ANGULAR DEPENDENCE OF THE LINE WIDTH OF A PLANAR FERRITE

by

Thomas C. Nelson

A Thesis Submitted to the Faculty of the

DEPARTMENT OF ELECTRICAL ENGINEERING

In Partial Fulfillment of the Requirements
For the Degree of

MASTER OF SCIENCE

In the Graduate College

THE UNIVERSITY OF ARIZONA

1 9 6 3

STATEMENT BY AUTHOR

This thesis has been submitted in partial fulfillment of requirements for an advanced degree at The University of Arizona and is deposited in The University Library to be made available to borrowers under rules of the Library.

Brief quotations from this thesis are allowable without special permission, provided that accurate acknowledgment of source is made. Requests for permission for extended quotation from or reproduction of this manuscript in whole or in part may be granted by the head of the major department or the Dean of the Graduate College when in their judgment the proposed use of the material is in the interests of scholarship. In all other instances, however, permission must be obtained from the author.

SIGNED: Thomas C. Nelson

APPROVAL BY THESIS DIRECTOR

This thesis has been approved on the date shown below:

Donald C. Stinson — 6-20-63

Donald C. Stinson
Professor of Electrical Engineering — Date

ACKNOWLEDGMENT

The author wishes to express his appreciation to Dr. Donald C. Stinson for his counsel, instruction and patient understanding without which this thesis would never have been completed. The author would also like to thank his wife not only for her moral support during the preparation of this thesis but also for typing the manuscript.

ABSTRACT

The line width of a single crystal anisotropic ferrite (Zn_2Y) was measured experimentally as a function of the orientation of the crystal in the static magnetic field. Two cases were considered: In the first the ferrite was rotated about an axis perpendicular to its preferred plane of magnetization. Relatively small differences in line width were found between orientations and no particular orientation had the lowest or highest line width over the range of frequencies considered. In the second case the ferrite was rotated about an axis contained in its preferred plane of magnetization. In this case the line width was always smallest when the preferred plane of magnetization was perpendicular to the static magnetic field and, at a particular frequency, largest when the preferred plane of magnetization was oriented parallel to the static magnetic field.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

CHAPTER I

INTRODUCTION

1.1 General Background

The first magnetic material known was the ferrite magnetite which is also the only ferrite found in nature. The properties of magnetite were first studied in the late ninteenth century. DuBois[1] measured the saturation magnetization in 1890 and Weiss[2] studied the B-H characteristics of magnetite with its crystal orientation as a parameter in 1896. It was realized early in the twentieth century that magnetite, since its resistivity is of the order of one thousand times larger than that of iron, would be useful in reducing eddy currents and therefore losses in transformers. Hilbert[3] in 1909 produced the first synthetic ferrites with the idea in mind of improving on the loss properties of magnetite. He experienced considerable difficulty in achieving consistancy. Improvements in the metallurgy and laminating techniques of iron transformers around the same time essentially killed the then budding interest in ferrites.[4]

It was not until the 1930's that any significant interest was again shown in ferrites. Most of the work done at this time was in the area of ferrite crystal structure. X-ray diffraction was the principal tool and with it Bourth and Posnjak[5] discovered in 1932 what is now called the inverted spinel structure which is required for the existance of the feromagnetic phenomenon in ferrites.

From 1933 until after World War II most of the significant work in ferrites was carried on at the Phillips research Laboratories in Eindhoven, Holland. Under the direction of Snoek, researchers at Phillips were able to make significant strides in increasing the permeability and decreasing the losses in ferrites as well as in developing the technology necessary for commercial production.

The most important postwar development in ferrites was Néel's[6] theory of ferrimagnetism. This explained the results of the discovery that certain kinds of ferrites were not ferromagnetic and had a normal rather than inverted spinel structure. Néel's theory induced the synthesis and study of even more exotic ferrites. Among these have been the substitution ferrites, the ferrimagnetic garnets and the barium ferrites of which Zn_2Y is one.*

Among the properties of ferrites currently of interest is the ferromagnetic line width which is defined

*These compounds are, strictly speaking, not ferrites but ferrimagnetic oxides, but will be referred to in this thesis as ferrites as is common practice.

as the incremental magnetostatic field between two points on the resonance curve where absorption is 3 db below peak value[7]. The line width is inversely proportional to the magnetic "Q" of the ferrite and is thus an important property.

1.2 Statement of the Problem

The line width of a planar ferrite is sensitive to the angular orientation of the ferrite in the magnetostatic field. The degree of sensitivity is maximum over a relatively narrow range of rf frequencies. This thesis will correlate experimental and theoretical data on the angular dependence of the line width over the above range of rf frequencies for a particular planar anisotropic ferrite (Zn_2Y).

1.3 Method of Treatment

A spherical single crystal sample will be placed in a cross guide coupler that has been modified to permit changing the orientation of the sample without disturbing any of the other parameters. Two cases will be considered: One in which the sample will be rotated about the "c" axis which is the axis perpendicular to the preferred plane of magnetization of the sample and the other in which the sample will be rotated about the hexagonal axis which is the axis contained in the preferred plane of magnetization. Line width measurements will be made at various angles as the ferrite is rotated about each of the axes.

CHAPTER 2

THEORY

2.1 Physical Characteristics

Chemically, the ferrimagnetic oxides are characterized by the addition of one or two divalent metal oxides to Fe_2O_3. Since Zn_2Y is a member of the barium group of ferrimagnetic oxides, the two divalent metal oxides present in addition to Fe_2O_3 are BaO and ZnO. The "Y" designation is one devised by Janker, Wijn and Braun. It, along with other designations devised by this same group and now generally accepted in describing the barium oxide group of ferrites are explained in Table I[8].

In the table Me can be, besides Zn or Mg, any of the divalent transition metals of the iron group. From the table then, Zn_2Y would be $2BaO\cdot 2ZnO\cdot 6Fe_2O_3$.

Crystals of the barium oxide group show hexagonal symmetry, but more importantly have large (8.7 - 28 kilo oersteds)[9] internal anisotropic magnetic fields oriented in one of two ways with respect to the hexagonal plane of symmetry. In the Z and Y compounds the anisotropy field strongly binds the magnetization of the crystal to the hexagonal plane, but leaves the magnetization comparatively free to rotate in the plane itself. The relative stiffness of rotation of the magnetization in

TABLE I

CHEMICAL RELATIONSHIPS OF THE BARIUM OXIDE FERRITES

Compound	Composition	Interrelation
S	$MeO \cdot Fe_2O_3$	
M	$BaO \cdot 6Fe_2O_3$	
W	$BaO \cdot 2MeO \cdot 8Fe_2O_3$	W = M + 2S
Y	$2BaO \cdot 2MeO \cdot 6Fe_2O_3$	
Z	$3BaO \cdot 2MeO \cdot 12Fe_2O_3$	Z = M + Y

the plane is of the order of 10^{-3} times that of rotation out of the plane for Z and Y compounds in general and of the order of 1 to 9000 for Zn_2Y in particular.[10] In the other barium oxides the anisotropy field binds the magnetization to an axis perpendicular to the hexagonal plane. This amounts to a built in permanent magnet which is highly useful in many ferrite devices.

These anisotropy fields can be explained by the Néel theory of ferrimagnetism, specifically by the concept of super exchange interaction.[6] The fact that some of the compounds have planar anisotropy and others uniaxial anisotropy is a result of the positions of the Fe and Me ions with respect to the O ions in the crystal.[11]

Measurements by Smit and Wijn[12], and Shaw[13] are in general agreement and give the following data for Zn_2Y:

H^A_ϕ	1 oersted
H^A_θ	8700 oersteds
$4\pi M_s$	2850 oersteds

The subscripts of H^A are the usual spherical coordinates and the hexagonal plane is coplanar with the ϕ plane.

2.2 Gyromagnetic Resonance Theory

Consider an electron spinning in a lossless environment as in Figure 2.1. Let $\bar{p}$ be the angular

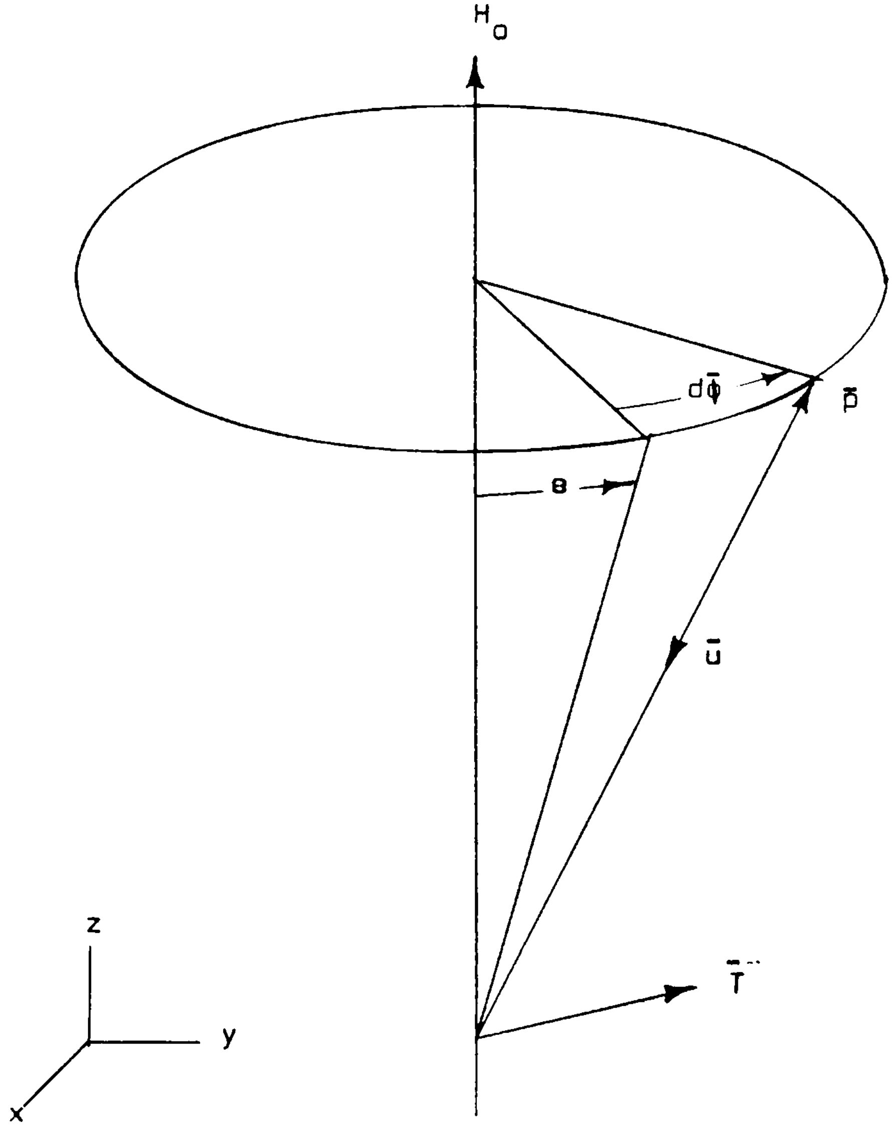


FIGURE 2.1 - PRECESSION OF A SPINNING ELECTRON

momentum of the electron, $\bar{u}$ the magnetic moment and $\bar{T}$ the torque resulting from the action of an applied magnetostatic field $\bar{H}_o$ on $\bar{u}$. Then

$$\bar{T} = \frac{d\bar{p}}{dt} = \bar{u} \times \bar{H}_o \qquad (2.01)$$

$$d\bar{p} = d\bar{\phi}\ p\sin\theta \qquad (2.02)$$

$$\frac{d\bar{\phi}}{dt} = \frac{\bar{u} \times \bar{H}_o}{p\sin\theta} \qquad (2.03)$$

$$\frac{d\phi}{dt} = \omega_o = \frac{uH_o\sin\theta}{p\sin\theta} \qquad (2.04)$$

$$\omega_o = \frac{u}{p} H_o = \gamma H_o \qquad (2.05)$$

where ω_o is the natural precessional frequency of the spinning electron. Also, if the magnetic moment per unit volumne is $\bar{M} = N\bar{u}$, where N is the number of magnetic dipoles per unit volumne, then if $\bar{H}$ is the sum of $\bar{H}_o$ and any other magnetic field in the ferrite,

$$\frac{d\bar{M}}{dt} = \gamma(\bar{M} \times \bar{H}) \text{ and} \qquad (2.06)$$

$$\gamma = \frac{u}{p} = ge/2mc \qquad (2.07)$$

where e, m and c are the charge and mass of an electron and the speed of light respectively. The quantity g is the spectroscopic splitting factor, usually called simply the g factor, which has a value slightly in excess of 2.

With reference to the coordinate system in Figure 2.1, suppose that in addition to the applied magnetostatic field $\bar{H}_o$ along the z axis, an rf $\bar{h}$ field is applied perpendicularly to $\bar{H}_o$ where $|\bar{h}| << |\bar{H}_o|$. Then the total magnetic field will be

$$\bar{H} = \bar{h}e^{j\omega t} + \bar{H}_o \tag{2.08}$$

The total magnetization will be

$$\bar{M} = \bar{m}e^{j\omega t} + \bar{M}_o \tag{2.09}$$

Also,

$$\bar{M}_o \times \bar{H}_o = 0 \tag{2.10}$$

for an isotropic ferrite, presuming a large enough $\bar{H}_o$ for saturation. Using these expressions for $\bar{M}$ and $\bar{H}$ in Equation (2.06) and neglecting all but the first order terms gives

$$j\omega\bar{m} = \gamma(\bar{M}_o \times \bar{h} + \bar{m} \times \bar{H}_o) \tag{2.11}$$

After some simple vector manipulations[10]

$$\bar{m} = \frac{1}{\omega_o^2 - \omega^2}\left[j\omega\gamma(\bar{M}_o \times \bar{h}) + \gamma^2(\bar{H}_o \cdot \bar{M}_o)\bar{h} - \gamma^2(\bar{H}_o \cdot \bar{h})\bar{M}_o \right] \tag{2.12}$$

Thus the rf component of magnetization has a maximum at $\omega = \omega_o = \gamma H_o$. Now if $\bar{h} = \bar{i}_x h_x + \bar{i}_y h_y$ is substituted in Equation 2.12

$$m_x = \frac{M_o \gamma}{\omega_o^2 - \omega^2}(\omega_o h_x - j\omega h_y) \tag{2.13a}$$

$$m_y = \frac{M_o \gamma}{\omega_o^2 - \omega^2}(j\omega h_x + \omega_o h_y) \qquad (2.13b)$$

$$m_z = 0 \qquad (2.13c)$$

Thus an rf field applied perpendicularly to $\bar{H}_o$ not only reinforces itself but also creates another rf field perpendicular to both itself and $\bar{H}_o$. That is, $\bar{m} = \langle X \rangle \cdot \bar{h}$ where $\langle X \rangle$ is the suseptibility tensor. In this case

$$\langle X \rangle = \begin{pmatrix} X_{xx} & X_{xy} & 0 \\ X_{yx} & X_{yy} & 0 \\ 0 & 0 & 0 \end{pmatrix} \text{ where} \qquad (2.14)$$

$$X_{yy} = X_{xx} = \frac{\omega_o 4\pi M_o \gamma}{\omega_o^2 - \omega^2} \qquad X_{xy} = -X_{yx} = \frac{-j\omega 4\pi M_o \gamma}{\omega_o^2 - \omega^2} \quad (2.15)$$

The factor 4π is necessary since, as is common in the ferrite literature, Gaussian and MKS units are mixed in the same equation.

In the analysis to this point, the following simplfying assumptions have been made: (1) The system is lossless, and (2) The field in any ferrite sample is simply the vector sum of the externally applied fields. There are, of course, losses. Also, in addition to the externally applied fields there are fields in any ferrite sample that result from the interaction of neighboring spinning electrons and from the boundary conditions of any finite sample. The former are called exchange fields and the latter demagnetizing fields. The boundary conditions for spheres are such that there are no demagnetizing fields. The effects of losses and exchange fields will be covered in the following sections of this chapter.

2.3 Damping

There are two formulations of damping or loss term. Both are added to the right hand side of Equation 2.06 and are supposed to account for "frictional" losses. The first was formulated by Landau and Lifshitz[14] and the other by Bloch and Bloembergen[15]. That there must be some such term is obvious in order to establish precession equilibrium as well as to keep $\bar{m}$ and $\langle X \rangle$ finite at resonance. Since these losses cause $\langle X \rangle$ to be finite at resonance they in turn cause the ferrite to have a non-zero magnetic line width. Any increase in losses causes greater line width. Bowers and Stinson[16] have shown that neither of the forms is adequate for the complete microwave spectrum.

2.4 Effects of Anisotropy on Resonance

Using a method devised by Smit[17], Buffler[18] has derived a resonance equation for planar anisotropic ferrites for the case in which the preferred plane of magnetization is parallel to the applied magnetostatic field.

It is

$$\left(\frac{\omega_0}{\gamma}\right)^2 = H_0(H_0+H^A) \qquad (2.16a)$$

For other orientations Lax and Button[19] point out that

$$\omega_0 = \gamma\left(H_0 + f(\theta)\right) \qquad (2.17)$$

where θ is the angle between $\bar{M}$ and $\bar{H}_0$ and is a function of $\bar{H}_0$, H^A, and the angle between $\bar{H}_0$ and the preferred plane of magnetization. Anisotropy, therefore, considerably complicates the relationship between ω_0 and H_0.

2.5 Spin Wave Theory

In addition to the losses in energy that are a direct result of magnetic dipole motion, i.e., those described by the Landau-Lifshitz and Bloch-Bloembergen loss terms, there are other losses that take place which are a result of so called spin waves. These losses have been described by Herring and Kittel[20] by adding another term to Equation 2.06. Physically, spin waves may be described as follows: Suppose an rf magnetic field is applied to one end of a ferrite specimen so as to cause some of the electron spins to precess with a greater angle than their neighbors. The internal exchange field H_{ex} tending to align dipoles will act to swing the neighbors into the larger precessional angle, but there will be a small delay. Thus the precessional angle disturbance will travel through the crystal in the form of a wave with both phase and amplitude changes between dipoles[21]. Therefore, as described by Clogston, Suhl, Walker and Anderson[22], energy is lost by the uniformly precessing spin dipoles to the spin wave reservoir.

2.6 Line Width in Anisotropic Ferrites

One of the ways in which anisotropy may affect the line width is by altering the loss term. For instance, if the Landau-Lifshitz loss term is included in Equation 2.06, then it can be shown[23] that Equation 2.11 has an additional term proportional to $\bar{i}_z \times \bar{m}$. As will be shown shortly, m_x and m_y in the case of anisotropic ferrites are proportional to the cosine of the angle between $\bar{M}_o$ and $\bar{H}_o$. Therefore for minimum losses this angle should be maximized which for a given planar anisotropic ferrite means that the preferred plane of magnetization should be perpendicular to the applied magnetostatic field.

The Herring-Kittel spin wave loss term depends on the term $\nabla^2\bar{M}$. Applying the indicated operation on Equation 2.09 gives

$$\nabla^2\bar{M} = \bar{i}_x\nabla^2 m_x + \bar{i}_y\nabla^2 m_y + \bar{i}_z\nabla^2 m_z \quad \text{and} \qquad (2.18)$$

from Equation 2.13

$$\nabla^2\bar{M} = \bar{i}_x\nabla^2 f_1(h_x,h_y) + \bar{i}_y\nabla^2 f_2(h_x,h_y) + \bar{i}_z\nabla^2 f_3(h_x,h_y) \qquad (2.19)$$

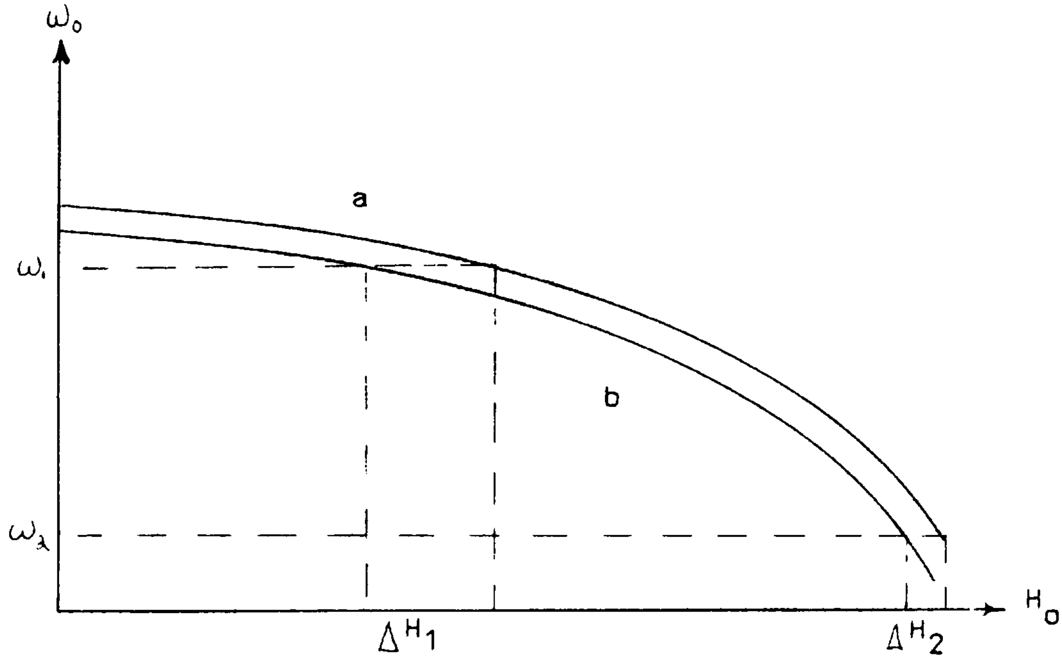


FIGURE 2.2 - QUALITATIVE PLOT OF ω_o vs H_o

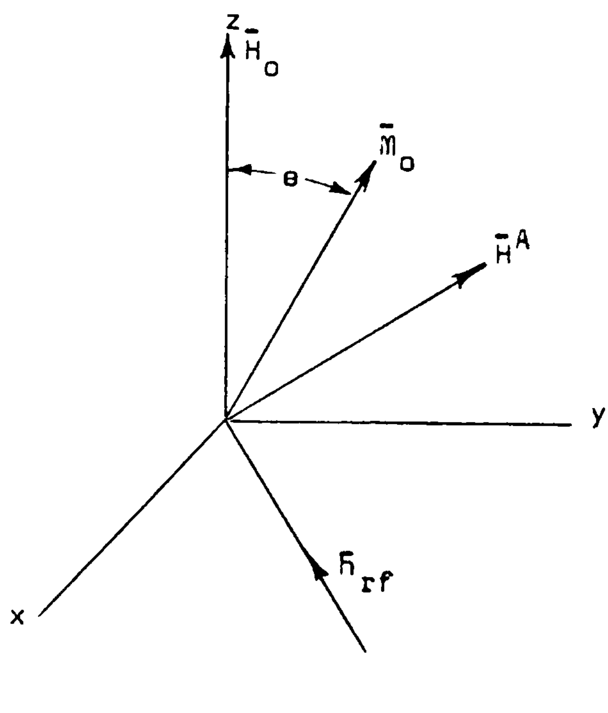


FIGURE 2.3 - ORIENTATION OF FERRITE

Since the ferrite sample used in the experiments described in the next chapter was much smaller than the wave length of the applied rf field, the assumption that $\nabla^2 \bar{m} = 0$ is reasonable if discontinuites of $\bar{m}$ due to physical imperfections in the sample are ignored. This subject has been covered elsewhere[24] and, since it is not in the area of interest of this thesis, it will be ignored here.

Another effect of anisotropy on line width becomes clear if Equation 2.17 is examined more closely and the presence of losses of some kind is taken into account. A qualitative rather than quantitative plot of the relation described by Equation 2.17 for a particular but arbitrary value of θ is shown in Figure 2.2. Curve a in the figure is plotted from the upper 3 db points and curve b from the lower 3 db points of the resonance curve. The line width $\Delta H = H_b - H_a$ can be seen to be smaller at the frequency ω_2 than at ω_1. That is $\Delta H \sim \left(\frac{d\omega}{dH}\right)^{-1}$.

One other possible effect of anisotropy comes to light when Equation 2.06 is solved again without the condition $(\bar{M}_o \times \bar{H}_o) = 0$. If the sample is oriented as in Figure 2.3 such that $\bar{M}_o \cdot \bar{i}_x = 0$ and $\bar{H}^A \cdot \bar{i}_x = 0$, and if the same procedure is used as in deriving Equations 2.13, then

$$m_x = \frac{\gamma M_o \cos \theta}{\omega_o^2 - \omega^2} \left(\gamma H_o h_x - j\omega h_y\right) \qquad (2.20a)$$

$$m_y = \frac{\gamma M_o \cos \theta}{\omega_o^2 - \omega^2} \left(j\omega h_x + \gamma H_o h_y \right) \qquad (2.20b)$$

$$m_z = \frac{-\gamma M_o \sin \theta}{\omega_o^2 - \omega^2} \left(j\omega h_x \right) \qquad (2.20c)$$

The significance of the differences between Equations 2.20 for the anisotropic case and Equations 2.13 for the isotropic case has already been discussed.

CHAPTER 3

EXPERIMENTAL

3.1 Experimental Procedure

A block diagram of the experimental arrangement is shown in Figure 3.1. Two klystrons were used: a Sperry 2K44 for the frequency range 5.7gc - 7.5gc and a Varian X-13 for a frequency range of 8.1gc to 9.2gc. Both klystrons were square wave modulated at 1000 cps for proper VSWR meter operation. The X-13 had a higher upper frequency limit than 9.2gc but this is the cut-off frequency for higher order modes in the 50 ohm coaxial cable used as well as the cross guide coupler. The ferrite isolator was used only with the X-13 for frequency stability purposes. VSWR meter #1 was used to tune the klystrons and as a frequency indicator when a tunable cavity type frequency meter was used with the X-13. VSWR meter #2 was used to indicate resonance in the ferrite. $\bar{H}_o$ was provided by an adjustable strength magnet with an upper limit of about 3500 oersteds for the gap used. The gauss-meter's operation is based on nuclear magnetic resonance and is read by means of a cathode ray tube, and charts supplied with the meter. More accuracy may be had with

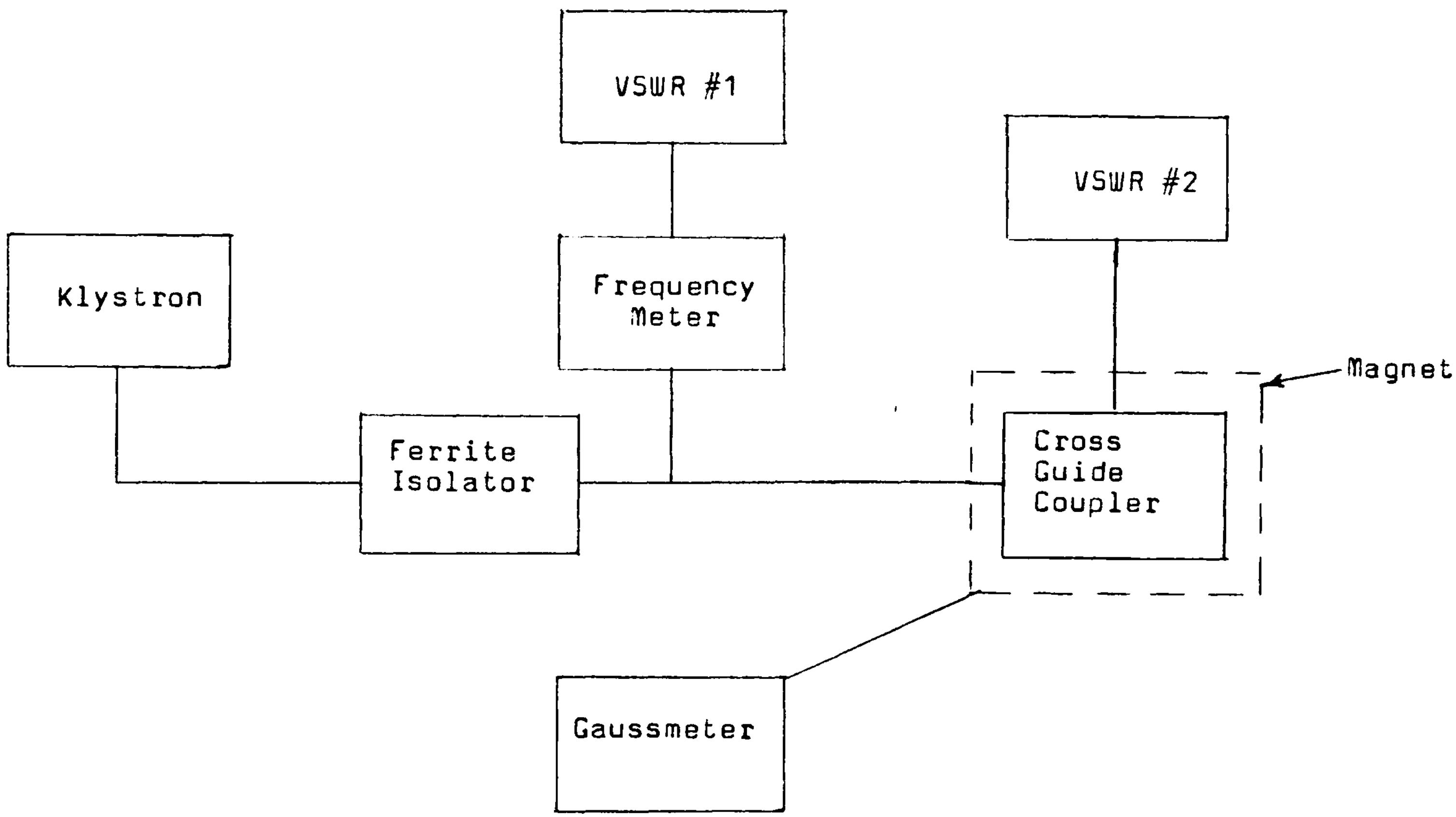


FIGURE 3.1 - EXPERIMENTAL ARRANGEMENT

the gaussmeter with additional equipment but this was unnecessary as the line widths encountered were 50 oersteds or more.

The theory and operation of the cross guide coupler is covered elsewhere[25] and will not be repeated here. The one used in this experiment was modified to permit changing the angular orientation of the ferrite easily. This was done as indicated in Figure 3.2. A .02 inch diameter spherical single crystal sample of Zn_2Y was glued on the end of the dielectric rod which was free to rotate in the coupler. The amount of rotation was indicated by the plastic indicator fixed to the rod.

For each of the two cases considered in this experiment, the ferrite crystal was oriented by sight on the end of the dielectric rod. A 10 power microscope was helpful in getting an accurate orientation. Even more helpful in getting an accurate orientation was the fact that a piece about 1/10 the diameter of the spherical sample was broken off along the plane of preferred magnetization. This left the preferred plane a shiny surface easy to see even with the naked eye. The relationship of the experimental orientations of the ferrite to the coordinate system used in discussing the theory in Chapter 2 is shown in Figure 3.3 for each of the two cases. The easy or preferred plane of the ferrite is indicated by a

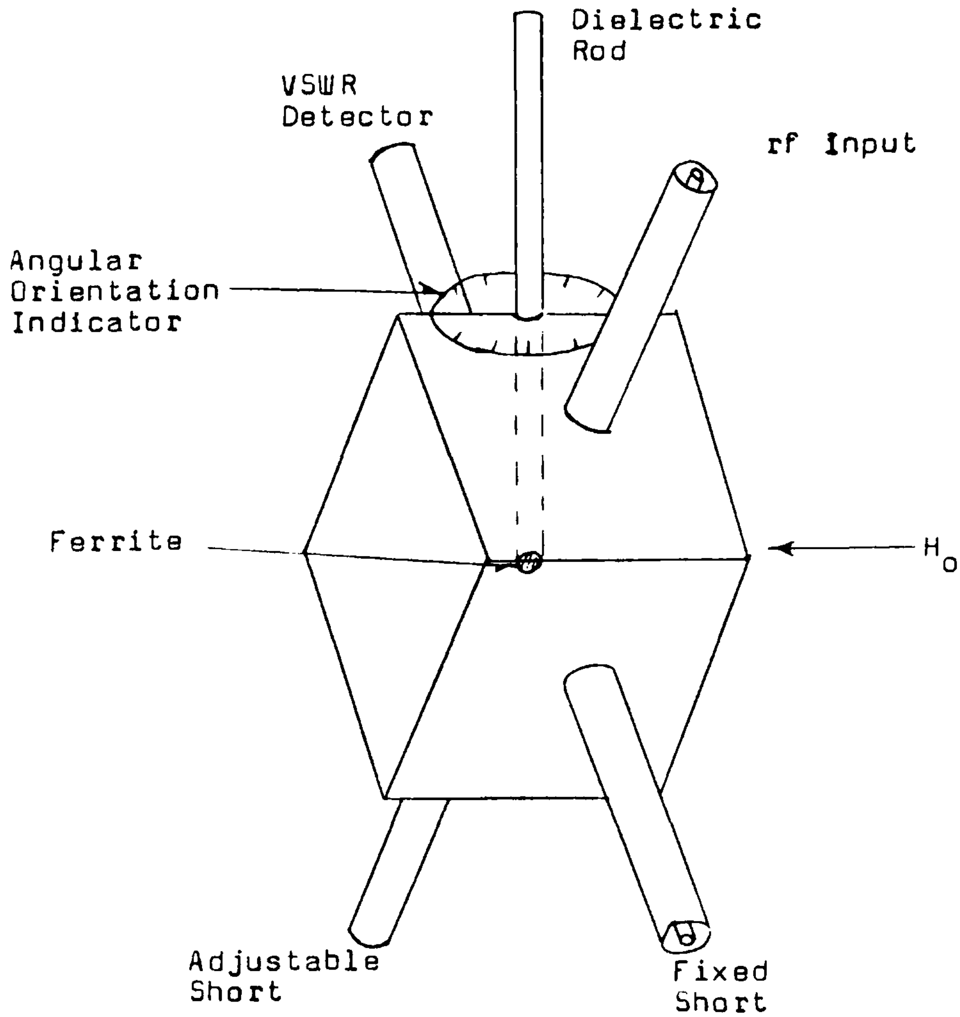
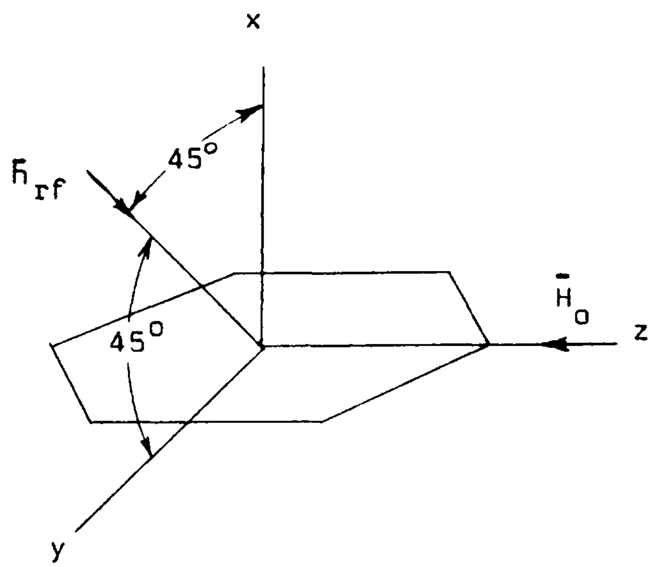
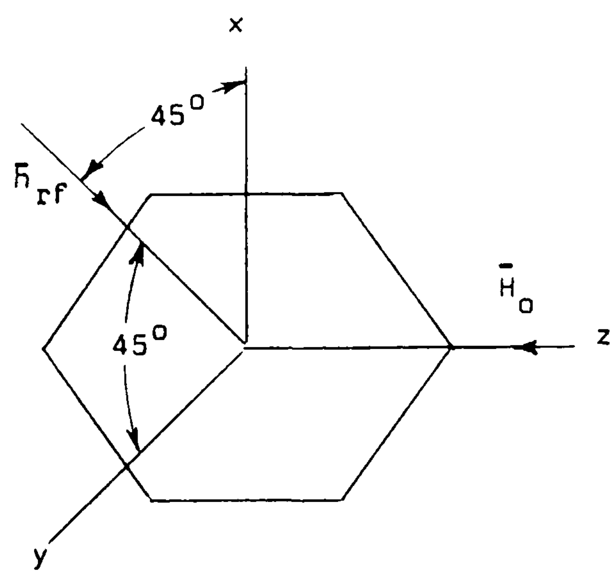


FIGURE 3.2 - MODIFIED CROSS GUIDE COUPLER



(a) Rotation About c Axis



(b) Rotation About Hexagonal Axis

FIGURE 3.3 - EXPERIMENTAL ORIENTATION OF THE FERRITE

hexagon. Rotation in both cases was done about the x axis.

This experimental arrangement had two serious shortcomings in that the upper limit on frequency and magnetic field strength imposed by the equipment prevented getting complete data.

3.2 Results For Rotation About the c Axis

The line width was measured as a function of frequency for four fixed angular orientations as shown in Figure 3.4. No line width measurements were made below 8.5gc since in this area the resonance became quite broad. A probable explanation offered by Buffler[26] states that when the ferrite sample becomes unsaturated the line width increases until resonance is no longer discernable. Substitution of 8.5gc into Equation 2.16 gives an H_o of 950 oersteds. A sphere of Zn_2Y becomes saturated when $H_o = 4/3\,\pi\, M_s = 915$ oersteds. The behavior of the curves in Figure 3.4 between 8.5gc and 8.6gc is identical to that found by Buffler and others for other anisotropic ferrites on the border of saturation.

The relation between line width and angular orientation is indicated in Figures 3.5 (a) - (d). According to both theoretical and experimental data obtained by Smit and Wijn[27] with other planar ferrites, the line width should have six cycles of variations for

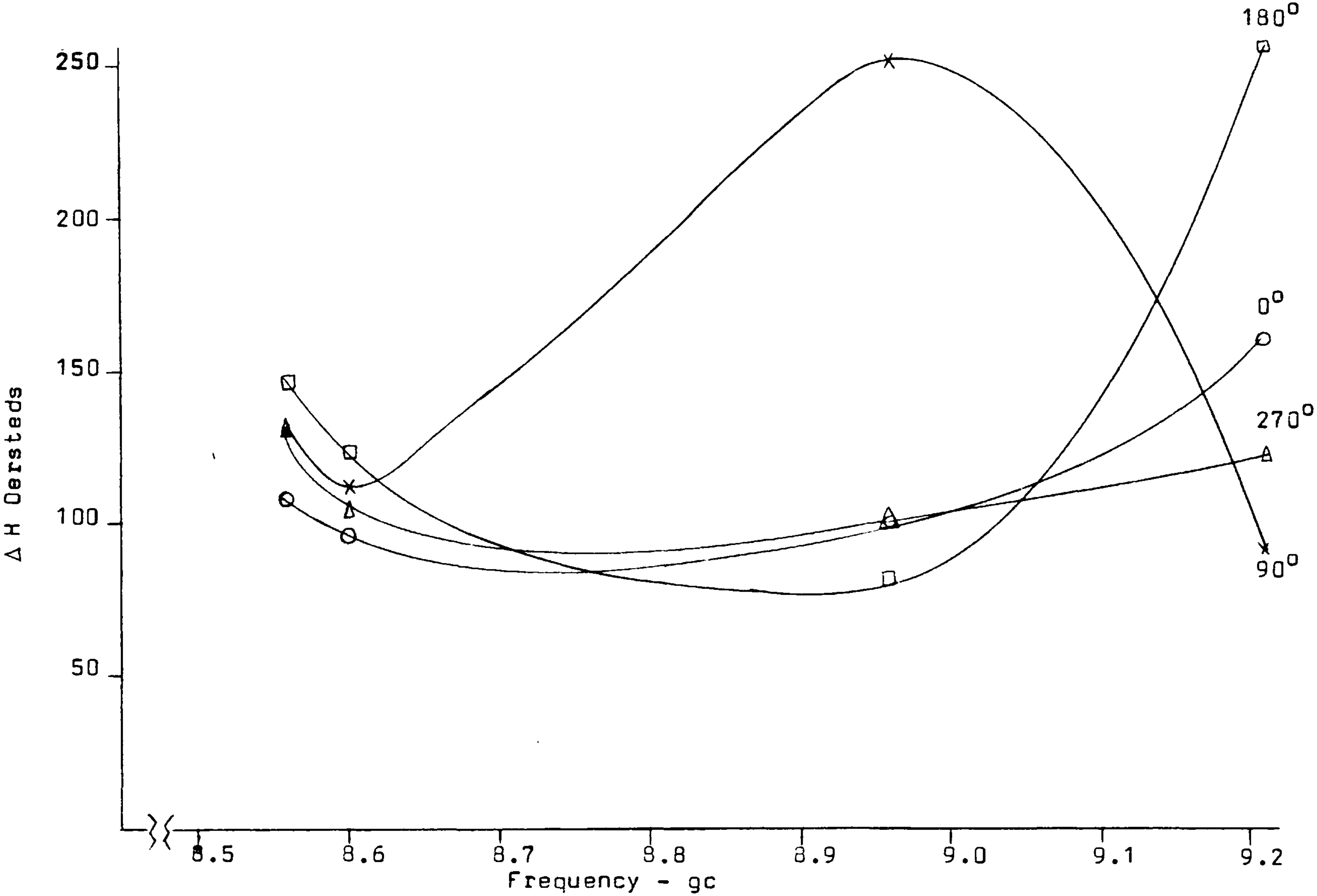
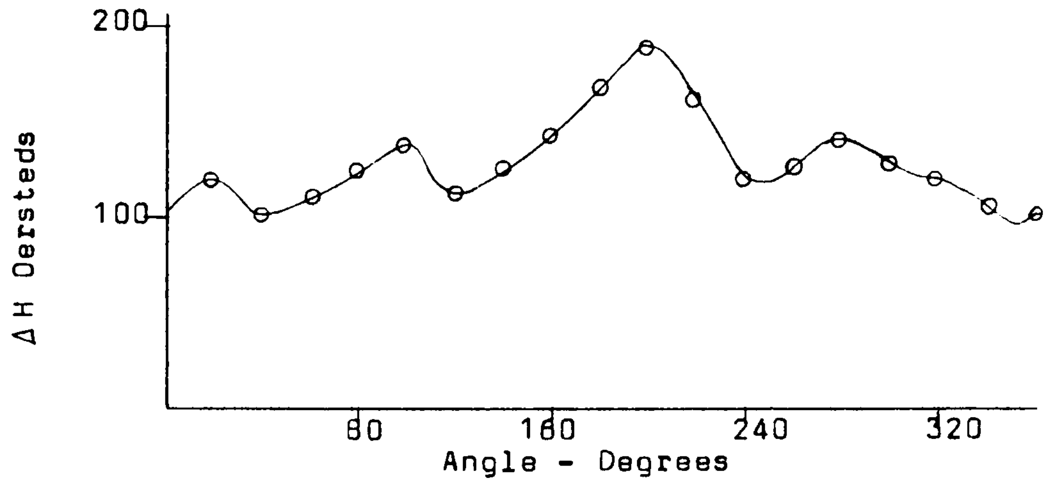
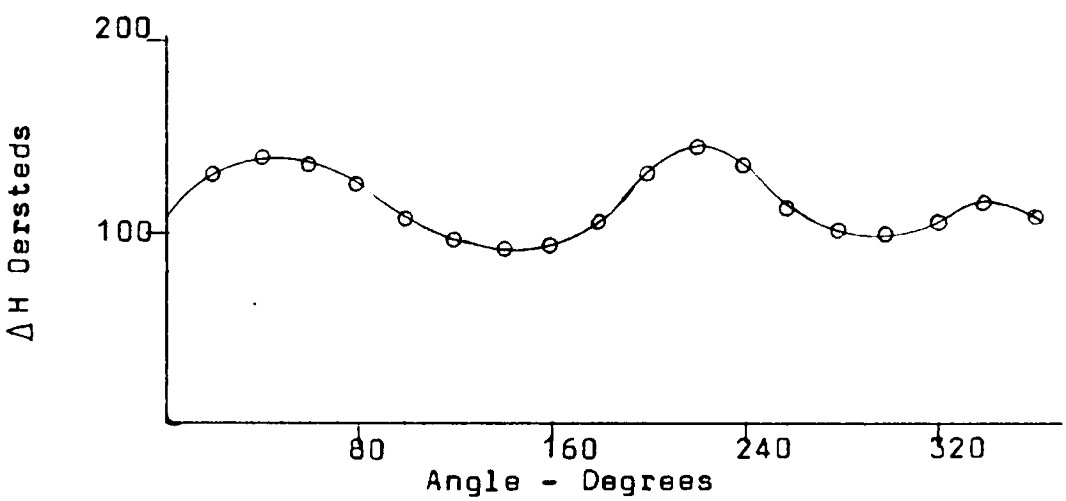


FIGURE 3.4 - LINE WIDTH VS FREQUENCY FOR SEVERAL ORIENTATIONS OF ROTATION ABOUT THE C AXIS

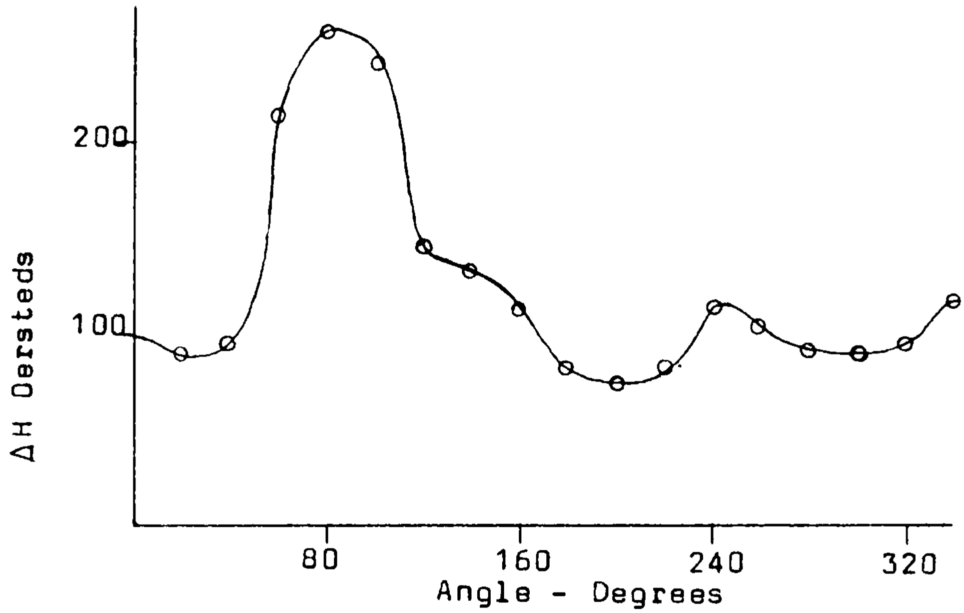


(a) Frequency 8.56gc

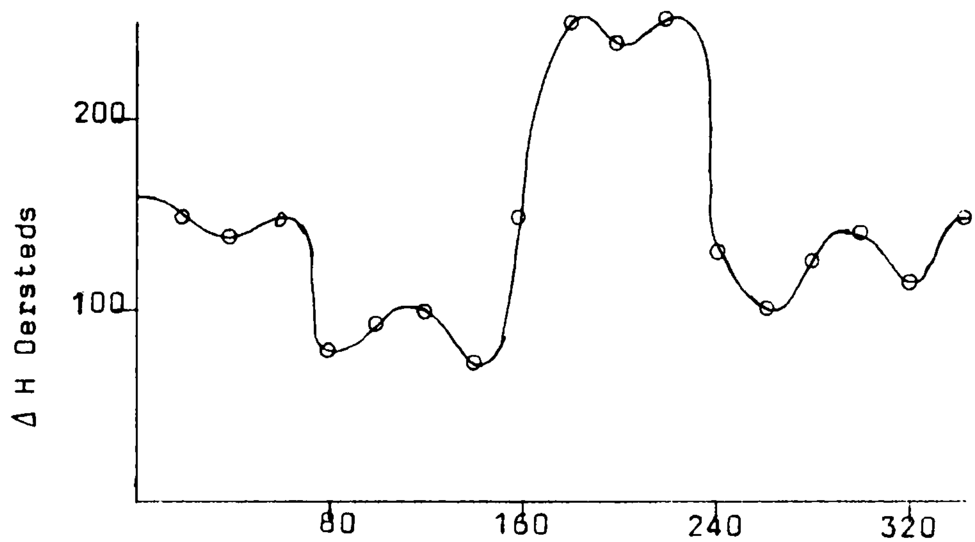


(b) Frequency 8.6gc

FIGURE 3.5 - LINE WIDTH VS ANGLE OF ROTATION ABOUT THE C AXIS



(c) Frequency 8.96gc



(d) Frequency 9.21gc

FIGURE 3.5 - LINE WIDTH VS ANGLE OF ROTATION ABOUT THE C AXIS

each 360^{o} of rotation. Only at a frequency of 9.21gc is this symmetry evident. The lack of sixfold symmetry at the other three frequencies is possibly the result of the fact that the anisotropy field restraining rotation of magnetization in the preferred plane of Zn_2Y is very small compared with other planar ferrites. Also, Néel[28] has postulated the existance of uniaxial magnetic anisotropy due to internal mechanical stresses. If this uniaxial anisotropy were present, it could alter the sixfold symmetry. However, the exact mechanism causing the dissymmetry as a function of frequency is not known. Also, the large increase in line width between 60^{o} and 120^{o} at a frequency of 8.9gc and between 140^{o} and 240^{o} at a frequency of 9.21gc is not explainable.

3.3 Results For Rotation About the Hexagonal Axis

Resonance in this case is also limited to frequencies above 8.5gc. Again, the sample becoming unsaturated might be the reason, although the behavior of the line width as indicated in Figure 3.6 in the region just above 8.5gc is unlike the previous case. Also, the resonance behavior below 8.5gc was unlike the previous case in that no detectable resonance was found, i.e. the behavior was more that of a cut-off phenomenon. Unfortunately, the behavior here is complicated by the

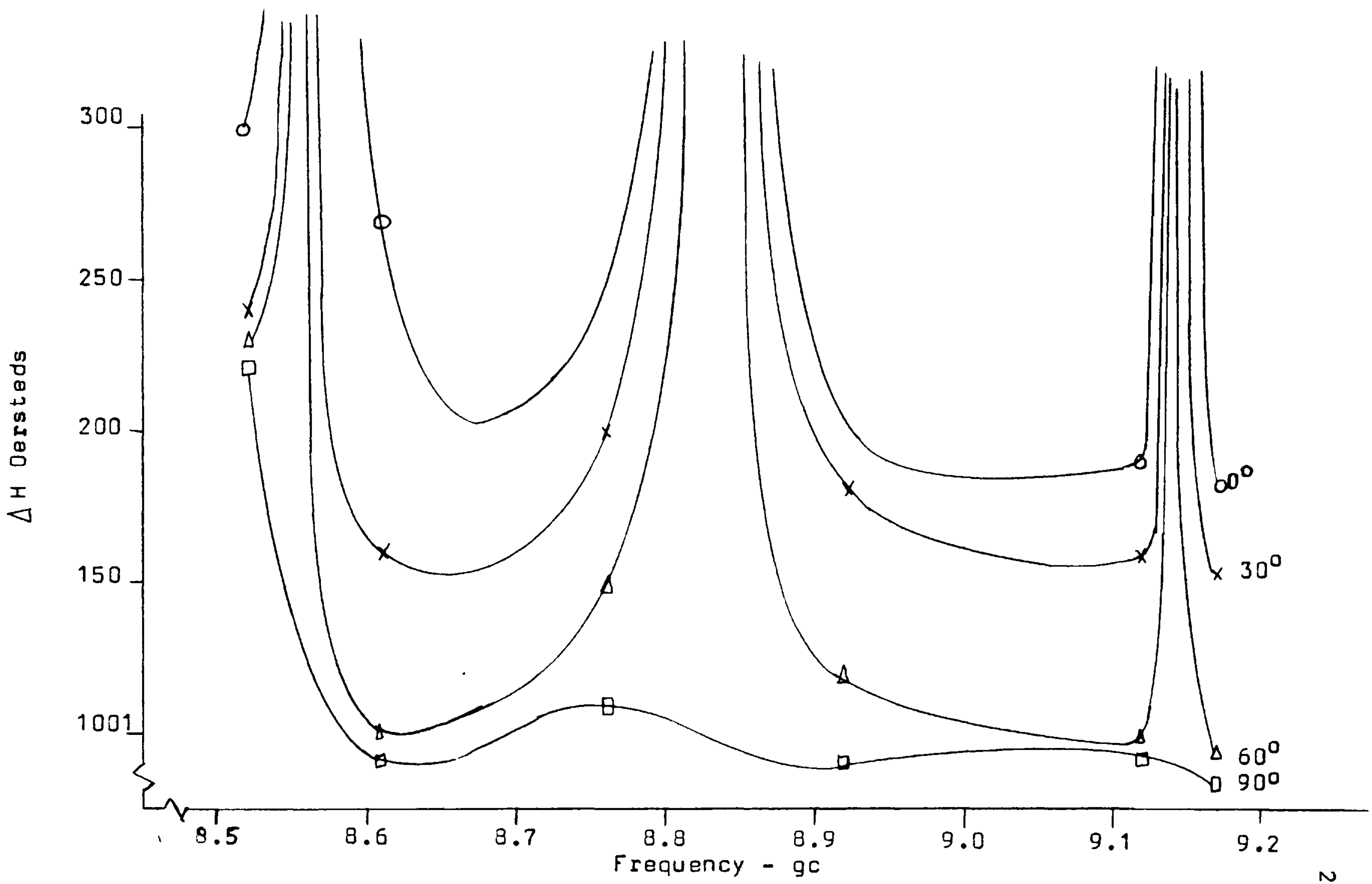
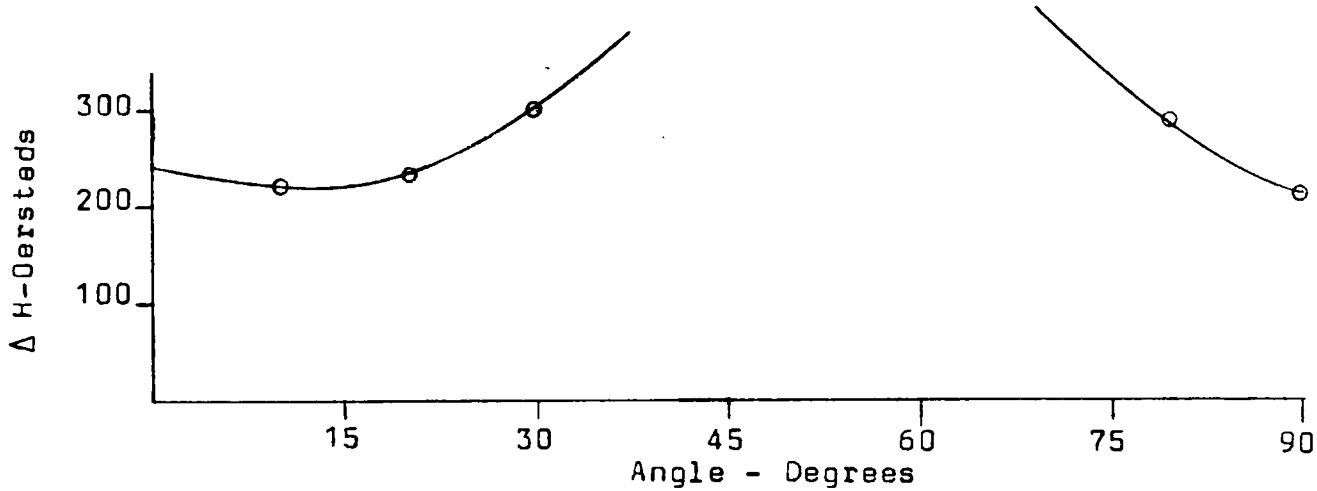
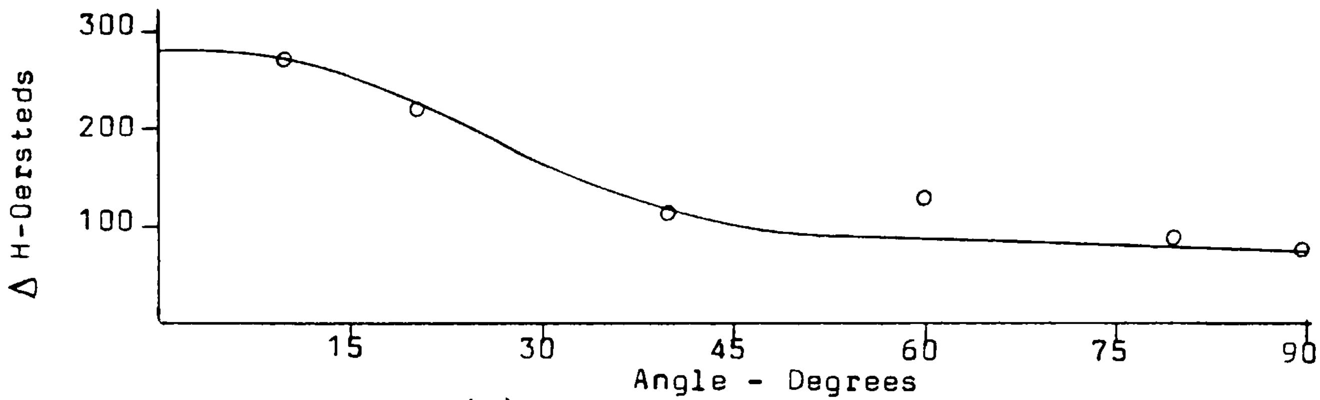


FIGURE 3.6 - LINE WIDTH VS FREQUENCY FOR SEVERAL ORIENTATIONS OF ROTATION ABOUT THE HEXAGONAL AXIS

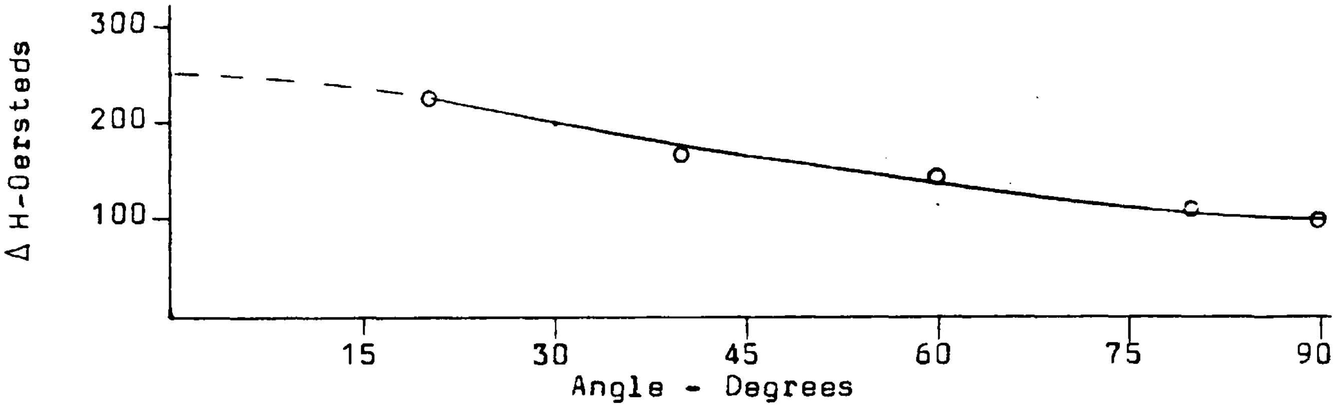


(a) Frequency 8.52gc - 8.58gc

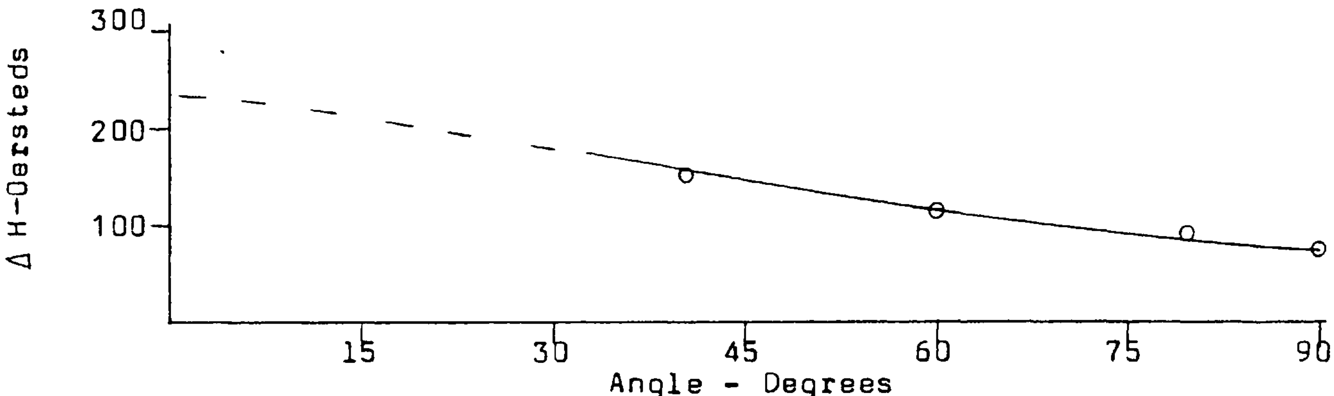


(b) Frequency 8.61gc

FIGURE 3.7 - LINE WIDTH VS ORIENTATION OF ROTATION ABOUT THE HEXAGONAL AXIS

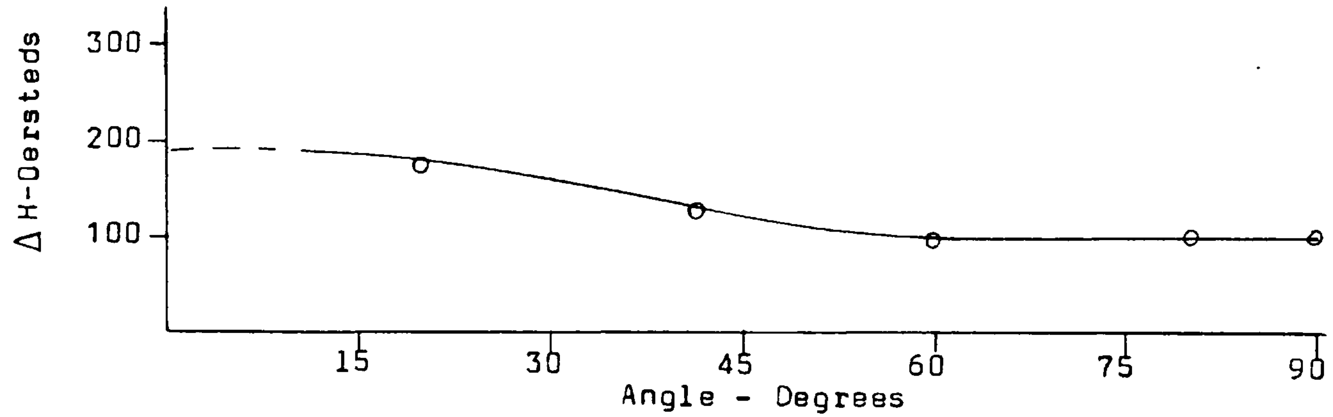


(c) Frequency - 8.76gc

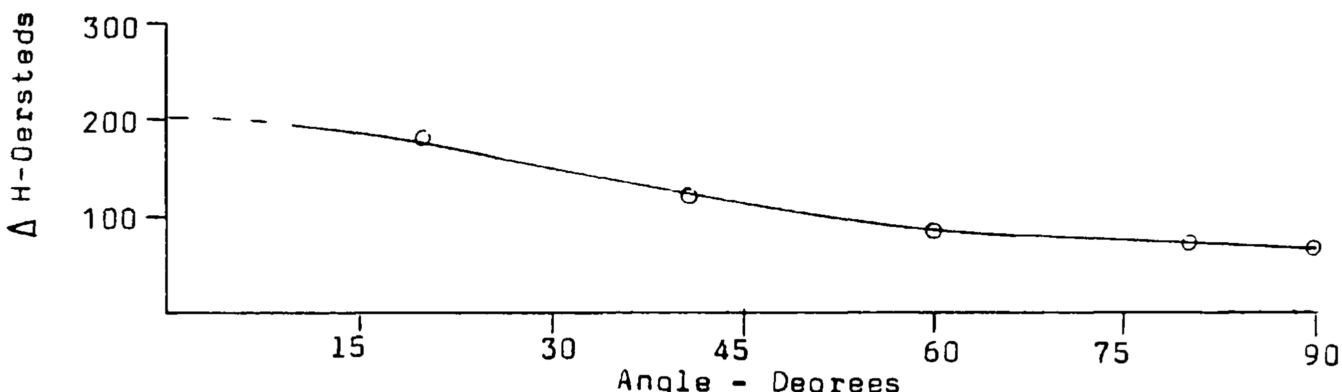


(d) Frequency - 8.92gc

FIGURE 3.7 - LINE WIDTH VS ORIENTATION OF ROTATION ABOUT THE HEXAGONAL AXIS



(e) Frequency - 9.1 gc



(f) Frequency - 9.17gc

FIGURE 3.7 - LINE WIDTH VS ORIENTATION OF ROTATION ABOUT THE HEXAGONAL AXIS

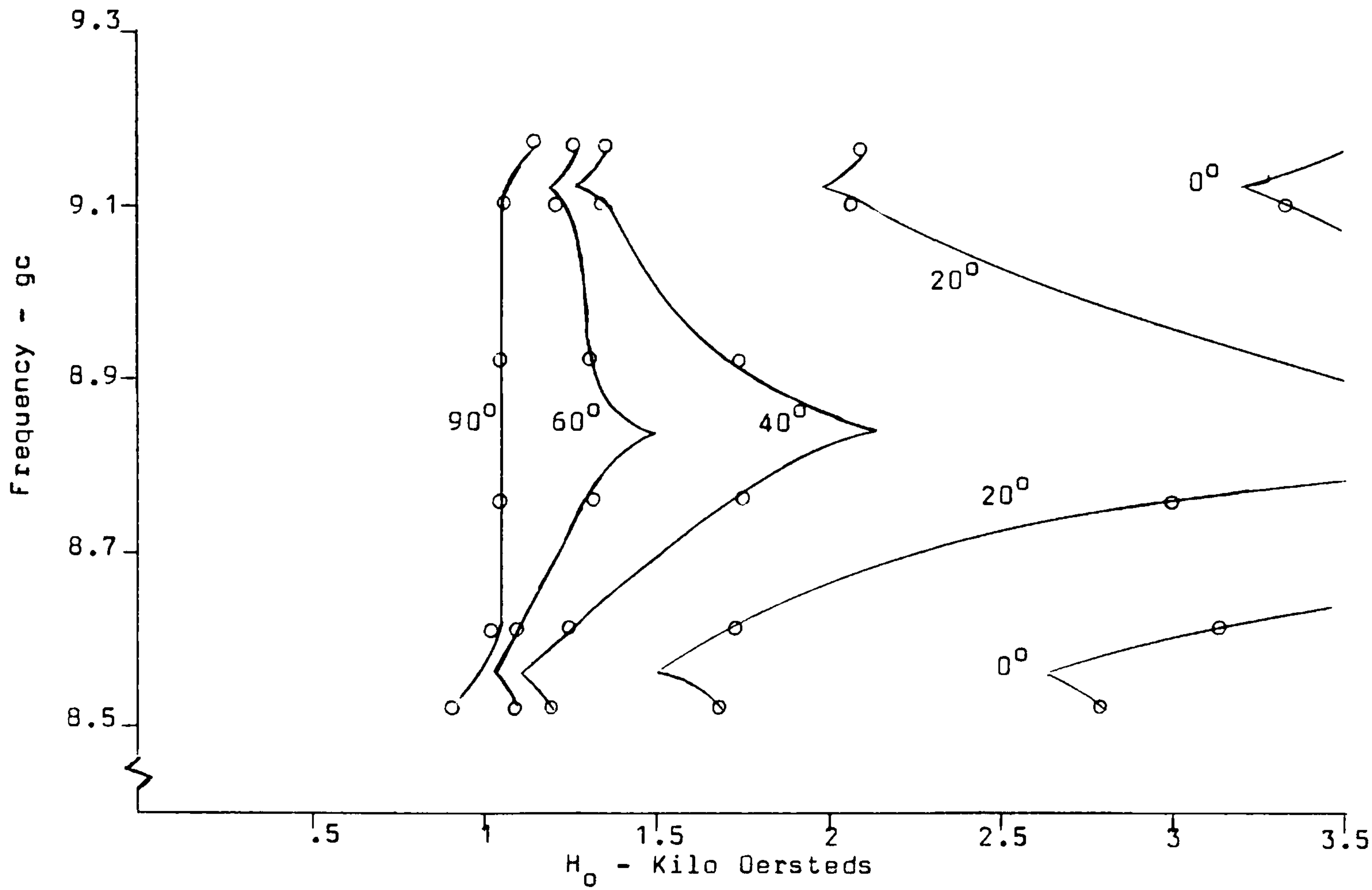


FIGURE 3.8 - f_o vs H_o For Several Orientations of Rotation About The Hexagonal Axis

fact that the slope of the ω_o vs H_o relationship as indicated in Figure 3.8 changes sign just above 8.5gc. As postulated in Chapter 2 this requires a large line width at the point where the slope is zero. That this actually occurred experimentally is illustrated in Figure 3.7a. When the measurements at this frequency were being made, the klystron frequency started drifting upward and actually passed through the point at 8.56gc where the break in the ω_o vs H_o curve takes place. These breaks in the slope, as indicated in Figures 3.6 and 3.8, occur every .28gc.

Figures 3.7 (a)-(f) indicate minimum line width at all frequencies at an angle between the applied magnetostatic field and the preferred plane of 90^o. This is also in agreement with the theory of Chapter 2. Only 90^o of rotation were examined in this case as the line width showed fourfold symmetry for each 360^o of rotation.

The relation between ω_o and H_o for various angular orientations is indicated in Figure 3.8. Although our present interest is only in the slopes of the curves, the functional relation between ω_o and H_o certainly warrants further investigation. For instance, resonance is almost ω_o independent when the angle between the applied magnetostatic field and the preferred plane is 90^o. This and the periodicity of the resonance relation with frequency is, as far as the literature to date indicates, unique.

CHAPTER 4

CONCLUSIONS

4.1 Conclusions

The following are concluded from the results and other discussions:

A. In the case of rotation about the c axis, the line width variations for Zn_2Y do not depend entirely on the symmetry of the crystal.

B. In the case of rotation about the hexagonal axis, the line width varies as the inverse of the slope of the ω_o vs H_o resonance relation and as the inverse of the angle between the magnetostatic field and the preferred plane of magnetization.

4.2 Recommendations for Further Study

A. The resonance phenomenon illustrated in Figure 3.8 should be investigated more thoroughly.

B. Some means of investigating both line width and resonance above the limits imposed by the present equipment should be devised.

C. Other factors, possibly affecting the line width of planar anisotropic ferrites should be studied. Among these might be surface polish, shape and size.

REFERENCES

1. H.E.J.B. Dubois, "On magnetization in strong fields at different temperatures", Phil. Mag., Vol. 29, p. 293; 1890.

2. P. Weiss, "Recherches sur l'aimantation de la magnetite cristallisée," J. Phys., ser. 3, vol. 5, p. 435; 1896.

3. S. Hilbert, "Genetische and konstitutive zusammenhange in dem magnetischen eigenschaften bei ferriten und eisenoxiden", Ber. Deut. Chem. Ges., vol. 42, p.2248; 1909.

4. B. Lax and K. J. Button, "Microwave Ferrites and Ferrimagnetics," McGraw-Hill Inc., New York, N. Y., pp. 1-5; 1962.

5. T.F.W. Barth and E. Posnjak, "Spinel structures", Z. Krist, vol. 82, p. 325; 1932.

6. L. Néel, "Proprietes magnetiques des ferrites, ferrimagnetisme et antiferrimagnetisme", Ann. Phys., vol. 3, p. 137; 1948.

7. W. P. Ayers, "Ferrites, limitation and measurements", Sylvania Technologist, vol 9; January,1956.

8. G.H. Jonker, H.P.J. Wijn, and P.B. Braun, "A new class of oxidic ferromagnetic materials with hexagonal crystal structures," Proc. Inst. Elec. Engrs. (London), vol. 104b, p. 249; 1957.

9. J. Smit and H.P.J. Wijn, "Ferrites," John Wiley and Sons, Inc., p. 204; 1959.

10. Ref. 9, p. 204 and p. 210.

11. Ref. 4, pp. 141-142.

12. Ref. 9, p. 204 and p. 210.

13. H. J. Shaw, "Pulsed Magnetic Field Millimeter Wave Generator," Microwave Laboratory, Stanford Univ., p. 57; 1962.

14. L. Landau and E. Lifshitz, "On the theory of the dispersion of magnetic permeability in ferromagnetic bodies," Physik Z. Sowjetunion, vol. 8, p. 153; 1935.

15. N. Bloembergen, "On the ferromagnetic resonance in nickel and supermalloy," Phys. Rev., vol. 78, p. 572; 1950.

16. R. K. Bowers and D. C. Stinson, "The frequency dependence of the line width of polycrystalline yttrium garnet ferrites," Eng. Exp. Sta. Bul. No. 12, E. E. Ser. No. 3, pp. 26-27; July 1960.

17. Ref. 9 pp. 80-81.

18. C. R. Buffler, "Resonance properties of single crystal hexagonal ferrites," J. Appl. Phys., vol. 33, p. 1360; March 1962.

19. Ref. 4, P. 466.

20. C. Herring and C. Kittel, "On the theory of spin waves in ferromagnetic media," Phys. Rev., vol. 81, p. 869; 1951.

21. Ref. 4, p. 172.

22. A. M. Clogston, H. Suhl, L. R. Walker, and P. W. Anderson, "Ferromagnetic resonance line width in insulating materials," J. Phys. Chem. Solids, vol. 1, p. 129; 1959.

23. Ref. 4, p. 153.

24. C. J. Landry, "Line width behavior of hybrid single crystal garnet ferrites," Thesis, U. of Ariz., pp. 8-11; 1962.

25. D. C. Stinson, "Ferrite line width measurements in a cross guide coupler," IRE Trans. of Microwave Theory and Techniques, vol. MTT-6, pp. 446-450; October 1958.

26. C. R. Buffler, "A Spin Wave Analysis of Ferromagnetic Resonance Relaxation," Gordon McKay Laboratory of Applied Science, Harvard Univ., p. 72; February 1960.

27. Ref. 9, p. 209.

28. L. Néel, "Nouvelle theorie du champ coercitief," Physica, vol. 15, pp. 225-234; 1949.