitude squaring effect of the multiplier. Solution of this problem could easily be the subject of another thesis. With the present oscillator, the full-scale adjustment remains accurate to better than 4%, varying primarily as a function of room temperature. This remaining respect in which the present circuit does not meet the original specifications could probably be remedied if the oscillator were immersed in the available temperature bath. In any event, the room temperature does not vary enough over the 100-second operating time of an experiment to make this a problem.

The effects introduced by lead inductance and leakage capacitance can for the most part be ignored. Although these effects do alter current and voltage magnitudes, the scale factor remains very nearly constant as long as the physical layout of the circuit does not change. Quadrature signal components introduced by inductive/capacitive effects are prevented from having any effect in the output by the phase detector.

The bridge design assures that the sensor will always have a constant current through it of approximately 1.1 milliamps. This gives a nominal sensor power dissipation of about 0.12 milliwatts; however, it varies with temperature. Such a small power dissipation in a sensor which is in intimate contact with the thick aluminum walls of the cloud chamber will only raise the sensor temperature a fraction of a millidegree C. It has been reported that a constant sensor current assures a constant self-heating; therefore, self-heating effects will never appear in the differential measurements made by the thermometer system.[10]

Dynamic temperature measurements suffer from at least two error sources which have no effect on static measurements: the sensor heat capacity, and bridge detector time constant. The heat capacity of a wire temperature sensor is sufficient to make it demonstrate a time constant of 72 milliseconds in air.[11] Although one would expect a surface mounted sensor to have a smaller time lag due to the greater thermal conductivity to its surroundings, this time constant must be considered for a quickly changing process. Together with the lag introduced by the detector output filter, this thermal lag brings the total system time constant of the final design to about 0.11 seconds, which is sufficient to cause a 5 m°C error in measuring a temperature changing at a rate of 45 m°C/second.

The multiplier (phase detector) is a potential source of several difficulties. Nonlinearities in the unit are specified at below 0.1% in static use, but there are no specifications available for the device which are really pertinent to its use in a phase detector. That the device perfectly rejects all signals in quadrature with the bridge drive signal, and provides perfectly linear response to in-phase signals is probably too much to expect.

Unfortunately extremely elaborate tests would have to be run to determine the true performance of the Motorola integrated circuit in its proposed environment. One major problem, that of input phase shift, is effectively cancelled if the detector filters are adjusted as described in the above initialization and calibration procedure.

B. RECOMMENDATIONS AND CONCLUSIONS

In addition to the minor changes suggested by the results discussed above, there is a change in design approach which might be made. A feedback loop similar to the one which Kirby suggested for cancelling out-of-phase signals might be used to make the bridge self-balancing. Though care must be exercised in its implementation, such a feedback loop would reduce the loading effect of the detector on the bridge, and further reduce the already negligible effects of sensor lead resistance on the measurements.

Another problem area deserving attention is that of packaging. The steel chassis boxes do not seem to have any noticeable noise reduction effect on the circuit, if indeed their effect is not the opposite. The more sensitive bridge and detector input circuits need to be shielded in a high permeability, high conductivity material, and careful attention should be given to the grounding of the shields.

The instrument described here is a simple yet significant extension of the work reported by Kirby. It makes possible the measurement and recording of cloud simulation chamber wall temperature changes at a fraction of the cost of commercial thermometer systems. Because of the great variety of sensor geometries available, and the overall simplicity of the bridge and detector, the instrument could easily be used in any number of measurement/control applications requiring high sensitivity, small time constant temperature measurement.

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VITA

Larry Dean Morris was born on June 23, 1949, in Chicago, Illinois. He received his primary education in Derby, Kansas, and his secondary education in Rolla, Missouri. He has received his college education from the University of Missouri-Rolla in Rolla, Missouri, where he received his Bachelor of Science degree in Electrical Engineering in December, 1970. He has been enrolled in the Graduate School of the University of Missouri-Rolla since January, 1971.

As an undergraduate, he worked as a student assistant for the Ceramics, Electrical, and Cloud Physics departments of the University of Missouri-Rolla. From 1970 to 1972, he held a research assistantship in the Cloud Physics department.