The design of a low temperature translation
balance for the measurement of paramagnetic
and diamagnetic susceptibilities

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M.S. Thesis submitted to Iowa State University

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Date Transmitted: May 1979

PREPARED FOR THE U.S. DEPARTMENT OF ENERGY
UNDER CONTRACT NO. W-7405-eng-82

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LIST OF SYMBOLS AND APPREVIATIONS

The following list is not intended to be a complete summary of magnetic units but includes important symbols used in the text of this report. Keeping with the 1974 Conference Proceedings on Magnetic Materials, the cgs electromagnetic system and associated symbolism will be used.

Symbol	Name
	<u>cgs:emu</u>
B	Flux density; magnetic induction
H	magnetic field strength
M	magnetization
X	volume susceptibility
X_p	mass susceptibility
X_{mole}	molar susceptibility
m	magnetic moment
M_B	Bohr magneton
General Symbols	Name
u	permeability
U	potential energy
v	volume
f	force in dynes
l	Horizontal balance beam displacement
h	vertical suspension length

S	balance sensitivity
F	specific force constant
[]	Book Reference
()	Figure Reference
T.C.	Thermocouple
STD	Standard

DEDICATION

TO

DARLENE

whose beautiful smile
made this worthwhile

The design of a low temperature translation
balance for the measurement of paramagnetic
and diamagnetic susceptibilities

by

Gregory Stephen Mowry

A Thesis Submitted to the
Graduate Faculty in Partial Fulfillment of
The Requirements for the Degree of
MASTER OF SCIENCE

Department: Materials Science and Engineering

Major: Metallurgy

Approved:

Committee Members:

In Charge of Major Work

For the Major Department

For the Graduate College

Iowa State University
Ames, Iowa

1978

ABSTRACT

A modified Foex and Forrer Translation Balance has been designed for measuring the paramagnetic and diamagnetic properties of materials over the temperature range 77-300°K. The systems' temperature range can eventually be extended to 4.2°K.

The apparatus incorporates a vertical Dewar of Standard variety in addition to a horizontal Dewar for cooling the sample holder and adjacent horizontal supports. The design also allows for the placement of a thermocouple junction in direct contact with a sample. The balance sensitivity, defined as the change in displacement per unit applied force, is 0.0044 cm/dyne. The precision of the balance is $\pm .5\%$ with an accuracy of 1.5%.

I. INTRODUCTION

Various methods have been employed for measuring magnetic susceptibilities of single crystals. Such measurements have usually been made by either the Faraday method or the Gouy method [1]. In either case the crystal must be rigidly fastened to the balance during the measurements so that the direction of the field coincides with the direction of a defined axis of the crystal. If there is an adequate quantity of available material under investigation, the Gouy method is usually preferred since an absolute measurement of high accuracy can easily be made. The Faraday method is recommended when only small crystals of the substance are available. The small size of available crystals necessitated the use of the Faraday method during the present study.

Several balances utilizing the Faraday method have been designed for measuring anisotropic susceptibilities. Jackson [2] used a modified Sucksmith Ring Balance [3] to study the principal susceptibilities of crystals. Krishman, Guha and Banerjee [4] measured anisotropic susceptibilities by timing the period of torsional oscillations of a single crystal suspended in a nonuniform magnetic field. More recently Aléonard [5] measured the susceptibility of single crystal rare earths by combining a vertical suspension similar to that used by Jackson and a Foex and Forrer translation balance [6].

For the present research it was decided that anisotropic measurements could best be performed with a translation balance because of the relative ease of positioning the crystal in a given orientation relative to the field direction. The rigid sample holder used in a translation balance also produces excellent positional stability for the sample without resorting to the complex anti-torque systems common to a system using a vertically suspended specimen. Further, it is possible to place a thermocouple junction in direct contact with the test specimen, something rather difficult to achieve with a suspended sample.

Dimensional constraints imposed by the electromagnet geometry made the Aléonard balance impractical in the present application. Therefore, a modified Foex and Forrer translation balance was designed. The apparatus was constructed to make susceptibility measurements on a single crystal using the Faraday method over the temperature range 20-300°K.

II. THEORY

A. Faraday Method

The potential energy of a para- or diamagnetic material of permeability u in a vacuum with a magnetic field H is defined by

$$U = - \frac{(u-1)}{8\pi} \int_{\text{sample volume}} H^2 dv \quad (1)$$

When a material is placed in a nonuniform field the force which tends to move a body along the gradient direction is

$$f_z = - \frac{\partial U}{\partial z} = \frac{(u-1)}{8\pi} \int \left(\frac{\partial H_x^2}{\partial z} + \frac{\partial H_y^2}{\partial z} + \frac{\partial H_z^2}{\partial z} \right) dv \quad (2)$$

where z is the gradient coordinate. This expression for f_z is correct only when the magnetic field is not distorted by the introduction of the material to be measured, a condition satisfied only for materials with small permeabilities.

The Faraday method employs a set of contoured pole pieces which minimize the first two terms in the integrand of eq. 2 and produce a volume over which the third term is constant. Hence eq. 2 reduces to

$$f_z = \frac{(u-1)}{8\pi} v \frac{dH_z^2}{dz} \quad (3)$$

Since $u = 1 + 4\pi X$, X defining the volume susceptibility, the force is given by

$$f_z = \frac{1}{2} X v \frac{dH_z^2}{dz} \quad (4)$$

Eq. 4 is called the Faraday equation. If the specific force, $\frac{dH_z^2}{dz}$, is accurately known then by measuring the force exerted by a nonuniform field on a material, Eq. 4 can be used to evaluate the susceptibility. Because the Faraday method is normally used with samples of irregular geometry the Faraday equation is usually written in terms of mass susceptibility X_p , rather than volume susceptibility, X ; this can be accomplished by the substitution $X_{pm} = Xv$.

B. Translation Balance

The translation balance operates by establishing equilibrium between a magnetically induced force f_z acting on a sample and a controllable restoring force f_r . The latter force can be produced by a solenoid acting on a permanent magnet attached to the balance beam. Dorfman [7] has derived a relation between f_z and the horizontal displacement L by applying small angle approximations to a freely suspended simple pendulum. If h is the length of the suspension and M the combined sample and beam mass, then

$$L = f_z \frac{h}{Mg} \quad (5)$$

where g defines the acceleration of gravity.

The sensitivity S of a translation balance is defined as the change in displacement per unit applied force. From eq. 5.

$$S = \frac{dl}{df_z} = \frac{h}{Mg} \quad (6)$$

III. APPARATUS

A. Magnet

In the present experimental apparatus magnetic fields are produced by a 6 inch Varian electromagnet model 4007-2 plus a 2.1 KW power supply model V-2200A. This magnet has a continuously adjustable air gap and the magnet may be rotated through an azimuthal angle of 200° . The magnet is fitted with contoured pole pieces which are used to produce a volume of constant $\frac{dH^2}{dz}$; a maximum specific force of 7 KGauss²/cm results at maximum magnetic strength. The voltage drop across a reference resistor in series between the power supply and the magnet has been used to monitor the magnet current. For convenience the model V-2200A power supply was modified by the substitution of a voltage reference based on solid state circuitry for the vendor's voltage reference which was a mercury cell battery.

B. The Balance Beam (Figure 1)

The beam was constructed from a 75 cm long quartz rod with a thermally insulated copper sample holder at one end and a permanent magnet at the other. The suspension consists of #40 B&S constantan(Cn) and #36 B&S copper(Cu) wires set 45° above the horizontal. The angular suspension restricts the beams' freedom to longitudinal motion. Beam rotation is prevented by small copper arms attached to the

Figure 1. The Balance Beam

suspension wires and a fiducial pointer provides translational reference.

C. Cryostat (Figure 2)

The cryogenic system consists of two parts, a vertical Dewar of standard variety and a horizontal Dewar. The vertical Dewar consists of two concentric chambers, the inner of which is made of type 321 stainless steel and can be filled with liquid helium. The outer chamber is made of copper and normally filled with liquid nitrogen. The overall diameter of the vertical Dewar over most of its length is six inches. The chamber necks to one inch at the bottom in order to fit between the pole pieces of the magnet. Similarly the horizontal nitrogen Dewar measures six inches in diameter near the cooling tunnel entrance and necks to one inch at the pole pieces.

The inner chamber of the vertical Dewar serves as a heat sink for the test specimen. Thermal contact between the test specimen and the inner chamber is provided by forcing the balance beam against the dry finger using the restoring solenoid. The horizontal nitrogen Dewar and accompanying heat shield provided thermal insulation of the balance beam from the external environment.

Figure 2. Side view of the Cryostat

D. Thermometry and Temperature Control

The sample temperature is measured over the range 30°K to 300°K with a copper vs constantan thermocouple. The cold junction of the thermocouple is attached to the sample pan next to the sample position. Electrical contact to this junction is obtained via the copper and constantan suspension wires.

All copper vs constantan thermocouples were calibrated using the temperature of ice water (273°K), liquid nitrogen (77°K) and liquid helium (4.2°K) as fixed reference points. Uncorrected junction voltages were always within $\pm 1\%$ of the New NBS reference tables [8]. A linear correction factor of the form

$$V_{Jn}(T) = \frac{V_{table}(T_{ref})}{V_{T.C.}(T_{ref})} \times V_{T.C.}(T)$$

was used to bring the thermocouple junction voltages into agreement with the listed reference table voltages. Identical correction factors were obtained for thermocouples made from wire of the same spool.

The temperature of the sample can be varied by a 200 ohm heater element wound noninductively on the cold finger of the helium DeWar. A DC power supply and a variable resistor supply current to the heater. Temperature is controlled manually by adjusting the current to the heater.

Temperature stability during a typical susceptibility measurement is $\pm 0.5^\circ\text{K}$ over 7-10 minutes.

E. Optics and Restoring System (Figures 3 and 4)

Translation of the quartz balance beam may be observed visually via optical magnification of the relative positions of the fiducial markers. The optical system provides an effective lever arm such that a balance beam displacement of 16 microns reflects a displacement of 1 cm in the fiducial image. The beam position can be located to within ± 5 microns.

A restoring solenoid was constructed by winding 200 turns of #18 copper wire on an austenitic stainless steel tube. The solenoid may be energized and controlled by an adjustable current supply.

The restoring solenoid and permanent magnet (see theory of balance and Appendix B) are positioned with their longitudinal axes aligned. A face of the solenoid and the midsection of the magnet lie in a common plane, thereby positioning the permanent magnet in the constant gradient portion of the solenoid.

Figure 3. The Optics system

Figure 4. The relative position of the solenoid and permanent magnet

IV. SUSCEPTIBILITY MEASUREMENT

In order to measure the magnetic susceptibility of the sample the magnetically induced force f_z , must be compensated by a force, f_r , from the restoring solenoid acting on the permanent magnet attached to the quartz balance beam. The restoring force is proportional to the current I in the solenoid (see Appendix B), $f_r \propto I$.

In order to correct for the presence of ferro-magnetic impurities, the method of Honda and Owen [9] is normally employed. The method assumes that the force per unit mass on a specimen containing ferromagnetic impurities is given by

$$(f_z)_i = \frac{1}{2} X_p \frac{\partial(H_z^2)_i}{\partial z} + C \sigma \frac{\partial(H_z)_i}{\partial z} \quad (7)$$

where C is the mass fraction of ferromagnetic impurity of specific saturation intensity σ ; e.g. common iron $\sigma \approx 220$ erg/gauss. [10]. The subscript i is used because several field determinations are necessary to determine the mass susceptibility. Writing eq. 7 in the form normally used when applying the Honda-Owen method results in

$$F_i I_i = X_p + C \sigma \frac{1}{H_i} \quad (8)$$

where F_i defines $k / H_i \frac{\partial H_i}{\partial Z}$, k being the force propor-

tionality constant of the solenoid. A plot of $F_i I_i$ VS $\frac{1}{H_i}$

for several field strengths allows extrapolation to evaluate

X_p at infinite field strength. Because of the field gradient

over the sample volume a mean value for $\frac{1}{H_i}$ must be used

for the Faraday method.

V. CALIBRATION AND ERROR ANALYSIS

The system was calibrated by determining the specific force constants F_i and the reciprocal field strengths H_i^{-1} in eq. 8 using the N.B.S. magnetic susceptibility standards platinum, palladium and aluminum. N.B.S. lists the susceptibilities of the above standards as follows:

$$\chi_{297^\circ\text{K}}^{\text{Pt}} = 0.991 \times 10^{-6} \frac{\text{emu}}{\text{g}},$$

$$\chi_{297^\circ\text{K}}^{\text{Pd}} = 5.26 \times 10^{-6} \frac{\text{emu}}{\text{g}},$$

$$\chi_{297^\circ\text{K}}^{\text{Al}} = 0.604 \times 10^{-6} \frac{\text{emu}}{\text{g}}$$

Figures 5-9 illustrate the zero response of the empty sample holder due to the applied field as a function of temperature. The data shown in Figures 5-9 have been fitted with a sixth order polynomial of form

$$\text{ZPT}(T^\circ\text{C})_{\text{mA}}^i = A + BT + CT^2 + DT^3 + ET^4 + FT^5 + GT^6 \quad (9)$$

in order to allow interpolation between data points. The superscript i indicates one of the five magnet field settings. Table 1 lists the calculated constants for each zero response curve.

The N.B.S. magnetic susceptibility standards are characteristically field independent i.e. the mass fraction C of ferromagnetic impurities in the standards are essentially

Figure 5. Empty sample holder zero response: Field setting #10

Figure 6. Empty sample holder zero response: Field setting #9

Figure 7. Empty sample holder zero response: Field setting #8

Figure 8. Empty sample holder zero response: Field setting #7

Figure 9. Empty sample holder zero response: Field setting #6

Table 1. Nonlinear least squares coefficients for the field response of the empty sample holder

Constants	Field Settings				
	10	9	8	7	6
A	-0.343	-0.224	-0.117	-0.043	-0.000
B x 10^4	8.876	6.661	7.567	3.843	2.469
C x 10^6	9.660	12.857	6.543	3.700	2.632
D x 10^7	-11.199	-8.714	-8.181	-5.790	-3.092
E x 10^8	-1.763	-1.507	-1.271	-0.888	-0.402
F x 10^{11}	-10.113	-9.049	-7.129	-4.923	-1.849
G x 10^{13}	-1.939	-1.789	-1.336	-0.910	-0.265

zero. Rewriting eq. 8 with this result yields

$$F_i = X_p^{\text{std}} / I_i \quad (10)$$

By measuring the solenoid currents which null the induced magnetic force of the standards in each field, the force constants can be calculated. Table 2a lists one such set of nulling currents used for calibrating the system. The data in Table 2a must be corrected for the response of the empty holder before substitution into eq. 10. The corrected currents and resulting F_i are shown in Table 2b.

Once the force constants were established, the relative field strengths were obtained by the following procedure. Initial estimates were determined using a calibrated Rawson gauss meter. The meter was calibrated in a homogenous field of 10.000 KGauss using ^{27}Al in a saturated solution of AlCl_3 in water. ^{27}Al has a nuclear frequency of 11.09404 MHz in a field of 10.000 KGauss. These measurements were then refined by examining the behavior of the N.B.S. aluminum standard as its ferromagnetic impurity concentration was increased. Since the paramagnetic and diamagnetic effects of ppm amounts of iron are negligible compared to its ferromagnetic response, adding such small quantities of iron to the aluminum does not alter the aluminum's susceptibility. Table 3a illustrates a representative response of the aluminum standard before and after being surface doped with iron powder. The final

Table 2a. Solenoid current required to null the induced magnetic force of palladium and platinum

	Field Setting				
	10	9	8	7	6
Solenoid Current in mA (23°C)	2.745	2.330	1.805	1.310	0.920
	2.728	2.323	1.798	1.298	0.918
	2.735	2.325	1.790	1.305	0.915
	2.735	2.325	1.790	1.305	0.915
	2.735	2.325	1.790	1.305	0.915
	2.735	2.325	1.795	1.315	0.925
	2.735	2.325	1.795	1.295	0.915
	2.730	2.325	1.795	1.305	0.915
	2.733	2.323	1.783	1.303	0.903
	2.738	2.328	1.788	1.303	0.908
Average	2.735	2.325	1.793	1.304	0.915
Standard deviation	0.004	0.002	0.006	0.005	0.006
Precision	0.17%	0.09%	0.33%	0.42%	0.65%

Table 2b. Force constants

	Field Settings				
	10	9	8	7	6
Zero adjusted Solenoid currents	3.083	2.550	1.911	1.352	0.915
Force Const. x 10 ⁴	6.372	7.704	10.281	14.531	21.471

Table 3a. Solenoid current required to null the induced magnetic force of aluminum

Field Settings					
	10	9	8	7	6
Solenoid current in mA for pure Aluminum	0.345 0.350 0.350 0.355 0.355	0.345 0.350 0.355 0.355 0.355	0.310 0.320 0.315 0.320 0.315	0.255 0.260 0.260 0.255 0.260	0.210 0.200 0.205 0.210 0.215
Average	0.351	0.352	0.316	0.258	0.208
Solenoid current in mA for doped Aluminum	3.270 3.270 3.265 3.265 3.265	3.010 3.010 3.010 3.005 3.005	2.600 2.600 2.595 2.595 2.595	2.150 2.155 2.145 2.145 2.145	1.720 1.725 1.720 1.715 1.715
Average	3.267	3.008	2.597	2.148	1.719

Table 3b. Field strengths

Field Settings					
	10	9	8	7	6
Gauss meter (KG)	11,613	10,545	9,205	7,875	6,666
Refined H_i	11.500	10.442	9.112	7.781	6.586
$H_i^{-1} \times 10^5$	8.695	9.576	10.974	12.852	15.184

field strength values were obtained by adjusting the original estimates to the aluminum data subject to the constraint of constant susceptibility. Table 3b lists these values.

Calibration of the system was checked by cycling the N.B.S. platinum standard between 78°K and room temperature. The resulting plot is shown in Figure 10. The N.B.S. room temperature susceptibility of platinum is 2% lower than that reported by Croat [11] and, Hoare and Matthews [12]. The resulting low temperature plot of X_p VS T for platinum is consistently 2% lower than reported by Hoare and Matthews.

The errors that arise in magnetic susceptibility measurements made at two different field strengths H_1 and H_2 may be developed from eq. 8 as follows

$$F_i I_i = X_p + \frac{C\sigma}{H_i} \quad (11)$$

$$\Delta(F_i I_i) = \Delta X_p - C\sigma \frac{\Delta H_i}{H_i^2} \quad (12)$$

$$H_1 \Delta(F_1 I_1) = \Delta X_p H_1 - C\sigma \frac{\Delta H_1}{H_1} \quad (13a)$$

$$H_2 \Delta(F_2 I_2) = \Delta X_p H_2 - C\sigma \frac{\Delta H_2}{H_2} \quad (13b)$$

subtracting eq. 13b from eq. 13a and simplifying yields

$$\Delta X_p = \frac{H_1}{H_1 - H_2} \Delta(F_1 I_1) + \frac{H_2}{H_1 - H_2} \Delta(F_2 I_2) + \frac{C\sigma}{H_1 - H_2} \left(\frac{\Delta H_1}{H_1} - \frac{\Delta H_2}{H_2} \right) \quad (14)$$

Figure 10. The Susceptibility versus Temperature of an NBS Platinum susceptibility standard.

From eq. 14 an upper bound in the systematic error in X_p can be determined. The maximum systematic error in X_p is bounded such that

$$|\Delta X_p| \approx 2 \frac{H_1}{H_1 - H_2} \Delta(F_1 I_1) \sqrt{\left(\frac{\Delta I_1}{I_1}\right)^2 + \left(\frac{\Delta F_1}{F_1}\right)^2} \quad (15)$$

where the first two terms in eq. 14 were assumed identical and the third term negligible since the per cent error $\frac{\Delta H_i}{H_i}$ is nearly identical for all fields. Eq. 15 indicates that the systematic error in X_p can be reduced in two ways: (1) maximizing the difference in field strengths, (2) decreasing the fractional error in the force constants and solenoid currents. Table 4 lists the maximum possible errors in I and F in addition to the order of magnitude for the quantities found in eq. 15. The maximum systematic error in X_p is then found to be

$$|\Delta X_p| \leq 3 \times 10^{-8} \text{ emu/g} \quad (16)$$

Table 4. Magnitudes and systematic errors for the quantities found in eq. 15.

Symbol	Error	Order of Magnitude
$\frac{H_i}{(H_i - H_{i+1})}$	---	10
$F_i I_i$	---	10^{-7}
$\frac{\Delta I}{I}$	10^{-2}	---
$\frac{\Delta F}{F}$	10^{-2}	---

VI. DISCUSSION

A. The Balance Beam

The balance beam is the heart of a translation balance. Its design directly affects the performance of the apparatus.

The copper sample holder was mechanically clamped to the quartz rod so that the sample holder could not be moved. Direct quenching of the sample holder assembly and rod into liquid nitrogen did not fracture the rod or cause the holder assembly to move. It was assumed that if the joint could survive a quench test it would not fail when slow cooled to 77°K. The mechanical joint overcame the inherent fragility of a fused bond between a quartz sample holder and the rod. Furthermore the mechanical joint eliminated all epoxies, glues, and varnishes in the vicinity of the main magnetic field. Tests had shown that chemical joints either fractured on quenching or altered their chemical nature with time thereby changing the zero response of the beam in the field.

Analysis of eq. 6 shows that the sensitivity is inversely proportional to the beam's mass. This limited the material selection to those materials light enough to satisfy mass restrictions and still function properly. The mass of the beam is 23 grams. Beam designs with a mass less than 18 grams always gave spurious results (probably due to an interaction with the support wires; an ideal pendulum does

not interact with its suspension). The torque resistors on the beam were bonded to the support wires using Duco cement. When G.E. Varnish was used to bond the torque resistors and suspension wires the beam tended to drift with time. Stereo-microscopy revealed that the G.E. Varnish flexed as the beam was displaced. When the beam position was nulled the bonds slowly returned to their original position thereby causing the drift.

Quartz rod was chosen as the main structural component of the beam primarily because quartz has a high strength to weight ratio and small thermal conductivity. Since conductive heat loss is proportional to area, the rod geometry minimized area while retaining rigidity. The final beam geometry minimized conductive heat loss. Although exact thermal calculations were not performed, comparative thermal calculations indicated the per cent change in heat flow as the beam geometry was altered.

The beam thermocouple was constructed from #44 B&S copper and #40 B&S constantan wire. The thermocouple was wound in a spiral along the quartz rod until the electrical contacts (the suspension wires) were reached (Figure 1). The thermocouple wires were kept as small as possible and wound in a spiral in order to decrease the area of the thermal conduction path and increase the thermal conduction path's length.

Extension of the system to the temperature range 4.2-77°K will require either a four point temperature sensing system or an additional thermocouple. In either case the present structural design would not easily encompass these additions. It is not obvious as to how the present direct temperature monitoring design could be extended to this lower temperature range.

B. Cryostat

Although the cryostat functioned satisfactorily, its construction was severely restricted by spacial constraints imposed by the Varian electromagnet geometry. Given sufficient space a number of the cryostat features would be redesigned. The cooling tunnel would be enlarged to encompass larger samples and to install a heater coil which would surround the sample holder and adjacent support rod. Baffling would also be introduced along the cooling tunnel to reduce radiation heat loss.

A shop error resulted in two Dewars being constructed with copper fill parts. Although the resulting heat leak did not adversely affect the susceptibility measurements it did decrease the liquid nitrogen's storage time. The copper fill parts would be replaced by stainless steel.

C. Optics and Restoring System

The optical system (Figure 3) is used to magnify the relative positions and displacements of the fiducial markers in order to observe and null the small magnetically induced beam displacements. Originally the fiducial markers were constructed as two pointers located in line above one another.

However a technique was never devised which could produce two points that would remain points when magnified 800 times. By extending the fiducial markers as shown in Figure 3 the edges could be aligned so that an equilibrium reference position could be defined. Magnifications above 1000X were unacceptable because the slight lateral displacement necessary to prevent marker contact eventually resulted in fuzzed images. The distortion arises because the primary focal plane of the first magnifying lens must lie midway between the fiducial markers. Chromic aberration was also a problem. By off centering the light source relative to the collimator all chromic aberration was eliminated. Chromic aberration could have been easily eliminated with a

monochromatic light source e.g. sodium vapor light or carbon arc. This was not possible in the present situation because of the unavailability of a monochromatic source. The off centering process reduced the available magnifying light and decreased the image-background contrast thereby limiting the acceptable magnification to approximately 800X. The quality of the images was excellent as long as the magnification was less than 800X.

The slight fuzzing of the fiducial marker edges at extreme magnification limited the positional reproducibility to ± 5 microns. An opto-electronic sensing system similar to that used by Dorfman and Kikoin [13] could be constructed which would increase positional reproducibility to ± 0.5 microns, thereby increasing the overall accuracy of the system and eliminating the need for an observer.

The components of the restoring system are the permanent magnet attached to the beam (Figure 4), the solenoid, and the solenoid current supply. The permanent magnet was made from samarium cobalt because it is presently the most coercive magnet material. This minimizes the demagnetization problem and accompanying change in calibration with time. The solenoid is an untapped 200 turn coil powered by a variable current supply having a controllable range extending from 1uA to 1A. The restoring system was constructed with this extreme range because the solenoid-magnet interaction

force could not be calculated before it was actually constructed. This was the only way of being sure that the solenoid-magnet force could null the sample induced force.

Since the induced magnetic force on an arbitrary sample can be bounded it would be useful to know the solenoid-magnet interaction force in order to predetermine the solenoid-magnet force range. However, the main drawback of the restoring system is the inability to calculate this interaction. The problem can be minimized by constructing a solenoid with a large combination of amp-turn possibilities, i.e. a tapped solenoid. Then by using a current supply with the previously mentioned range almost any magnet-solenoid force could be controlled.

VII. SUMMARY

A translation balance was constructed to perform magnetic susceptibility measurements on magnetically anisotropic single crystals over the temperature range 77-300°K. The balance incorporates a horizontal sample holder on which a single crystal can be oriented with a given crystallographic axis parallel to the field direction. A cryostat was designed with a horizontal addition to cool the specimen and adjacent support rod. The balance design also allows for the direct measurement of the specimen's temperature. The sensitivity of the balance is 0.0044 cm displacement/dyne.

Room temperature calibration was accomplished by a comparative method based on the accepted susceptibilities of the N.B.S. standards, platinum, palladium, and aluminum. The susceptibility of the N.B.S. platinum standard was measured as a function of temperature (77-300°K) in order to check the system's calibrations. The resulting data were consistently 2% lower than that reported by Hoare and Matthews. The precision of the system is $\pm 0.5\%$ with a room temperature accuracy of 1.5% and a subambient accuracy of $\pm 2\%$.

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X. ACKNOWLEDGMENTS

I would like to express my gratitude to Professors John F. Smith, Frank X. Kayser and Donald L. Parker for the assistance tendered me in the course of this project.

The discussions, advice and suggestions of Mr. John Greiner and Mr. Bernie Beaudry were invaluable and sincerely appreciated.

Finally the author would like to sincerely thank Mr. Bernie Evans, Mr. Gary Reynolds and Miss Darlene Gallagher, for without their continual support and help this thesis would not have been possible.

XI. APPENDIX A

A simple derivation of Eq. 5 will show the relation between the horizontal displacement l of a simple pendulum due to a force f and the physical parameters of the pendulum.

$$l = h \sin \theta \approx h \theta \quad (a)$$

$$f = Mg \tan \theta \approx Mg \theta \quad (b)$$

substituting for θ in Eq. (a)

$$l = f \frac{h}{Mg} \quad (c), (5)$$

A translation balance is a simple pendulum. For such a pendulum small angle approximations, $\theta = \sin \theta = \tan \theta$, are valid for small displacements.

XII. APPENDIX B

The restoring force produced by the field of a solenoid acting on a permanent magnet is proportional to the solenoid current when two conditions are met: (1) the longitudinal axes of the permanent magnet and solenoid coincide, (2) the center of the permanent magnet and the face of the solenoid lie in a common plane.

In a nonuniform field a magnet experiences a torque and a translatory force. If the magnet is unable to rotate, only translation will result. Consider a magnet of pole strength $\pm Q_m$ (Figure 11a) in a nonuniform magnetic field which increases in the positive Z direction. The magnetic moment of the permanent magnet is $m = d Q_m$ and is inclined at an angle θ to a field B. The value of B at the magnet center is B_0 . The force on a pole of strength Q_m in a field B is

$$F = Q_m B. \quad (a)$$

The total force on the magnet is the sum of the forces on the poles due to the field. Therefore,

$$F_R = \left[B_0 + \frac{\partial B}{\partial Z} \frac{d}{2} \cos \theta \right] (Q_m) + \left[B_0 - \frac{\partial B}{\partial Z} \frac{d}{2} \cos \theta \right] (-Q_m) \quad (b)$$

simplifying

$$F_R = Q_m d \frac{\partial B}{\partial Z} \cos \theta \quad (c)$$

(a) Permanent Magnet in a nonuniform Magnetic field

Percent field intensity versus distance along axis of solenoid.
 "a" defines solenoid radius

Figure 11. Solenoid and magnet characteristics

$$F_R = \frac{\partial B}{\partial Z} m \cos \theta \quad (d)$$

where m defines the magnetic moment of the permanent magnet. Eq. (d) implies that the magnet experiences a force toward the stronger portion of the field. This force is proportional to the gradient of the field and to the component of the magnetic moment in the direction of the field.

It can be shown that the magnetic field of a solenoid along its axis is of the form

$$B \propto nI (\sin \alpha \pm \sin \beta) \quad (e)$$

where n defines the number of turns of wire per unit length, I the solenoid current, and α and β the angles between the point of interest and the solenoid faces. Near a solenoid face $\sin \alpha \approx \frac{a}{L}$

$$B \propto nI (\sin \alpha - \sin \beta)$$

$$B \propto nI (\sin \alpha + \sin \beta)$$

where "a" defines the radius of the solenoid and L the solenoid length. Also $\sin \beta \approx \beta$. Assuming the sign convention

B positive inside the solenoid and negative exterior to the solenoid, Eq. (e) becomes

$$B = nI \left(\frac{a}{L} + \theta \right) \quad (f)$$

a plot of B VS θ yields a straight line and represents the linear portion of Figure 11b about a solenoid face. Taking the gradient of Eq. (f) yields

$$\frac{\partial B}{\partial \theta} \propto I \quad (g)$$

and is a constant since the solenoid current is independent of θ . Substituting this result into Eq. (d) results in

$$F_R \propto I \quad m \quad \cos \theta \quad (h)$$

If the magnet lies along the axis of the solenoid $\cos \theta$ is constant. The magnetic moment of the permanent magnet is also constant leaving the desired result

$$F_R \propto I \quad (i)$$