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Field orientation and temperature dependence of auto-oscillations in yttrium iron garnet films

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The Ohio State University, 1993
FIELD ORIENTATION AND TEMPERATURE DEPENDENCE OF AUTO-OSCILLATIONS IN YTTRIUM IRON GARNET FILMS

DISSERTATION

Presented in Partial Fulfillment of the Requirements for the Degree Doctor of Philosophy in the Graduate School of The Ohio State University

By

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* * * * *

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1993

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To my family
ACKNOWLEDGEMENTS

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Publications


**Fields of Study**

Major Field: Condensed Matter Physics
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CHAPTER I

Introduction

The development of the computer has had an enormous impact on modern society, drastically altering everything from commerce and technology to recreation. In the sciences it has opened the way for fascinating investigations, both theoretical and experimental, into systems which in the past were far too complex to successfully analyze. Nowhere is this more evident than in the area of nonlinear dynamics.

The birth of modern day interest in nonlinear systems can be traced to the numerical investigations of meteorologist E. N. Lorenz in 1963 [16]. While his results on the behavior of a coupled set of nonlinear differential equations were not immediately appreciated, they are now credited as one of the first observations of deterministic chaos. The 1970's subsequently witnessed the blossoming of the new discipline of chaos. Examples of chaotic systems were identified in fields of study ranging from economics (behavior of the stock market) to the physical sciences (population dynamics, chemical reactions, fluid turbulence). In the 1980's magnetism launched its experimental contribution to this new discipline with a rebirth of interest in the nonlinear behavior observed in magnetic resonance.

The earliest observations of nonlinear effects in magnetic resonance date back to the 1950's with the works of Bloembergen and Wang [2] and Damon [7]. The first
theoretical framework for understanding spinwave instabilities at high power levels was provided by Suhl [31]. In the 1960's numerous high power experimental results were reported. While many of these focused upon the onset of anomalous absorption levels for purposes of industrial applications, some workers reported observations of hysteretic absorption (foldover) [28] and others examined the development of an oscillatory character (auto-oscillations) in the power absorption [3,10,35]. A good deal of effort was focused upon the theory in the 1970's with major contributions coming from Sparks [29], Wolfram [38], L’vov [17], and Zakharov [41]. Interest in chaos and nonlinear dynamics as well as developments in microwave electronics produced a plethora of experimental results in the field during the 1980's. Experiments have been performed on both antiferromagnetic [27,34,39] and ferromagnetic [1,4,5,8,19,24,40] materials in both bulk and thin film form under a variety of magnetic field configurations. The emphasis has been upon detailing and interpreting observations of auto-oscillations and the multiple periodicities and chaos which develop as the power levels are increased.

The first theoretical attempt to account for the auto-oscillatory phenomena was presented by Wang [36] in the late 1960's. A much more detailed formalism, and the basis for most of the current theories, was developed by L’vov and Zakharov [17,41]. Known as the S-theory, it is based upon a microscopic Hamiltonian which couples the spinwaves through three and four-magnon interactions. Intended for bulk samples, a difficulty arises from the truncation necessary for computer modeling of the system. Nakamura and co-workers [22,23] have attempted such a truncation and produced
results which are qualitatively, but not quantitatively, similar to those of experiments on bulk samples. Lim and Huber [14, 15] attempted to extend these models to a finite spin system with as many as a hundred modes, but with limited success. An alternative approach, which attempts to account for the entire degenerate spinwave manifold by using center manifold techniques, has been proposed by Zhang and Suhl [32, 42].

The difficulty inherent in all of these models is the vast number of degenerate spinwave modes which are involved in the dynamics. It is a characteristic of all bulk systems; hence, truncation will always be a necessary part of any modeling effort. In contrast to this situation a thin film at perpendicular resonance provides a system with a much more limited density of modes. Much of the observed behavior is in fact explicable in terms of the interactions of a countable number of modes with wavelengths comparable to the dimensions of the sample, the magnetoexchange modes. The relative positions and the intensities of these modes can be readily modified by adjusting the physical dimensions of the sample. A thin film therefore provides a flexible system within which nonlinear interactions can be readily observed and modeled. Indeed, a microscopic Hamiltonian has been developed which yields simulation results which are among the best reported in the field [19].

Although numerous works have been published which detail the wide range of auto-oscillatory phenomena exhibited by bulk and thin film materials, very little exists which considers the effects of the size of the sample and nothing exists on the effects of sample temperature and the orientation of the bias magnetic field for a thin film disk in the perpendicular pumping configuration. Because of these observations,
the present work focuses upon the influence of geometric (sample size, field orientation) and material (temperature) factors on the auto-oscillatory behavior of thin film disks of yttrium-iron-garnet (YIG) in perpendicular resonance. Actually a ferrimagnetic material, YIG is an insulator which exhibits low dielectric losses, making it an ideal material for numerous microwave circuit devices. It is an easily grown, readily available material that has been studied for many years. The motivation for using YIG to probe nonlinear effects stems mostly from its exceptionally narrow resonance linewidth, often less than 1 G, which allows delineation of individual resonance modes typically separated by only 2-3 G.

The theory which explains this experimentally observed mode separation is but one of the topics presented in Chapter II. In order to develop a cohesive framework for presenting these results and the formalism which leads to equations of motion, the chapter opens with a brief overview of ferromagnetic resonance (FMR) and spinwaves. This is followed by a presentation of the normal modes of excitation for a thin film disk in perpendicular resonance and the dispersion relations which explain the observed mode separation. With this structure as a foundation, the Hamiltonian formalism for the system is presented and the equations of motion derived. These are the same equations used so successfully in Reference [19] as a model for the dynamics of the system. In the present work they were incorporated into a numerical simulation, provided in Appendix C, which was used to investigate the ability of the equations of motion to replicate the experimental observations of the sample size and temperature effects.
Before any discussion of experimental results can be fully appreciated it is useful to know something of the apparatus and samples used in those experiments. This is covered in Chapter III which starts with the details of the FMR spectrometer and its use at both low and high microwave power levels. Next comes a summary of the properties of the four pre-existing samples which were used in this work. The optical measurements of their diameters are presented along with low power FMR measurements which yield estimates of the sample thicknesses. A beautiful illustration of the effect of crystalline orientation on the results of low power FMR is shown in Figure 3.5 and is used to verify the orientation of each sample.

Armed with a background knowledge of the equipment and the samples, the next important topic is the experimental results. Chapter IV details the results of experimental investigations into the effect of sample size, sample temperature, and orientation of the bias magnetic field on auto-oscillatory behavior. While it will be shown that each sample produces some unique characteristics, the four samples conveniently group into two sets of two when classified by the ratio of their radius to their thickness. It is this ratio which is responsible for the separation of the magnetostatic modes at low power and therefore, within a given set the samples, might be expected to yield similar auto-oscillatory behavior. Room temperature experimental results are presented which validate this expectation and which yield two general trends: smaller samples produce higher onset frequencies, and they require higher power levels for excitation. The experimental effects of lowering the sample temperature are presented next. These indicate that both the onset frequency and the power level
increase with decreasing temperature. Unfortunately, the data for the onset location relative to the low power positions of the magnetostatic modes is too inconsistent to allow for any generalization about its behavior as a function of sample temperature.

Changing the orientation of the bias magnetic field is the last experimental investigation and, in at least one aspect, the most interesting. A fundamental assumption in the derivation of equations of motion for this system is that the bias field is perpendicular to the film plane. A truly perpendicular alignment is an experimental dream, not reality. Fortunately, the results presented indicate that there is very little effect in the observed auto-oscillatory behavior within about 5° of perpendicular. As the angle becomes more oblique the data indicates that the onset frequency decreases, as does the power level needed for excitation of the first "finger". Higher order "fingers" apparently require higher power levels, but also show a decrease in onset frequency. The most interesting aspect of this investigation is the discovery of a region beyond roughly 15° off of perpendicular where the observed auto-oscillations have a dramatically different character from what exists at less oblique angles. Results are given which detail the existence of such a transition in three of the four samples.

The numerical results are the topic of Chapter V. Beginning with the general features of the simulation and a discussion of experimental versus numerical sensitivity, the room temperature results are discussed. These focus upon the differences which exist among the samples because of sample size as well as other physical variations. A discussion of which modes to incorporate into the model is presented for each sample and is predicated by what was observed experimentally. The linewidth, indicative of
damping effects within the system, plays an important role in the numerical results. Because of this influence a series of simulations are presented which indicate the extent to which model results are affected by the linewidth. While its effect of increasing the minimum power necessary for exciting auto-oscillations is predictable, its influence on the frequency of those oscillations remains unclear. Having established the most appropriate model for each sample, a comparison of numerical and experimental results is presented which illustrates that the equations of motion yield excellent agreement with both observed onset power levels and onset locations relative to the magnetostatic modes while providing modest agreement with observed onset frequencies. Using the models developed to study the sample size effects, data is presented for comparison with the temperature dependent experimental results. As will be shown, the experimentally observed trends of increasing onset frequency and power as the sample temperature decreases are well modeled. A summary of all the numerical results and the experimental investigations which inspired them is presented in the conclusions contained in Chapter VI, while the three computer programs which were of greatest importance to this work are provided in the Appendices.
CHAPTER II

Theory

2.1 Magnetic Resonance

The principles of magnetic resonance form the underpinnings for numerous analytical techniques for investigating material properties. Nuclear magnetic resonance (NMR) is perhaps the most visible tool with its many applications in medical diagnostics. In the study of magnetic materials, ferromagnetic resonance (FMR) has proven to be invaluable. Regardless of which specific technique is of interest, they all share a common starting point: a magnetic moment, $\vec{m}$, in the presence of an external magnetic field, $\vec{H}_0$.

When a magnetic moment is placed in a magnetic field it experiences a torque given by

$$\vec{\tau} = \vec{m} \times \vec{H}_0.$$  \hfill (2.1)

Since the torque is the time rate of change of the angular momentum, $\vec{J}$, and the magnetic moment is related to the angular momentum by $\vec{m} = -\gamma \vec{J}$, where $\gamma$ (1.76 $\times$ 10$^7$ $s^{-1}G^{-1}$ for the electron) is the gyromagnetic ratio, Equation 2.1 may be transformed into

$$\frac{d}{dt} \vec{m} = -\gamma \vec{m} \times \vec{H}_0.$$  \hfill (2.2)
This is the basic equation of magnetic resonance. Consider what happens when a static magnetic field is directed along the $z$-axis, $\vec{H}_0 = H_0 \hat{z}$. Equation 2.2 then yields

\begin{align*}
\dot{m}_z &= -\gamma H_0 m_y \\
\dot{m}_y &= \gamma H_0 m_z \\
\dot{m}_z &= 0
\end{align*}

(2.3)

which demonstrates that $m_z$ is constant. It can readily be shown that in addition $\frac{d}{dt} |\vec{m}| = 0$, so in fact the magnetic moment precesses about the direction of $\vec{H}_0$. An explicit solution to Equation 2.3 is

\begin{align*}
m_x &= m_\perp \sin \omega t \\
m_y &= m_\perp \cos \omega t
\end{align*}

(2.4)

where the Larmor precession frequency is $\omega = \gamma H_0$, and $m_\perp = \sqrt{m^2 - m_z^2}$. If an additional magnetic field is now placed in the $xy$-plane and allowed to oscillate at the Larmor frequency the magnetic moment will absorb energy from that field, the basis of resonant absorption.

This, of course, is a microscopic description of the phenomena. Any bulk sample used experimentally contains numerous magnetic moments tightly packed in some type of crystalline structure. In order to circumvent the difficulties associated with labelling each magnetic moment individually, a bulk magnetization, $\vec{M}(\vec{r})$, is introduced. It is defined as the average magnetic moment per unit volume at position $\vec{r}$ within the crystal. With all those moments packed together a number of interactions arise which alter the magnetic field actually affecting the individual moments. Such
effects include the influence of the sample shape, the quantum mechanical exchange interaction, the dipole interaction generated by the individual fields produced by the various moments, and crystalline anisotropy which makes it energetically favorable to align the moments in a particular direction within the crystal. Typically all of these effects are included along with the external magnetic field in an effective field, $\vec{H}_{\text{eff}}$. The macroscopic equivalent of Equation 2.2 is then given by

$$\frac{\partial}{\partial t} \vec{M}(\vec{r}) = -\gamma \vec{M}(\vec{r}) \times \vec{H}_{\text{eff}}.$$  \hspace{1cm} (2.5)

The behavior of this equation is of course the same as Equation 2.2 and resonant absorption occurs at the frequency $\omega = \gamma H_{\text{eff}}$. In a typical FMR experiment the frequency of the oscillating field is fixed and the external bias field, $\vec{H}_0$, is varied in magnitude to sweep the system through resonance.

A useful relation for estimating the sample magnetization can be derived from Equation 2.5 by including only the shape dependent effect in $\vec{H}_{\text{eff}}$. Placing a magnetic sample in the presence of an external field tends to align the sample magnetization along the direction of the field, but doing so produces "free" magnetic charges on the sample surface. This results in an effective field, known as the shape demagnetization field, which opposes the external field. Assuming an external field given by $\vec{H}_0$ and that the sample is ellipsoidal with its principle axes aligned with the axes of a Cartesian coordinate system, the $x$-component of the effective field is given by

$$H_{\text{eff},x} = H_{0,x} - 4\pi N_x M_x$$  \hspace{1cm} (2.6)

where $N_x$ is the $x$-component of the demagnetization tensor, a purely geometric quantity. Similar equations hold for the $y$ and $z$ components. If the external field is directed
along the z-axis, $\vec{H}_0 = H_0 \hat{z}$, then it can be shown that to first order $\dot{M}_z = 0$ and $M_z = M_s$ where $M_s$ is the saturation magnetization of the sample. Substitution of Equation 2.6 and the $y$-component equivalent into Equation 2.5 produces a pair of coupled equations:

$$
\begin{align*}
\dot{M}_x &= -\gamma (H_0 + 4\pi M_s (N_y - N_z)) M_y \\
\dot{M}_y &= \gamma (H_0 + 4\pi M_s (N_x - N_z)) M_x.
\end{align*}
$$

(2.7)

Assuming an $e^{-i\omega t}$ time dependence for the $x$ and $y$ components of the magnetization, a nontrivial solution to this coupled pair exists provided that

$$
\begin{vmatrix}
  i\omega & -\gamma (H_0 + 4\pi M_s (N_y - N_z)) \\
  \gamma (H_0 + 4\pi M_s (N_x - N_z)) & i\omega
\end{vmatrix} = 0.
$$

(2.8)

This condition establishes the dispersion relation

$$
\left( \frac{\omega}{\gamma} \right)^2 = (H_0 + 4\pi M_s (N_x - N_z))(H_0 + 4\pi M_s (N_y - N_z)).
$$

(2.9)

The demagnetization tensor for a flat plate or disc lying in the $xy$-plane has $N_x = N_y = 0$ and $N_z = 1$. In this case the external field, denoted by $\vec{H} = H_\perp \hat{z}$, is normal to the surface of the disc and the dispersion relation reduces to

$$
\frac{\omega}{\gamma} = H_\perp - 4\pi M_s.
$$

(2.10)

Placing the disc in the $xz$-plane yields a demagnetization tensor with components $N_x = N_z = 0$ and $N_y = 1$. The external field now lies in the plane of the sample and is denoted $\vec{H} = H_\parallel \hat{z}$. In this case the dispersion equation becomes

$$
\left( \frac{\omega}{\gamma} \right)^2 = H_\parallel (H_\parallel + 4\pi M_s).
$$

(2.11)
An experimental determination of the parallel and perpendicular resonant fields, measured with the same frequency excitation field, can thus be combined with Equations 2.10 and 2.11 to yield a first order estimate of the saturation magnetization of the sample:

\[
4\pi M_s = \frac{1}{2} \left[ 2H_\perp + H_\parallel \pm \sqrt{(2H_\perp + H_\parallel)^2 - 4(H_\perp^2 - H_\parallel^2)} \right], \tag{2.12}
\]

with the minus sign providing the physical solution.

### 2.2 Spinwaves

All of the spins in a ferromagnet are parallel when the system is in the ground state. As shown in many elementary texts [13, 9] and generally discussed in statistical mechanics, the first excited state of a ferromagnet does not consist of a single flipped spin. Rather, it is far more energetically favorable to share the excitation among all of the spins, thereby forming a spinwave or magnon. In ferromagnetic resonance the equivalent of the ground state, known as the uniform mode, is the state in which all of the spins precess in phase and with the same amplitude. This is the mode assumed in the derivation of Equation 2.9. It happens that the uniform mode is only a normal mode of excitation if the interaction is limited to Zeeman and exchange terms [31]. The inclusion of dipole interactions resulting from the individually precessing magnetic moments produces a more complicated excited state comprised of spinwaves which couple to the uniform mode. The derivation of a dispersion relation for these spinwaves was first presented by Suhl [31] and an excellent review of the derivation is provided in the chapter by Chen and Patton in Reference [37].
The dispersion relation, derived in [31] for a spinwave of wavevector \( \mathbf{k} \) traveling at an angle \( \theta_k \) with respect to the z-axis, is
\[
\left( \frac{\omega}{\gamma} \right)^2 = (H_0 - 4\pi N_z M_s + Dk^2)(H_0 - 4\pi N_z M_s + Dk^2 + 4\pi M_s \sin^2 \theta_k)
\] (2.13)
where the external field is defined as \( H_0 \hat{z} \), \( 4\pi N_z M_s \) is the shape demagnetization contribution discussed in section 2.1, and \( D \) is known as the exchange constant. Two fundamental assumptions are involved in the derivation of this relation. The first is that electromagnetic propagation effects can be ignored because the sample dimensions are typically much smaller than the wavelength of the microwave excitation field. The second assumption is that the sample dimensions are much larger than the wavelength of the spinwaves so that aside from the shape demagnetization effect, other sample boundary effects may be ignored.

In order to more fully appreciate the origin of the additional terms in Equation 2.13, the magnetization must be expanded in a spatial Fourier series
\[
\vec{M}(\vec{r},t) = M_z \hat{z} + \sum_{k \neq 0} \vec{m}_k(t)e^{-i\vec{k} \cdot \vec{r}},
\] (2.14)
where the first part is the uniform precession and the summation represents the small transverse deviations generated by the spinwaves. Aside from the contributions of the external and shape demagnetization fields, the first new contribution to Equation 2.13 derives from the application of the exchange interaction to this spatial series. Expressed in terms of an effective field the exchange interaction is given by
\[
\vec{H}_{ex} = D\nabla^2 \vec{M}
\] where \( D = 0.54 \text{ Oe}\mu\text{m}^2 \) for YIG. Substitution of Equation 2.14 into this effective field produces a term proportional to \( Dk^2 \) which accounts for such terms in the dispersion relation.
The origin of the term proportional to $\sin^2 \theta_k$ lies in the demagnetization field, $\tilde{h}_d$, generated by the variations in the direction of the magnetization. Maxwell's equations, ignoring propagation effects, yield

$$\nabla \cdot \vec{B} = \nabla \cdot (\tilde{h}_d + 4\pi \vec{M}) = 0$$  \hfill (2.15)$$

$$\nabla \times \tilde{h}_d = 0.$$  \hfill (2.16)

The latter equation implies that $\tilde{h}_d$ can be expressed as the gradient of a scalar potential

$$\tilde{h}_d = -\nabla \Psi$$  \hfill (2.17)

which may then be substituted into Equation 2.15 to get

$$\nabla^2 \Psi = 4\pi \nabla \cdot \vec{M}.$$  \hfill (2.18)

Just as the magnetization was expressed in terms of a spatial Fourier series, the scalar potential can likewise be expanded:

$$\Psi = \sum_k \alpha_k e^{ik\cdot\vec{r}}.$$  \hfill (2.19)

Substitution of the expansions for $\vec{M}$ and $\Psi$ into Equation 2.18 yields

$$-\sum_k \alpha_k k^2 e^{ik\cdot\vec{r}} = \sum_k 4\pi i (\vec{m}_k \cdot \vec{k}) e^{ik\cdot\vec{r}}.$$  \hfill (2.20)

Equating terms with the same value of $k$ shows that

$$\alpha_k = -4\pi i \frac{\vec{m}_k \cdot \vec{k}}{k^2}.$$  \hfill (2.21)
Substitution of the expansion which results for $\Psi$ into Equation 2.17 produces the following expression for the demagnetization field:

$$h_d = \sum_k \vec{h}_k e^{i\vec{k} \cdot \vec{r}}$$

(2.22)

where

$$\vec{h}_k = -4\pi \frac{\vec{m}_k \cdot \vec{k}}{k^2}.$$  

(2.23)

Since $\vec{m}_k$ lies in the $xy$-plane, $(\vec{m}_k \cdot \vec{k}) \propto \sin \theta_k$ where $\theta_k$ is the angle between the direction of propagation of the spinwave, $\vec{k}$, and the $z$-axis. Because the demagnetization energy of a particular spinwave is proportional to $\vec{m}_k \cdot \vec{h}_k^*$ the result is a term dependent upon $\sin^2 \theta_k$ which accounts for the similar term in the dispersion relation.

In addition to this result it can readily be seen that the demagnetization field produces an elliptical, rather than circular, precession of the magnetization. Up to this point the choice of a specific direction for the $x$ and $y$ axes remains arbitrary. If it is assumed that $\vec{k}$ lies in the $xz$-plane the direction of the $x$-axis becomes well defined. Since the demagnetizing field is parallel to $\vec{k}$ it must also lie in the $xz$-plane thereby destroying the symmetry of the equations of motion in the $x$ and $y$ directions which result from Equation 2.5.

One of the principle ramifications of the dispersion relation presented in Equation 2.13 is the existence of a spinwave band, illustrated in Figure 2.1, which is bounded by the two extremes $\theta_k = 0$ and $\theta_k = \pi/2$. The exact placement of these limits depends on the sample shape through the shape demagnetization tensor. For a sphere the terms of the demagnetization tensor are $N_x = N_y = N_z = \frac{1}{3}$ which produces a lower limit at $k = 0$ of $\omega/\gamma = H_0 - \frac{4}{3} \pi M_s$ and an upper limit
at \( \omega/\gamma = \sqrt{(H_0 - \frac{4}{3}\pi M_s)(H_0 + \frac{8}{3}\pi M_s)} \). This places the uniform precession mode, \( \omega/\gamma = H_0 \) well into the spinwave band, making it degenerate with a vast number of other spinwave modes. In contrast the lower limit for a thin film lying in the \( xy \)-plane is given by the uniform precession relation \( \omega/\gamma = H_0 - 4\pi M_s \), which makes that mode non-degenerate. It is this aspect of the thin film geometry which makes it such an attractive choice for nonlinear studies. As evidenced by the low power spectra of the samples used in this work, only a few discrete modes are involved in the dynamics of the system.

The result of this coupling between the uniform precession and higher order spinwaves is dramatically different when examined at high power levels. At low power the system responds linearly with the spinwave coupling merely providing an additional loss of power from the uniform mode. When the power level is increased a threshold is found to exist above which the growth of the number of spinwaves increases catastrophically at the expense of the uniform precession. For the configuration used in this work the microwave pumping field, \( \tilde{h}_p \), is perpendicular to the bias field, \( \tilde{H}_0 \), hence it is known as perpendicular pumping. For this arrangement, when the power is increased above the threshold level two \( k = 0 \) spinwaves are annihilated and a pair of spinwaves with wavevectors \( k \neq 0 \) and nearly degenerate in frequency are excited through a four magnon interaction. This is known as the second order Suhl instability. The strongest coupling in this case is to those spinwaves which are parallel to the bias field, \( \theta_k = 0 \).
Figure 2.1: The spinwave band which results from Equation 2.13 for the case of a thin film in the $xy$-plane ($N_x = N_y = 0, N_z = 1$). All of the spinwaves lie between the extremes defined by propagation along the $z$-axis ($\theta = 0^\circ$) and normal to the $z$-axis ($\theta = 90^\circ$).
This work utilizes a thin disk of YIG placed in the perpendicular pumping configuration. Such a sample exhibits two prominent features at high power levels where the nonlinear effects become significant. The first is a hysteretic absorption of power known as foldover. Above a certain threshold power level sweeping the bias field upward from below the observed resonances produces an abrupt jump in the power absorbed from the microwave field as the system switches to a high amplitude state. Sweeping the bias field down from above the resonances produces a hysteretic high amplitude state which eventually decays abruptly to the low amplitude state previously found while sweeping upfield. An illustration of this effect is presented in Figure 2.2(A). Experimental aspects of this effect were previously reported in [20] and will not be pursued further in this work. The second nonlinear feature of thin YIG disks, and the focus of this work, is the phenomena of auto-oscillations. At sufficiently high power levels the power absorbed by the sample develops an oscillating component, typically in the range 0.1 to 20 MHz. An example of such an observed response is shown in Figure 2.2(B). While auto-oscillations are also found in bulk specimens, and as noted in the introduction they have been extensively studied in spherical form, the thin film geometry possesses a unique advantage in that the modes which are involved in the nonlinear process are few in number and well delineated. This makes it possible to attribute the observed auto-oscillations to particular resonant modes and to successfully model their interactions.
Figure 2.2: (A) An example of the foldover effect showing the jump to a high amplitude state on the upfield sweep of the bias field (bottom curve) and the hysteretic character of both the main resonance (top curve) and the next lower resonance (middle curve) when sweeping downfield. (B) An example of an auto-oscillation as seen in the power reflected from a resonant cavity containing a thin disk of YIG.
2.3 Magnetoexchange Modes

The normal modes of excitation for a thin, circular film are known collectively as the magnetoexchange modes. The "magneto" is indicative of the normal modes which exist in the plane of the film, while the "exchange" refers to the modes across the thickness of the film. For a thick film ($\gg 1\mu m$) the magnetostatic, in-plane spinwave is dominant and the low power spectra consists of magnetostatic modes with many nearly degenerate exchange modes hidden within them. At the other extreme, a very thin film ($\ll 1\mu m$) is dominated by the exchange modes across the thickness of the film so that the low power spectra exhibits the various exchange branches while burying the nearly degenerate magnetostatic modes. The samples used in this work fall between these extremes of thickness so that their low power spectra consist principally of magnetostatic modes with clearly identifiable exchange branches.

The mathematical form of the magnetoexchange modes for a circular film is

$$m(\vec{r}) \propto J_\nu(k_f \rho) \cos(\nu \phi) \left\{ \begin{array}{c} \cos(k_z z) \\ \sin(k_z z) \end{array} \right\}$$

(2.24)

where $\rho$ and $\phi$ are the in-plane coordinates, $z$ is in the direction across the film thickness, and $J_\nu$ is the Bessel function of order $\nu$. The in-plane wavevector is given by $k_f = x_{\nu,s}/a$ where $x_{\nu,s}$ is the $s^{th}$ zero of $J_\nu$ and $a$ is the radius of the sample. These standing waves form because the demagnetization field near the edge of a circular sample is significantly less than that in the interior of the film which results in the edge spins being off resonance and therefore pinned. The Bessel function form of these modes produces two categories of magnetostatic mode: direct modes which are those associated with $J_0$ and can couple directly to a uniform pumping field, and hidden
modes which result from $J_{\omega \neq 0}$ and have no net dipole moment in the plane of the film preventing them from coupling directly to a uniform pumping field. The low power FMR magnetostatic spectra will thus consist of only direct modes unless the sample is somehow imperfectly circular or the pumping field is in some way nonuniform. The lowest order modes are presented in Figure 2.3.

Across the thickness of the film the wavevector is $k_z = n\pi/S$ with $S$ being the thickness of the sample and $n = 0, 1, 2, \ldots$. The functional form of these modes is determined by the pinning of the spins at the air-sample and sample-substrate interfaces. If the spins are unpinned at the surfaces then it is assumed that $dm/dz = 0$ at those boundaries and the appropriate form is $\cos(k_z z)$. Unless $n = 0$ these modes are just like the hidden modes in the plane of the film, they have no net dipole moment and therefore cannot couple to a uniform pumping field. Thus the low power spectra for an unpinned film will exhibit only magnetostatic modes for which the magnetization across the thickness of the film will be uniform. If the spins at the sample boundaries are pinned, then $m = 0$ at these surfaces and the appropriate form is $\sin(k_z z)$. Provided that $n = 1, 3, \ldots$ these modes do have a net dipole moment and will couple to a uniform pumping field, making them visible in the low power FMR spectra. In the event that the conditions at the two surfaces are not identical or in some way the pinning is incomplete, then all of the exchange branches may couple to the pumping field and be visible in the spectra.
Figure 2.3: The lowest order direct and the lowest order hidden magnetostatic modes for a circular thin film as indicated by equations 2.26 and 2.27.
At this point it is possible to formulate an orthonormal set of basis functions from the magnetoexchange modes. The appropriate normalization is

$$\frac{1}{\mathcal{V}} \int_{\Omega} m_i^*(\mathbf{r}) m_j(\mathbf{r}) d\mathbf{r} = \delta_{ij}$$

(2.25)

where $\mathcal{V}$ is the sample volume. Following the form established in Equation 2.24, the modes for uniform magnetization across the thickness of the film are

$$m_{0,0}(\mathbf{r}) = \frac{J_0(x_{0,0} \rho/a)}{J_1(x_{0,0})}$$

$$m_{\nu \neq 0,0}(\mathbf{r}) = \frac{J_\nu(x_{\nu,0} \rho/a)}{J_{\nu+1}(x_{\nu,0})} \sqrt{2} \cos(\nu \phi)$$

(2.26)

while for the odd exchange branches they are given by

$$m_{0,0}(\mathbf{r}) = \frac{J_0(x_{0,0} \rho/a)}{J_1(x_{0,0})} \sqrt{2} \sin(n \pi z/S)$$

$$m_{\nu \neq 0,0}(\mathbf{r}) = \frac{J_\nu(x_{\nu,0} \rho/a)}{J_{\nu+1}(x_{\nu,0})} 2 \cos(\nu \phi) \sin(n \pi z/S).$$

(2.27)

Combining the exchange and magnetostatic modes, Sparks [29] showed that the dispersion relation for the case of uniform magnetization across the sample thickness is given by

$$\omega / \gamma = H_0 - 4\pi M_s + 4\pi M_s \frac{k_f S}{4}. \quad (2.28)$$

For the higher order modes where some degree of pinning is evidenced by the appearance of higher order exchange branches in the low power spectra, the appropriate dispersion relation is

$$\omega / \gamma = H_0 - 4\pi M_s + D k^2 + 4\pi M_s \frac{2k_f S}{\pi^2}. \quad (2.29)$$

These equations will prove quite useful in obtaining estimates of the sample thicknesses.
2.4 Hamiltonian Theory

An alternative to the macroscopic approach represented by Equation 2.5 for determining the equations of motion for the magnetoexchange modes is to derive the Hamiltonian for the system. This technique has already been detailed in Reference [20], including an analysis of the relative magnitudes of higher order interactions. What follows is an overview of that derivation in which only those terms deemed large enough to significantly affect the equations of motion are presented.

The Hamiltonian consists of four terms

\[ \mathcal{H} = \mathcal{H}_{\text{static}} + \mathcal{H}_{\text{demag}} + \mathcal{H}_{\text{dipole}} + \mathcal{H}_{\text{pump}}, \]  

(2.30)

where \( \mathcal{H}_{\text{static}} \) results from the interaction with the bias field, \( \mathcal{H}_{\text{demag}} \) is due to the shape demagnetization effect, \( \mathcal{H}_{\text{dipole}} \) results from the demagnetization fields generated by the oscillating moments, and \( \mathcal{H}_{\text{pump}} \) represents the interaction of the system with the microwave pumping field. All of these effects can be expressed in terms of the sample magnetization \( \vec{M} \), but to facilitate this it is necessary to introduce the variables \( M^+ = M_x + iM_y \) and \( M^- = M_x - iM_y \). Unfortunately these variables are only canonical variables provided that \( M_z \approx M_z \) so it is also necessary to make a transformation defined by

\[
M^+ = a\sqrt{2\gamma M_z - \gamma^2 a a^*}, \\
M_z = M_z - \gamma a a^*,
\]

(2.31)

where \( \gamma \) is again the gyromagnetic ratio. This is the classical equivalent of the Holstein-Primakoff transformation [12]. Notice that this transformation assumes a
circular precession. This is not unreasonable since the typical bias field is 5000 G and the saturation magnetization for YIG at room temperature yields $4\pi M_s = 1760$ G while from the spacing of the magnetostatic modes the dynamic demagnetization fields, shown in section 2.2 to be responsible for the elliptical precession, are on the order of 2-5 G.

One final step remains before returning to the individual components of the Hamiltonian. Since the variable $a$ relates to the macroscopic sample magnetization $\vec{M}$ it has a spatial dependence. This is best expressed by an expansion of the form

$$a = \sum_i a_i m_i(\vec{r})$$

subject to the constraint that the orthogonal basis functions satisfy

$$\frac{1}{V} \int_V m_i^*(\vec{r}) m_j(\vec{r}) = \delta_{ij}$$

where $V$ is the sample volume. For the case of a circular thin film the appropriate basis functions have already been determined and are given in Equations 2.26 and 2.27. Once the Hamiltonian is expressed in terms of $a$ and $a^*$ the expansion given by Equation 2.32 can be inserted and the equations of motion can be derived from

$$\dot{a}_j = -i \frac{\partial H}{\partial a_j^*}.$$  

The first term in the Hamiltonian results from the interaction of the magnetization and the bias field. With the sample lying in the $xy$-plane and the bias field given by $\vec{H}_0 = H_0 \hat{z}$, the energy density is $-H_0 M_z$ which transforms to $-H_0 M_s + \gamma H_0 a^* a$. Inserting the spatial expansion for $a$ presented in Equation 2.32, integrating over the
volume of the sample, and dividing by the volume yields

\[ H_{\text{static}} = -H_0 M_s + \gamma H_0 \sum_i a_i^* a_i. \]  \hspace{1cm} (2.35)

The next term is due to the shape demagnetization field. It produces an energy density of \(2\pi M_s^2\) which transforms into \(2\pi M_s^2 - 4\pi M_s \gamma a^* a + 2\pi \gamma^2 a^* a^* a a\). The expansion of \(a\) and subsequent integration and volume normalization give

\[ H_{\text{demag}} = 2\pi M_s^2 - 4\pi M_s \gamma \sum_i a_i^* a_i + 2\pi \gamma^2 \sum_{ijkl} A_{ijkl} a_i^* a_j^* a_k a_l, \]  \hspace{1cm} (2.36)

where a new interaction parameter has been defined by

\[ A_{ijkl} = \frac{1}{V} \int_V m_i^*(\vec{r}) m_j^*(\vec{r}) m_k(\vec{r}) m_l(\vec{r}) d\vec{r}. \]  \hspace{1cm} (2.37)

Using the form of the magnetoexchange modes given by Equations 2.26 and 2.27 these interaction parameters can be readily calculated, though the task is best left to a good numerical integration routine.

Deriving the form of the dipole term requires the introduction of the dipole fields

\[ h_d^+ = h_{d,x} + i h_{d,y} \quad \text{and} \quad h_d^- = h_{d,x} - i h_{d,y}. \]

The energy density is then given by \(\frac{1}{2}(M^+ h_d^+ + M^- h_d^-)\). These components must then be expanded into spatial series

\[ h_d^+ = \sum_i h_{d,i} m_i(\vec{r}) \]
\[ M^+ = \sum_i b_i m_i(\vec{r}) \]  \hspace{1cm} (2.38)

where the expansion coefficients are related by \(h_{d,i} = D_{ij} b_j\) because of the linear relation which exists between \(h_d^\pm\) and \(M^\pm\), see [29]. While the expansions could be chosen to diagonalize \(D_{ij}\), they are actually selected on the basis of sample geometry
as discussed in Section 2.3. Meanwhile for analytical tractability it will be assumed that $D$ is diagonal. Substitution of all the appropriate parts and a normalized volume integration then produces

$$\mathcal{H}_{\text{dipole}} = \sum_i D_{ii} b_i^* b_i.$$ \hspace{1cm} (2.39)

The coefficients $b_i$ can be related back to the $a_i$ since both form spatial expansions of $M^\pm$, with the result being

$$b_i \approx \sqrt{2 \gamma M_* a_i}.$$ \hspace{1cm} (2.40)

Changing variables from $b_i$ to $a_i$, the dipole contribution to the Hamiltonian thus becomes

$$\mathcal{H}_{\text{dipole}} = 2 \gamma M_* \sum_i D_{ii} a_i^* a_i.$$ \hspace{1cm} (2.41)

There is also a quartic term which evolves from this analysis, but that was shown in [20] to produce a significantly smaller contribution than the quartic term which arises from the shape demagnetization effect. It is therefore not included in this derivation.

The last term in the Hamiltonian is that due to the microwave pumping field, the energy density for which has the form $M_x h_p \cos \omega t$. This transforms to

$$\frac{1}{2} h_p (a^* + a) \sqrt{2 \gamma M_* - \gamma^2 a^* a} \cos \omega t.$$ \hspace{1cm} (2.42)

Expansion of the radical, substitution of the spatial expansion for $a$, and integration over the sample volume then produces

$$\mathcal{H}_{\text{pump}} = h_p \sqrt{\frac{\gamma M_*}{2}} \sum_i (a_i^* I_i^* + a_i I_i) \cos \omega t,$$ \hspace{1cm} (2.43)
where higher order terms have been discarded on the basis of comparative magnitudes, and where the normalized dipole moment, $I_i$, is defined as

$$I_i \equiv \frac{1}{V} \int_V m_i(\vec{r})d\vec{r}. \quad (2.44)$$

For the spatial form of the magnetostatic modes of a thin disk these dipole moments can be readily calculated. If $\nu \neq 0$ then $I = 0$ for both uniform magnetization and higher exchange branches. For the case $\nu = 0$ and uniform magnetization the result is

$$I_{0,*} = \frac{2}{x_{0,*}}. \quad (2.45)$$

while for the odd exchange branches

$$I_{0,*} = \frac{4\sqrt{2}}{n\pi x_{0,*}}. \quad (2.46)$$

The complete Hamiltonian can now be written by combining Equations 2.35, 2.36, 2.41, and 2.43:

$$\mathcal{H} = -H_0 M_s + 2\pi M_s^2 + \gamma \sum_i (H_0 - 4\pi M_s + 2M_sD_{ii})a_i^*a_i$$

$$+ 2\pi\gamma^2 \sum_{ijkl} A_{ijkl}a_i^*a_j^*a_k^*a_l + h_p \sqrt{\frac{\gamma M_s}{2}} \cos(\omega t) \sum_i (a_i^*I_i^* + a_iI_i). \quad (2.47)$$

### 2.5 Equations of Motion

Having developed a Hamiltonian for the system, Equation 2.34 may now be applied to produce the equations of motion

$$\frac{da_j}{dt} = -i\gamma[H_0 - 4\pi M_s + D_{jj}]a_j - 4\pi i\gamma^2 \sum_{klm} A_{ijkl}a_k^*a_l a_m - ih_p \sqrt{\frac{\gamma M_s}{2}} I_j^* \cos(\omega t). \quad (2.48)$$
What is lacking at this point is any account of the relaxation processes which occur in a typical sample. Because of surface imperfections and a variety of crystalline interactions the spinwaves require the constant influx of energy from the pumping field, otherwise they simply damp out over a period of time. To account for this effect the Landau-Lifshitz phenomenological damping mechanism is included in the equations of motion. The general form of this damping is

$$\left( \frac{d\vec{M}}{dt} \right)_{\text{damp}} = -\alpha \vec{M} \times (\vec{M} \times \vec{H}),$$

(2.49)

where \( \alpha \) is a measure of the strength of the damping. For the particular case of \( \vec{H} = (H_0 - 4\pi M_s)\hat{z} \) the \( z \) component of this equation becomes

$$\left( \frac{dM_z}{dt} \right)_{\text{damp}} = \alpha (H_0 - 4\pi M_s)(M^2_z + M^2_y).$$

(2.50)

Transformation of this result into one expressed in terms of the canonical variables \( a \) and \( a^* \) yields

$$\gamma \frac{d(aa^*)}{dt} = -\alpha (H_0 - 4\pi (M_s - \gamma aa^*))aa^*(2\gamma M_s - \gamma^2 aa^*)$$

(2.51)

which can be simplified to

$$\frac{da}{dt} = -\gamma \Gamma a,$$

(2.52)

by defining \( \Gamma = \frac{\alpha}{\gamma} (H_0 - 4\pi M_s)M_s \) and ignoring higher order terms in the expansion. Experimentally, \( \Gamma \) is the half-width at half-maximum of the magnetoexchange mode resonance. For modeling purposes this expression for the damping will be added to Equation 2.48.
In a typical FMR experiment the frequency of the pumping field, \( \omega \), is held constant while the bias field, \( H_0 \) is varied to sweep the system through resonance. It thus becomes convenient to define a resonant field for mode \( j \) by

\[
H_j^{res} = \frac{\omega}{\gamma} + 4\pi M_s - 2M_s D_{jj}.
\]  

(2.53)

Inserting this and the damping term into Equation 2.48 produces

\[
\frac{da_j}{dt} = -i\gamma(H_0 - H_j^{res} - i\Gamma)a_j - 4\pi i\gamma^2 \sum_{klm} A_{jklm} a_k^* a_l a_m - ih_p \sqrt{\frac{\gamma M_s}{2}} I_j^* \cos(\omega t) \tag{2.54}
\]

as the equation of motion for mode \( j \). In order to model the behavior of the system numerically, one final transformation to a set of slowly varying variables is made. Defining

\[
c_j = \sqrt{\frac{2\gamma}{M_s}} a_j e^{i\omega t} \tag{2.55}
\]

and ignoring terms which vary as \( 2\omega t \) the final equation of motion for mode \( j \) becomes

\[
\frac{dc_j}{dt} = -i\gamma(H_0 - H_j^{res} - i\Gamma)c_j - 2\pi i\gamma M_s \sum_{klm} A_{jklm} c_k^* c_l c_m - \frac{1}{2} i\gamma h_p I_j^*. \tag{2.56}
\]

From the linear portion of this equation the steady-state behavior of the system can be derived. To that end consider the equation

\[
\dot{c}_j = -i\gamma[(H_0 - H_j^{res} - i\Gamma)c_j + \frac{1}{2} h_p I_j^*] = 0, \tag{2.57}
\]

which has the solution

\[
c_j = \frac{-h_p I_j^*}{2(H_0 - H_j^{res} - i\Gamma)}. \tag{2.58}
\]

This result can be decomposed into real and imaginary components which reveal something of the behavior of the system:

\[
\Re(c_j) = \frac{-h_p I_j^* (H_0 - H_j^{res})}{2[(H_0 - H_j^{res})^2 + \Gamma^2]} \tag{2.59}
\]
Notice that the imaginary part of the solution produces a Lorentzian lineshape centered at \( H_j^{\text{res}} \) with a linewidth \( \Gamma \) and an amplitude of \( \frac{1}{2} h_p I_j^* \Gamma \). This term is thus directly dependent upon the dipole moment of the mode and increases in intensity as the pumping power increases. Both of these effects are typical of the experimental observations of the magnetoexchange modes. The overall lineshape is also in agreement with experimental observations. Meanwhile the real part is zero at \( H_j^{\text{res}} \), so it seems reasonable to expect the experimentally observed signal to be modeled by the imaginary part of \( c_j \). A simple argument based upon the energy of the system being proportional to the product \( c_j c_j^* \) which examines the time-rate-of-change of this quantity indicates that the experimental signal should be well modeled by the quantity

\[
-\gamma h_p \sum_j I_j^* \Im(c_j) .
\]  

(2.61)

Of course the steady-state behavior is not the real interest in this work; rather the nonlinear response of the system at high pumping power is the main focus. As noted in the introduction one of the high power responses of the magnetic resonance system is the development of an oscillatory component to the power absorbed by the sample, auto-oscillations. This effect can be duplicated by numerical modeling of the equations of motion. The determination of when a point in the variable space of bias field, \( H_0 \), and microwave pumping field, \( h_p \), will auto-oscillate is the only challenge. It turns out to be quite straightforward. For a given pair of values for \( H_0 \) and \( h_p \) the steady-state solution to Equations 2.56, defined by \( \dot{c}_j = 0 \), is first determined. Next
the Jacobian of the equations of motion is evaluated using the steady-state solution. Finally the eigenvalues of the evaluated Jacobian are computed and examined. If all of the eigenvalues have negative or zero real parts then the system is stable in time. When a pair of complex conjugate eigenvalues has a positive real part then the system has undergone a Hopf bifurcation and an oscillatory time dependence will exist. The analysis is further simplified in that for a Hopf bifurcation the frequency of the oscillation is equal to the magnitude of the imaginary part of the eigenvalue pair with positive real part. Of course this breaks down somewhat when the dynamics becomes complicated by more than one pair of eigenvalues crossing the real axis, but it suffices as a means of mapping out where auto-oscillatory behavior is to be expected. This procedure has been implemented in a numerical model of the system. The program which resulted is provided in Appendix III. The techniques discussed here are available in more mathematical detail in Reference [6], while a simple overview of the Hopf bifurcation can be found in Reference [25].
CHAPTER III

Experimental Procedure

3.1 Spectrometer

The experiments were performed using an X-band, balanced-bridge type of reflection spectrometer. Figure 3.1 illustrates the apparatus in block diagram format. The magnetic field is produced by a 15" Varian electromagnet with a Varian 910012-13 power supply and is controlled by an OSU M596A magnet controller. The M596A provides a menu based computer interface as shown in Figure 3.2. The electronics and the GPIB interfacing for the controller were designed by the department electronics shop, while the software was written as part of this experiment and is included in Appendix A. Calibration of the magnetic field was performed using the Ventron G502 NMR gaussmeter over the range 100 - 15000 G and with the Bell 640 gaussmeter from 15000 to 23000 G. The inherent flexibility of the computer system allowed for multiple fits of the calibration data with the result that there is less than 0.5% error in the set center field over the range 0 - 15000 G and less than 2.0% error from 15000 - 23000 G. Since the system is most often used in a configuration where the magnetic field is swept over a particular range of values, the sweep range also required calibration. The electronics used for the sweep have some sensitivity to the set center field so the
Figure 3.1: Block diagram of the ferromagnetic resonance apparatus as used in the experimental portion of this work.
**Figure 3.2: M596A magnet controller menu.**

<table>
<thead>
<tr>
<th>F1</th>
<th>F2</th>
<th>F3</th>
<th>F5</th>
<th>F6</th>
<th>F7</th>
<th>F9</th>
<th>F10</th>
<th>F11</th>
<th>F12</th>
</tr>
</thead>
<tbody>
<tr>
<td>DOWN</td>
<td>HOLD</td>
<td>UP</td>
<td>BOTTOM</td>
<td>CENTER</td>
<td>TOP</td>
<td>FIELDS</td>
<td>RATE</td>
<td>MODE</td>
<td>DOS</td>
</tr>
</tbody>
</table>

- **Center Field:** 5000
- **Present Field:** 4940
- **Sweep Range:** 120
- **Sweep Time:** 1 min
  (Fields in Gauss)
- **Mode:** Manual
- **Pole caps:** Off
- **Vernier:** +0
sweep range was optimized for a center field of 5000 G, a value typical of the fields used in the auto-oscillation experiments. The error in the sweep range is less than 0.2% from 100 - 4000 G at a center field of 5000 G and less than 5.0% over the same range for a center field of 10000 G.

For ease of description it is simplest to divide the waveguide portion of the spectrometer into three branches: source, cavity, and detector. These branches are joined by a circulator which directs the source microwaves into the cavity branch and directs the signal reflected from the cavity into the detector branch. The source branch consists of an HP 716B klystron power supply, a Varian X-13 reflex klystron operating at approximately 9.2 GHz, an isolator, and a Waveline 622 precision attenuator. The isolator prevents reflected signals from interfering with the frequency stability of the klystron, while the attenuator is used to vary the power output of the system.

The cavity branch of the spectrometer is composed of a slide-screw tuner and a TE_{102} cavity. The dimensions of the cavity are 4.5 x 2.25 x 1.0 cm. For almost all of the experiments the sample was placed on the narrow side-wall of the cavity approximately 1.1 cm above the bottom as shown in Figure 3.3. This location places the sample in a position of maximum rf magnetic field and comes closest to ensuring that the rf field lies in the plane of the crystal. Such a configuration corresponds to the perpendicular pumping orientation. (The only exception to this placement was for experiments done to verify the crystal orientation of the samples. In this case the sample was placed in the center on the bottom of the cavity.) When freshly polished and cleaned the cavity has a Q value of 3700 without any sample inside. Loaded
Figure 3.3: A $\text{TE}_{102}$ cavity illustrating the electromagnetic fields and the two sample placements used in this work. Sample sizes are actually much smaller than shown and their placement is intended to be in the region of largest amplitude and most uniform pumping field.
with a sample and no longer pristine the typical Q value is about 2500. Ideally the cavity is critically coupled to the waveguide so that all of the incident power is absorbed by the cavity. In practice the slide-screw tuner is used to slightly decouple the waveguide-cavity system. This produces a reflected signal which serves to bias the detector thereby improving its sensitivity.

In some of the experiments it was necessary to control the temperature of the sample. For this purpose the cavity and a portion of the waveguide which connects it to the slide-screw tuner are immersed in a Janus 8DT dewar. There are three chambers in the dewar: an outer chamber intended for liquid nitrogen, a middle chamber for liquid helium, and an inner chamber for the waveguide and cavity. The cryogen is leaked from the middle chamber into the sample chamber by means of a needle valve. The temperature is measured and controlled via a Lake Shore 520 controller. This unit measures the voltage drop across a silicon diode which is mounted on the outside at the base of the cavity. The voltage drop is compared to an internally generated reference voltage and any difference between the two indicates a deviation of the measured temperature from that which the user has set. Should the temperature drop below the set point a means of heating the sample chamber is required. This is accomplished by a 20 Ω manganin heater wire wrapped around the cavity and connected to the temperature controller. At a fixed temperature there will be a constant flow of cryogen into the sample chamber counterbalanced by a constant current through the heater wire. If a deviation between the set and measured temperatures is found, the current to the heater wire will either be increased or decreased, whichever
is appropriate. For the majority of these experiments the required temperature was above the boiling point of liquid nitrogen. In such cases there was no need to use liquid helium: instead, both the outer and middle reservoirs were filled with liquid nitrogen which is both an easier to use and less expensive cryogen than liquid helium. While the accuracy of this temperature control system is probably better than 1 K, it was not a major issue for these experiments because the magnetic effects observed change rather slowly with temperature. The stability of the system was excellent, an effect readily noted by the stability of the observed auto-oscillations which are very sensitive to changes in the magnetic properties of the material, and therefore also very sensitive to the sample temperature.

The detector branch contains an HP X532B frequency meter for determining the operating frequency of the system, and an HP423B crystal detector. Inserting an HP 431C power meter following the slide-screw tuner, it was found that at 0 dB attenuation the klystron produces 47 mW at 9.22 GHz. As may be seen in Figure 3.1 there are two distinct methods of processing the output signal from the detector: one for the analysis of low power absorption spectra and another for the study of auto-oscillations.

The characterization of the fundamental properties of a sample is done at low power using an absorption spectra obtained by sweeping the magnetic field. Since the samples are quite small the signal which results is rather weak and cannot be observed directly. To overcome this difficulty requires the use of lock-in amplifier techniques. A pair of Helmholtz coils are mounted around the poles of the Varian
magnet. These coils produce a weak ac magnetic field which modulates the much larger field produced by the Varian magnet. The reference signal for the coils is generated by a PAR 124 lock-in amplifier and then fed through a Macintosh MC240 audio amplifier. A frequency of 400 Hz is used for the modulation and the rms amplitude of the modulating magnetic field is about 1 G. By comparing the modulated signal from the detector to the reference signal the signal-to-noise ratio is vastly improved and low power spectra are readily observed. The output from the lock-in amplifier is fed to the y-axis of an HP 7045B X-Y recorder while the x-axis input is obtained from the magnet controller. Since the magnetic field is modulated the plot which results is the derivative of the absorbed power with respect to the magnetic field, $dP/dH$.

For studying the auto-oscillatory behavior of the system, the signal from the detector must be observed directly without the use of modulation techniques. Since the output signal is still quite weak, even at the higher powers associated with nonlinear phenomena, it first passes through a pre-amplifier then a power amplifier before observation. The pre-amp is an OSU model M591A built by the department electronics shop. For future reference the circuit diagram is provided in Figure 3.4. The amplifier is either an HP 461A or a Mini-circuits ZHL-32A, the more recent experiments being done with the latter because the HP 461A was found to be a significant noise source. Power for both the pre-amplifier and the Mini-circuits amplifier is provided by a pair of HP E3611A dc power supplies, while the HP 461A is a self-contained unit. Once the signal is appropriately amplified it is fed into both a TEK 7L13 spectrum
Figure 3.4: Circuit diagram of the M591A pre-amplifier used as an aid in the detection of an auto-oscillatory signal.
analyzer and a LeCroy 9400A digitizing oscilloscope. Auto-oscillations then appear as an oscillatory signal on the scope and a Fourier spectral peak on the analyzer. Since the spectrum analyzer is an analog device it provides only a rough estimate of the frequency of the observed auto-oscillations. A more precise frequency measurement is obtained by using the Fast-Fourier Transform (FFT) capability of the LeCroy scope. When it is useful to download the signal from the LeCroy or to plot it, a transfer program running on the HP Vectra computer is used. The transfer program was written in Asyst and is provided in Appendix B. It allows for the downloading of signal data from all four of the LeCroy data memories (channels 1 and 2, memories C and D), a screen dump from the LeCroy to an HP 7470A plotter, and conversion from binary to ASCII file format. Earlier versions of the program provided for complete control of the functions of the oscilloscope, but much greater flexibility results from the manual control of the scope.

3.2 Samples

Four samples were used in these experiments, all of them made for previous experimental work by other researchers. As such they have pre-existing labels which mark their containers in the laboratory, but for convenience they will be referred to as samples 1 through 4 in this document. Sample 1, known in the laboratory as T-18-C, is of recent origin, and consequently its history is well known. It was made from a YIG film (T-18) provided by the Airtron Corporation. The original film was grown by liquid phase epitaxy (LPE) on a gadolinium-gallium-garnet (GGG) substrate to a thickness of roughly 3.0 μm. Using an RTV sealant mask and a phosphoric acid
etch [30], a circular sample with a 1.1 mm diameter was produced. After removal of
the RTV sealant the sample was carefully etched to reduce its thickness and thereby
separate the individual magnetostatic modes [20]. The same level of historic detail is
not available for samples 2 (3-111-20), 3 (3-111-10), and 4 (388-10B-HT). They were
grown by chemical vapor deposition (CVD) on GGG substrates in the early 1970's
by what was then North American Rockwell [21]. Circular samples were then made
using photolithographic techniques. While it is known that sample 1 was grown with
the [111] axis normal to the film plane, the orientation of the other samples was less
than certain based on available documentation.

To clarify the growth orientation of the samples low power FMR was performed
with the samples in the alternate position previously illustrated in Figure 3.3. With
this configuration both the microwave pumping and the resonant fields lie in the
plane of the film. By measuring the magnitude of the resonant field as a function
of angle (the origin is arbitrary) the underlying crystal symmetry is exposed. The
experiment for sample 1 covered 230° in 10° increments, while those for samples 2,
3, and 4 ranged over 235° in 5° increments. A subset of the results, suitably shifted
for clarity, is shown in Figure 3.5. Sample 1 displays an asymmetric profile with a
periodicity approaching 180° and an amplitude of 6 Oe. Since this is known to be a
[111] oriented film, this result indicates that the sample was not oriented with both
the bias and pumping fields perfectly parallel to the plane of the film. In as much as
the sample has been etched and lies on a minute blob of vacuum grease on the bottom
of the cavity, such a result is not surprising. For the other three films the periodicity
is 90°, typical of the cubic anisotropy found in [100] oriented films. Samples 2 and 3 have an anisotropy field of 58 Oe, while for sample 4 the anisotropy is 65 Oe.

There are two low-power FMR techniques for estimating the thickness of the samples. The first method relies upon the spacing of the higher order exchange branches. The dispersion relations, equations 2.28 and 2.29, illustrate that the resonant fields of the exchange branches vary as $Dk^2$. For a sample with fully free or fully pinned spins at the sample surfaces, $k = \frac{n\pi}{S}$ where $n = 1, 2, 3, \ldots$. This implies that a plot of resonant field versus $n^2$ should be linear with a slope given by

$$\frac{D\pi^2}{S^2}, \quad (3.1)$$

where $D = 0.5$ Oe $\mu$m$^2$. If the surface spin pinning is asymmetric, then, just as with the standing waves in a closed organ pipe, $k = \frac{n\pi}{2S}$ where again $n = 1, 3, 5, \ldots$. In this case a plot of resonant field versus $n^2$ should have a slope of

$$\frac{D\pi^2}{4S^2}. \quad (3.2)$$

The room temperature measurements of the resonant fields of the higher order exchange branches for each of the samples is given in Table 3.1. The fields listed are relative to the location of the (0,1) magnetostatic mode, the negative sign indicating that they are to be found at lower fields. A plot of the field locations versus $n^2$ and the linear least-squares fit to the data are shown in Figure 3.6. As illustrated in the plot, the linear fit to the data is excellent. Table 3.1 lists the slopes of the fitted lines and the resulting estimates of the sample thicknesses. For sample 1 the modes listed correspond to the $n = 3, 4, 5, 7,$ and 8 exchange branches which indicates
Figure 3.5: Resonant field as a function of angle using the alternate sample placement shown in Figure 3.3 for each of the four samples. The results clearly indicate the [100] orientation of samples 2, 3, and 4, as well as the [111] orientation of sample 1.
Table 3.1: Locations of the higher order exchange branches relative to the (0,1) magnetostatic mode, the slope of the least-squares fit of the field vs. \( n^2 \), and the resulting estimate of the sample thickness.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Resonant Field (G)</th>
<th>Slope (G)</th>
<th>Thickness (( \mu m ))</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-22</td>
<td>-3.66</td>
<td>1.17</td>
</tr>
<tr>
<td>2</td>
<td>-39</td>
<td>-5.09</td>
<td>0.49</td>
</tr>
<tr>
<td>3</td>
<td>-56</td>
<td>-7.50</td>
<td>0.41</td>
</tr>
<tr>
<td>4</td>
<td>none</td>
<td></td>
<td>-</td>
</tr>
</tbody>
</table>

that the surface spins are neither fully free nor fully pinned. The slope which results from fitting this data yields a thickness of 1.17 \( \mu m \). A distortion in the spectra approximately 7 G below the (0,1) mode indicates the location of the \( n = 2 \) mode. This mode was not included in the analysis because it is not a well defined resonance in the spectra and also because of the potential distortion of its position from the branch repulsion effect [11]. The \( n = 6 \) branch could not be located. In contrast to the complexity of sample 1, samples 2 and 3 exhibit only odd exchange branches. Thickness estimates derived from the slope of the fitted line are 0.49 \( \mu m \) for sample 2 and 0.41 \( \mu m \) for sample 3. No higher order exchange branches were found for sample 4, indicating uniform magnetization across the film thickness.

The second method for estimating the sample thickness relies upon the spacing of the magnetostatic modes and knowledge of the sample radius. The sample diameters were determined with an optical microscope and a calibrated eyepiece grating. Sample 1 has a diameter of 1.1 mm, sample 2 is 0.50 mm, and samples 3 and 4 are 0.25 mm
Figure 3.6: Resonant field of the higher order exchange branches versus $n^2$, where $n$ is the branch order, and the linear least-squares fit to the data.
in diameter. Equation 2.28 showed that for the case of uniform magnetization across the thickness of the film a plot of resonant field versus $x_{\nu,s}$, the $s^{th}$ zero of the Bessel function $J_{\nu}$, should be linear with a slope given by

$$4\pi M_s \frac{S}{4a},$$  \hfill (3.3)

where $4\pi M_s = 1760$ Oe at room temperature, $a$ is the sample radius, and $S$ is the sample thickness. For the higher order modes equation 2.29 applies and the slope is given by

$$4\pi M_s \frac{2S}{\pi^2 a}.$$ \hfill (3.4)

Plots of the locations of the first five magnetostatic modes versus the appropriate Bessel function zeros are provided in Figure 3.7. The mode locations are measured relative to the location of the $(0,1)$ mode, which is arbitrarily shifted to 20 G for convenience. These measurements were all made at room temperature at -30 dB attenuation.

A summary of the mode locations and the slopes of the data fits are provided in Table 3.2. These values were then used in conjunction with either equation 3.4 (samples 1, 2, and 3) or equation 3.3 (sample 4) and the measurements of the sample diameters to get an estimate of their thicknesses. The estimate for sample 1 is $1.25 \mu m$, that for sample 2 is $0.51 \mu m$, sample 3 yields $0.42 \mu m$, and sample 4 is estimated to be $0.38 \mu m$ thick. The thickness estimates of the two methods compare quite well, differing by no more than 7%. The sample containers for samples 2, 3, and 4 list their thicknesses as $0.56$, $0.56$, and $0.48 \mu m$ respectively. These sizes differ substantially from the experimental values, reflecting either a fairly large experimental
Figure 3.7: Resonant fields of the magnetostatic modes versus the zeros of the Bessel function $J_0$ and the linear least-squares fit to the data for (A) samples 1 and 3 and (B) samples 2 and 4. Separate plots are used for visual clarity.
error or perhaps previous unrecorded etching of the samples. Lacking more detailed knowledge of their history, it will be assumed that the experimental thicknesses are valid to within ±10% and that the best estimate is given by the average of the two experimental methods.

A complete summary of the samples is provided in Table 3.3. The thickness estimates are the averages of the experimental values discussed above. The aspect ratio, defined as the radius divided by the thickness ($a/S$), provides a convenient means of noting the range of variation of the physical dimensions of the samples used in this study. It further indicates that samples 1 and 2 may share similar behavior, as may samples 3 and 4, since in each case the aspect ratios are fairly close in value.

There are two further characteristics which have not yet been discussed and which are not contained in the summary table. The optical examination of the samples indicated that sample 1 is the least circular of the samples. It showed a fair degree of ellipticity, with one measurement yielding a diameter of 1.2 μm while most others

<table>
<thead>
<tr>
<th>Sample</th>
<th>Resonant Field (G)</th>
<th>Slope (G)</th>
<th>Thickness (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>20.0 17.3 14.8 12.1 9.9</td>
<td>-0.81</td>
<td>1.25</td>
</tr>
<tr>
<td>2</td>
<td>20.0 17.6 15.2 13.0 10.8</td>
<td>-0.73</td>
<td>0.51</td>
</tr>
<tr>
<td>3</td>
<td>20.0 15.8 11.9 8.3 5.0</td>
<td>-1.20</td>
<td>0.42</td>
</tr>
<tr>
<td>4</td>
<td>20.0 15.7 11.5 7.5 3.5</td>
<td>-1.32</td>
<td>0.38</td>
</tr>
</tbody>
</table>
Table 3.3: Sample summary: laboratory labels, growth characteristics, physical dimensions, and aspect ratio (radius/thickness).

<table>
<thead>
<tr>
<th>Sample</th>
<th>Laboratory Label</th>
<th>Growth Process</th>
<th>Growth Orientation</th>
<th>Diameter (mm)</th>
<th>Thickness (µm)</th>
<th>Aspect Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>T-18-C</td>
<td>LPE</td>
<td>111</td>
<td>1.1</td>
<td>1.21</td>
<td>455</td>
</tr>
<tr>
<td>2</td>
<td>3-111-20</td>
<td>CVD</td>
<td>100</td>
<td>0.50</td>
<td>0.50</td>
<td>500</td>
</tr>
<tr>
<td>3</td>
<td>3-111-10</td>
<td>CVD</td>
<td>100</td>
<td>0.25</td>
<td>0.42</td>
<td>298</td>
</tr>
<tr>
<td>4</td>
<td>388-10B-HT</td>
<td>CVD</td>
<td>100</td>
<td>0.25</td>
<td>0.38</td>
<td>329</td>
</tr>
</tbody>
</table>

produced the quoted 1.1 µm diameter. The other samples were highly circular, the diameter measurements never differing by more than 0.01 µm. The second characteristic not listed above is that sample 4 is recorded as having been subjected to a high temperature anneal. While the details are unavailable, the recorded history of other annealed samples from that time frame would indicate that it was most likely done in an oxygen atmosphere.
4.1 General Features

Prior to examining the effects of temperature and field orientation on the nonlinear behavior of the samples, the room temperature characteristics of each sample were studied. At low power, typically -30 dB attenuation, the spacing between the magnetostatic modes was measured from differential spectra. This data provides a measure of the overlap of the respective resonances and reflects the ease or difficulty in exciting their interaction. The spacing between mode \( m \) and mode \( n \) is denoted by \( \delta H_{mn} \). Also measured from the same low power spectra was the linewidth, \( \Gamma \), which is indicative of the damping effects within each sample. Assuming a Lorentzian lineshape for the resonances given by

\[
f(x) = \frac{A}{(x - x_0)^2 + \Gamma^2}
\]  

where \( A \) is the amplitude, \( x_0 \) is the center of the resonance, and \( \Gamma \) is the half-width at half-maximum, the differential spectra will have peaks at

\[
x = x_0 \pm \frac{\Gamma}{\sqrt{3}}.
\]
Table 4.1: Sample aspect ratio (radius/thickness), room temperature measurements of the spacing between modes (0,1) and (0,2), $\delta H_{12}$, (0,2) and (0,3), $\delta H_{23}$, (0,3) and (0,4), $\delta H_{34}$, and the linewidth, $\Gamma$.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Aspect Ratio</th>
<th>$\delta H_{12}$ (G)</th>
<th>$\delta H_{23}$ (G)</th>
<th>$\delta H_{34}$ (G)</th>
<th>$\Gamma$ (G)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>455</td>
<td>2.7</td>
<td>2.5</td>
<td>2.7</td>
<td>0.7</td>
</tr>
<tr>
<td>2</td>
<td>500</td>
<td>2.4</td>
<td>2.4</td>
<td>2.2</td>
<td>0.8</td>
</tr>
<tr>
<td>3</td>
<td>298</td>
<td>4.2</td>
<td>3.9</td>
<td>3.6</td>
<td>0.8</td>
</tr>
<tr>
<td>4</td>
<td>329</td>
<td>4.3</td>
<td>4.2</td>
<td>4.0</td>
<td>0.6</td>
</tr>
</tbody>
</table>

A measurement of the peak-to-peak separation, $2(x - x_0)$, therefore yields the linewidth measurement

$$\Gamma = \frac{\sqrt{3}}{2} (2(x - x_0)).$$

(4.3)

The room temperature results of these low power measurements are presented in Table 4.1 along with the aspect ratio (radius/thickness) of each sample as a reminder of their relative sizes.

At high powers the samples exhibit auto-oscillations which when plotted in attenuation - bias field space produce a map with finger-like structures. Following the convention of [20], the fingers are labeled by the nearest low power magnetostatic mode resonance which lies at higher field than the auto-oscillation onset point. Figures 4.1 and 4.2 present the room temperature auto-oscillation maps observed for each sample as the bias field is swept upfield from well below the onset points. Hysteretic effects as the bias field is swept down from above the onset points have been
noted in [20] and are not studied here. The positions of the low power resonances are indicated in the figures along with the resulting assignment of labels for the various fingers.

The map for sample 1 clearly indicates the finger-like structure and the assignment of finger labels in association with the low power resonances. Finger 1 actually consists of two parts which are distinguishable on the basis of a shift in the auto-oscillation frequency. Sample 2 presents a bit of a dilemma because following the label assignment rule yields fingers 2 and 4 with no sign of fingers 1 and 3. There are two frequency distinct parts to finger 4 which may indicate that what is really seen are fingers 3 and 4, but since the locations of the onsets relative to the low power resonances is reproducible the labeling will be as shown in Figure 4.1. Sample 3 presents three clearly defined fingers and, like sample 1, produces a two part first finger. Comparison with other maps for sample 3 indicates that the frequency of the klystron drifted slightly between the time the low power data were taken and the time the map was made. This resulted in a downfield shift of the map relative to the positions of the low power resonances. The map for sample 4 shows only two distinct fingers, 1 and 3, coupled with two small stubs on the downfield sides of these fingers which are tentively labeled as fingers 2 and 4.

While the overall structure of the auto-oscillation maps distinguishes quite well between the various samples, the fingers themselves also show quite a unique variety in their onset characteristics. This work focuses on their onset frequency ($f$), attenuation ($\text{Att}$), and field separation from the associated low power resonance ($\Delta H$). The
Figure 4.1: Maps of the regions in attenuation - resonant field space where auto-oscillations are found, the associated finger labels, and the positions of the low power magnetostatic mode resonances for: (A) sample 1 and (B) sample 2.
Figure 4.2: Maps of the regions in attenuation - resonant field space where auto-oscillations are found, the associated finger labels, and the positions of the low power magnetostatic mode resonances for: (A) sample 3 and (B) sample 4.
weakest characteristic is the onset attenuation because the microwave power directed to the sample is strongly dependent upon the placement of the sample within the cavity and the tuning of the klystron. Variations of as much as 2-3 dB have been seen for a sample which has been moved within the cavity. This means that comparisons of onset attenuation between samples or from one data set to another for a single sample may be subject to considerable error and must be made with caution. Comparison of the relative onset attenuations for the various fingers within a single auto-oscillation map are not subject to this type of error. For all of the maps reported in this work the value reported for the onset attenuation is actually an upper limit, the lower limit being 0.5 dB lower. This variation results from the original data being taken in increments of 0.5 dB.

Locations of onset relative to low power resonances is a slightly better characteristic than attenuation, but it is subject to drift in the klystron frequency which can readily occur during the two hours required to make a detailed map. While for most of the maps this was not a significant problem, drift did occasionally occur and will be noted when such data are reported. Unless otherwise indicated the error in the onset location is probably limited to 0.5 G. The most well defined characteristic is the onset frequency. It is reproducible from run to run even if the sample placement within the cavity changes or the klystron is re-tuned. The error in onset frequency is certainly no worse than \( \pm 0.1 \) MHz. A summary of all of these characteristics for the room temperature maps is provided in Tables 4.2 and 4.3.
Based upon their similar aspect ratios it was anticipated that samples 1 and 2 would exhibit comparable behavior, as would samples 3 and 4. The data does support this expectation. Samples 1 and 2 show similar behavior in the characteristics of the second finger and to a limited extent in the fourth finger. Likewise samples 3 and 4 exhibit very similar results for the first, second, and third fingers. Comparing one set to the other, two trends seem apparent. First, the smaller diameter samples (3 and 4), which have a larger mode separation at low power, produce higher onset frequencies. Secondly, the smaller samples also exhibit lower onset attenuations, indicating that higher power levels are required to excite the auto-oscillations than are needed by the larger samples. This latter comparison is valid, despite the earlier warning about making inter-sample comparisons of attenuation, because of the large differences (\( > 5 \) dB) which the two sets of samples exhibit. The need for higher power levels by the smaller samples is consistent with the larger mode separation such samples exhibit: since the resonances are farther apart more power is required to excite their interaction.

Two other general features, which will prove to be significant when examining the effect of field orientation, are the nature of the onset and the behavior of the frequency within a finger as the bias field is increased. In the perpendicular orientation the auto-oscillations appear abruptly with a well defined megahertz frequency and, though they may weaken somewhat in intensity, they vanish abruptly as the field is increased. Within the finger the frequency is found to smoothly decrease with increasing field, excepting of course those instances where multiple fingers are merging.
Table 4.2: Experimentally observed onset frequency ($f$), attenuation ($Att$), and field separation between the onset and the associated low power resonance ($\Delta H$) for fingers 1 and 2 of the room temperature auto-oscillation maps.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Finger</th>
<th>$f$ (MHz)</th>
<th>$Att$ (dB)</th>
<th>$\Delta H$ (G)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>1.4</td>
<td>-15.0</td>
<td>2.3</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>4.1</td>
<td>-13.0</td>
<td>3.3</td>
</tr>
<tr>
<td>2</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>2.5</td>
<td>-8.0</td>
<td>4.5</td>
</tr>
<tr>
<td>4</td>
<td>4</td>
<td>6.4</td>
<td>-8.0</td>
<td>4.8</td>
</tr>
</tbody>
</table>

Table 4.3: Experimentally observed onset frequency ($f$), attenuation ($Att$), and field separation between the onset and the associated low power resonance ($\Delta H$) for fingers 3 and 4 of the room temperature auto-oscillation maps.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Finger</th>
<th>$f$ (MHz)</th>
<th>$Att$ (dB)</th>
<th>$\Delta H$ (G)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3</td>
<td>3.4</td>
<td>-11.0</td>
<td>1.2</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>5.8</td>
<td>-9.0</td>
<td>1.5</td>
</tr>
<tr>
<td>2</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>6.8</td>
<td>-5.5</td>
<td>1.0</td>
</tr>
<tr>
<td>4</td>
<td>4</td>
<td>9.9</td>
<td>-4.0</td>
<td>2.0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Sample</th>
<th>Finger</th>
<th>$f$ (MHz)</th>
<th>$Att$ (dB)</th>
<th>$\Delta H$ (G)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3</td>
<td>3.4</td>
<td>-11.0</td>
<td>1.2</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>5.8</td>
<td>-9.0</td>
<td>1.5</td>
</tr>
<tr>
<td>2</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>6.8</td>
<td>-5.5</td>
<td>1.0</td>
</tr>
<tr>
<td>4</td>
<td>4</td>
<td>9.9</td>
<td>-4.0</td>
<td>2.0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Sample</th>
<th>Finger</th>
<th>$f$ (MHz)</th>
<th>$Att$ (dB)</th>
<th>$\Delta H$ (G)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3</td>
<td>3.4</td>
<td>-11.0</td>
<td>1.2</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>5.8</td>
<td>-9.0</td>
<td>1.5</td>
</tr>
<tr>
<td>2</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>6.8</td>
<td>-5.5</td>
<td>1.0</td>
</tr>
<tr>
<td>4</td>
<td>4</td>
<td>9.9</td>
<td>-4.0</td>
<td>2.0</td>
</tr>
</tbody>
</table>
4.2 Sample Temperature Effects

As the temperature of YIG decreases the saturation magnetization, $M_s$, increases. The equations of motion, Equation 2.56, indicate that such an effect increases the magnitude of the nonlinear coupling. How such a change influences the behavior of the system is not immediately clear from these equations, consequently the temperature dependence of the auto-oscillatory behavior of samples 1 and 2 was investigated. The more detailed investigation was done with sample 1 for which data was taken from 290 down to 130 K in increments of 20 K. For redundancy sample 2 was examined at 295 (room temperature), 250, 200, and 150 K. For both samples the lower temperature limit was determined by the power limitations of the klystron; at temperatures below the lower limit it was not possible to excite auto-oscillations.

In section 2.1 it was shown how a measurement of the resonant field with the field oriented in the plane of the film and a measurement of the field when it is oriented normal to the film plane can be used to obtain an estimate of $4\pi M_s$. Such measurements were taken at low power for each temperature and an estimate of $4\pi M_s$ was computed. Likewise, low power measurements of the linewidth, $\Gamma$, and the magnetostatic mode separation, $\delta H_{mn}$, were taken. The results of these measurements are given in Table 4.4 for both samples. In addition, the linewidth and mode separations for sample 1 are presented graphically in Figure 4.3.

Measurements for both samples indicate that the linewidth steadily increases as the temperature is lowered. As expected $4\pi M_s$ increases with decreasing temperature, an effect which also causes an increase in the mode separation with decreasing tem-
Table 4.4: Temperature dependent measurements of saturation magnetization ($4\pi M_s$), linewidth ($\Gamma$), and the magnetostatic mode spacing ($\delta H_{mn}$) for samples 1 and 2.

<table>
<thead>
<tr>
<th>$T$ (K)</th>
<th>Sample 1</th>
<th>Sample 2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$4\pi M_s$ (Oe)</td>
<td>$\Gamma$ (G)</td>
</tr>
<tr>
<td>295</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>290</td>
<td>1779</td>
<td>0.70</td>
</tr>
<tr>
<td>270</td>
<td>1848</td>
<td>0.70</td>
</tr>
<tr>
<td>250</td>
<td>1920</td>
<td>0.75</td>
</tr>
<tr>
<td>230</td>
<td>1985</td>
<td>0.75</td>
</tr>
<tr>
<td>210</td>
<td>2046</td>
<td>0.80</td>
</tr>
<tr>
<td>200</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>190</td>
<td>2103</td>
<td>0.90</td>
</tr>
<tr>
<td>170</td>
<td>2154</td>
<td>0.95</td>
</tr>
<tr>
<td>150</td>
<td>2208</td>
<td>1.10</td>
</tr>
<tr>
<td>130</td>
<td>2259</td>
<td>1.25</td>
</tr>
</tbody>
</table>
Figure 4.3: Temperature dependence of the linewidth and mode separations for sample 1. All show a gentle increase with decreasing temperature except $\delta H_{34}$ which is directly influenced by the second exchange branch.
perature. While this effect is consistent with the dispersion equations, Equations 2.28 and 2.29, the experimental data indicate that the mode separation stabilizes beyond a certain threshold, an effect not predicted by the theory. Both samples show this trend, with the more extensive data for sample 1 indicating that the higher order modes stabilize first.

The first three temperature measurements of $\delta H_{34}$ for sample 1 were found to decrease, in direct contrast to all the other measurements. This discrepancy can be accounted for by noting that in reducing the temperature from 290 to below 250 K the observed location of the second exchange branch shifts from below the (0,3) mode to above it, thereby reducing the distortion of the separation between the (0,3) and (0,4) modes.

The effect which reducing the sample temperature has upon the auto-oscillatory behavior of sample 1 has been compiled in Tables 4.5 and 4.6 which list the onset frequency, attenuation, and separation from the associated magnetostatic mode for each of the first four fingers. The data for fingers 1 and 2 were taken from a different data set than that used in compiling the data for fingers 3 and 4 which explains why no data is listed at 270 and 230 K for the latter two fingers. The onset attenuation is accurate to within -0.5 dB, corresponding to the coarseness of the map when the data was taken. However, the attenuation data for fingers 3 and 4 should not be directly compared to that for the first two fingers since the sample was removed from the cavity between the two data runs.
Table 4.5: Temperature dependent measurements of the onset frequency ($f$), attenuation ($Att$), and separation between the onset and the associated magnetostatic mode ($\Delta H$) for auto-oscillation fingers 1 and 2 of sample 1.

<table>
<thead>
<tr>
<th>T (K)</th>
<th>Finger</th>
<th>1 (MHz)</th>
<th>1 (dB)</th>
<th>1 (G)</th>
<th>2 (MHz)</th>
<th>2 (dB)</th>
<th>2 (G)</th>
</tr>
</thead>
<tbody>
<tr>
<td>290</td>
<td>1.4</td>
<td>-13.0</td>
<td>2.3</td>
<td>4.5</td>
<td>-11.0</td>
<td>1.9</td>
<td></td>
</tr>
<tr>
<td></td>
<td>4.1</td>
<td>-11.0</td>
<td>3.3</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>270</td>
<td>1.5</td>
<td>-13.0</td>
<td>2.5</td>
<td>4.7</td>
<td>-11.0</td>
<td>1.7</td>
<td></td>
</tr>
<tr>
<td></td>
<td>4.2</td>
<td>-11.5</td>
<td>3.2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>250</td>
<td>1.7</td>
<td>-12.5</td>
<td>2.6</td>
<td>4.9</td>
<td>-11.0</td>
<td>1.9</td>
<td></td>
</tr>
<tr>
<td></td>
<td>4.5</td>
<td>-11.0</td>
<td>3.4</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>230</td>
<td>1.8</td>
<td>-12.0</td>
<td>2.3</td>
<td>5.1</td>
<td>-10.5</td>
<td>1.4</td>
<td></td>
</tr>
<tr>
<td></td>
<td>4.7</td>
<td>-11.0</td>
<td>2.6</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>210</td>
<td>1.8</td>
<td>-12.5</td>
<td>2.4</td>
<td>5.3</td>
<td>-10.5</td>
<td>1.7</td>
<td></td>
</tr>
<tr>
<td></td>
<td>5.0</td>
<td>-10.0</td>
<td>3.3</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>190</td>
<td>2.0</td>
<td>-12.0</td>
<td>2.1</td>
<td>5.8</td>
<td>-8.5</td>
<td>1.7</td>
<td></td>
</tr>
<tr>
<td></td>
<td>5.2</td>
<td>-9.0</td>
<td>3.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>170</td>
<td>2.1</td>
<td>-10.5</td>
<td>0.8</td>
<td>5.4</td>
<td>-8.0</td>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td></td>
<td>5.1</td>
<td>-9.5</td>
<td>1.3</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>150</td>
<td>2.3</td>
<td>-9.0</td>
<td>1.1</td>
<td>5.4</td>
<td>-7.0</td>
<td>0.4</td>
<td></td>
</tr>
<tr>
<td></td>
<td>5.3</td>
<td>-6.5</td>
<td>1.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>130</td>
<td>2.5</td>
<td>-6.5</td>
<td>1.9</td>
<td>9.0</td>
<td>-5.0</td>
<td>0.7</td>
<td></td>
</tr>
<tr>
<td></td>
<td>6.6</td>
<td>-5.0</td>
<td>3.3</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table 4.6: Temperature dependent measurements of the onset frequency (f), attenuation (Att), and separation between the onset and the associated magnetostatic mode ($\Delta H$) for auto-oscillation fingers 3 and 4 of sample 1.

<table>
<thead>
<tr>
<th>$T$ (K)</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$f$ (MHz)</td>
<td>$\Delta H$ (G)</td>
</tr>
<tr>
<td>290</td>
<td>3.4</td>
<td>-11.0</td>
</tr>
<tr>
<td>270</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>250</td>
<td>3.5</td>
<td>-11.5</td>
</tr>
<tr>
<td>230</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>210</td>
<td>6.7</td>
<td>-9.5</td>
</tr>
<tr>
<td>190</td>
<td>7.4</td>
<td>-10.0</td>
</tr>
<tr>
<td>170</td>
<td>7.8</td>
<td>-8.5</td>
</tr>
<tr>
<td>150</td>
<td>7.8</td>
<td>-5.5</td>
</tr>
<tr>
<td>130</td>
<td>8.1</td>
<td>-2.5</td>
</tr>
</tbody>
</table>
Figure 4.4 graphically illustrates the behavior of the onset attenuation for sample 1. The overall trend found in each finger is that lower temperature produces a decrease in onset attenuation, indicating that higher power is required in order to excite the auto-oscillations. This is reasonable since the spacing between the resonances is found to increase, an effect which reduces the overlap of the various resonance modes. At the same time the linewidth increases which indicates an increase in system damping. The combination of these two effects thus makes it more difficult to excite a particular nonlinear interaction.

The measurements of the onset field separation, $\Delta H$, are accurate to about $\pm 1$ G. This large uncertainty results from the sweep width (10 G) used in taking most of the auto-oscillation data for sample 1. With such a small sweep width any drift in the klystron frequency is greatly magnified. In addition, this data was taken prior to the installation of the new magnet controller and both the accuracy and the stability of such a narrow sweep are suspect. Measurements of $\Delta H$ at 170 and 150 K are significantly out of line with the rest of the measurements, an effect directly attributable to the drift of either the klystron or the bias field. Even with these considerations the remainder of the data is too erratic to allow for any generalization about the behavior of the onset field separation as a function of temperature.

A plot of the onset frequency for each of the fingers of sample 1 is shown in Figure 4.5 (recall that finger 1 has two parts). All show a gentle increase in frequency with decreasing temperature except finger three. The dramatic jump in frequency for the third finger occurs as the second exchange branch moves from below to above the
Figure 4.4: Temperature dependence of the onset attenuation of the first four fingers of auto-oscillation for sample 1. The effect of the second exchange branch is visible in the minimum exhibited by finger 4.
low power position of the (0,3) mode and is most likely attributable to this change. The slight bump in the frequencies of the first and second fingers at 190 K may result from the further movement of the second exchange branch through the positions of the (0,2) and (0,1) modes. Unfortunately it is impossible to determine from the low power spectra since the exchange branch is too weak compared to the other modes to be seen directly and no visible distortion of the magnetostatic spectra is apparent. The reason for the jump in frequency of the first and second finger at 130 K is not known. Based upon the room temperature observations where larger mode separations led to higher onset frequencies, the gentle increase in frequency is consistent with the increase in mode spacing which occurs as the temperature decreases.

The measurements characterizing the temperature dependent behavior of the auto-oscillations for sample 2 are summarized in Table 4.7. As with sample 1, both the frequency and onset power are found to increase with decreasing temperature. With the exception of the measurements at 200 K, where the frequency of the klystron apparently drifted between the time of the low power measurements and the mapping of the auto-oscillations, the location of the onset relative to the associated magnetostatic mode appears fairly constant.

4.3 Field Orientation Effects

Having the external bias field aligned perpendicular to the film surface is a fundamental assumption of the derivation of the dispersion relations given in Section 2.3 and for the derivation of the equations of motion presented in Sections 2.4 and 2.5. As soon as the field is rotated off of perpendicular the symmetry which allows the motion to
Figure 4.5: Temperature dependence of the onset frequency of the first four fingers of auto-oscillation for sample 1. The abrupt jump in frequency for finger 3 is attributable to the influence of the second exchange branch.
Table 4.7: Temperature dependent measurements of the onset frequency (f), attenuation (Att), and separation between the onset and the associated magnetostatic mode ($\Delta H$) for the auto-oscillation fingers of sample 2.

<table>
<thead>
<tr>
<th>T (K)</th>
<th>f (MHz)</th>
<th>Att (dB)</th>
<th>$\Delta H$ (G)</th>
<th>f (MHz)</th>
<th>Att (dB)</th>
<th>$\Delta H$ (G)</th>
</tr>
</thead>
<tbody>
<tr>
<td>295</td>
<td>4.0</td>
<td>-10.0</td>
<td>1.1</td>
<td>6.8</td>
<td>-5.5</td>
<td>1.0</td>
</tr>
<tr>
<td>250</td>
<td>4.3</td>
<td>-10.5</td>
<td>1.1</td>
<td>7.5</td>
<td>-5.0</td>
<td>0.8</td>
</tr>
<tr>
<td>200</td>
<td>4.6</td>
<td>-9.0</td>
<td>2.6</td>
<td>7.9</td>
<td>-4.0</td>
<td>2.5</td>
</tr>
<tr>
<td>150</td>
<td>5.2</td>
<td>-6.0</td>
<td>1.9</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

be separated into a component along the bias field and a component transverse to this direction is destroyed. In an oblique configuration the saturation magnetization and the bias field are no longer colinear. Furthermore, the system begins to rise above the bottom of the spinwave band which provides coupling to an ever-increasing number of long wavelength magnons. The theoretical analysis of the oblique orientation has been studied by Kalinikos and Slavin [26] but does not yield readily modeled equations of motion. Even in the thin film geometry the coupling of additional spinwaves produces the same type of truncation problem associated with bulk samples.

Given that the alignment of the bias field has such an enormous impact on the theoretical analysis of the system and the experimental difficulty of attaining a highly
Table 4.8: Spacing of the magnetostatic modes ($\delta H_{mn}$) as a function of $\theta$, the angle between the resonant field and the plane of the film, for samples 1 and 2. ($\theta = 90^\circ$ is normal to the film plane.)

<table>
<thead>
<tr>
<th>$\theta$ (deg)</th>
<th>Sample 1</th>
<th>Sample 2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\delta H_{12}$</td>
<td>$\delta H_{23}$</td>
</tr>
<tr>
<td>90</td>
<td>2.7 (G)</td>
<td>2.7 (G)</td>
</tr>
<tr>
<td>88</td>
<td>2.5 (G)</td>
<td>2.8 (G)</td>
</tr>
<tr>
<td>86</td>
<td>2.4 (G)</td>
<td>3.4 (G)</td>
</tr>
<tr>
<td>84</td>
<td>2.4 (G)</td>
<td>3.6 (G)</td>
</tr>
<tr>
<td>82</td>
<td>2.4 (G)</td>
<td>4.2 (G)</td>
</tr>
<tr>
<td>80</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>78</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>76</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

accurate alignment, the auto-oscillatory behavior of the four samples was examined as a function of the orientation of the bias field. Tables 4.8 and 4.9 list the low power observations of the spacing between the various magnetostatic modes for each sample. The angle, $\theta$, is defined as the angle between the plane of the film and the direction of the bias field so that $\theta = 90^\circ$ corresponds to the perpendicular alignment used in the experimental work presented in Sections 4.1 and 4.2. For each sample the measurements cease either because it was no longer possible to delineate the higher order modes or, in the case of the last measurement listed for each sample, because that angle marks the beginning of a region with dramatically different auto-oscillatory behavior.
Table 4.9: Spacing of the magnetostatic modes ($\delta H_{mn}$) as a function of $\theta$, the angle between the resonant field and the plane of the film, for samples 3 and 4. ($\theta = 90^\circ$ is normal to the film plane.)

<table>
<thead>
<tr>
<th>$\theta$ (deg)</th>
<th>Sample 3</th>
<th>Sample 4</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\delta H_{12}$</td>
<td>$\delta H_{23}$</td>
</tr>
<tr>
<td>90</td>
<td>4.2</td>
<td>3.9</td>
</tr>
<tr>
<td>88</td>
<td>4.3</td>
<td>3.9</td>
</tr>
<tr>
<td>86</td>
<td>4.3</td>
<td>3.8</td>
</tr>
<tr>
<td>84</td>
<td>4.4</td>
<td>3.7</td>
</tr>
<tr>
<td>82</td>
<td>4.4</td>
<td>3.6</td>
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<tr>
<td>80</td>
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</tr>
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<td>78</td>
<td>4.2</td>
<td>3.0</td>
</tr>
<tr>
<td>76</td>
<td>4.1</td>
<td>2.5</td>
</tr>
<tr>
<td>74</td>
<td>3.9</td>
<td>2.1</td>
</tr>
<tr>
<td>72</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>
Sample 1 shows a slight decrease in spacing between both the (0,1) and (0,2) modes and the (0,2) and (0,3) modes as the bias field rotates away from perpendicular. In contrast, the spacing between the (0,3) and (0,4) modes was found to increase, an effect no doubt related to the influence of the second exchange branch which is located between those two modes. For sample 2, no change in mode spacing was observed. The spacing between the (0,1) and (0,2) modes for sample 3 fluctuates somewhat indicating either a fair degree of experimental error or perhaps the influence of some of the hidden modes. Recall that this sample produced a two-part first finger of auto-oscillation which is indicative of hidden mode interactions. The spacing between modes (0,2) and (0,3) shows a gradual decrease, while for the range over which it was measurable the (0,3) to (0,4) spacing appears constant. Finally, for sample 4, disregarding the measurement at 80° as an obviously bad data point, all of the measured spacings show a gradual decrease as the field rotates away from perpendicular. The overall trend appears to be that rotation of the bias field away from the film normal decreases the separation between the magnetostatic modes. Based upon the room temperature observations of the effect of mode spacing, such a decrease in mode separation is expected to produce decreasing onset frequencies and increasing onset attenuations.

The low power observations of the linewidth were not observed to change with angle for samples 1, 2 and 3. For sample 4, some variation was found (≈ 0.2 G), but it was of the same order as the variations which have been observed during repeated measurements of the linewidth in the perpendicular orientation. Such changes can be easily generated by varying the settings used on the lock-in amplifier or by changing
the speed at which the bias field is swept. Because of these effects and the results for the other samples, the observed variations found for sample 4 are best attributed to experimental error and the linewidth assumed constant.

Table 4.10 lists the onset frequency and attenuation for the most prominent fingers of samples 1 and 2. A graphical display of these results is shown in Figure 4.6. The labeling of the fingers is in accordance with that which was used in section 4.1. No measurements of the location of the onset relative to the associated magnetostatic mode, $\Delta H$, are listed because of the difficulty of obtaining an accurate measurement of the location of the higher order modes at oblique angles.

For sample 1 the onset frequency was found to decrease for the first finger and increase for the second. In addition, the second finger produced a high frequency component at oblique angles which can probably be attributed to hidden mode interactions. For both fingers the onset attenuation was found to decrease, indicating that less power was necessary to excite the nonlinear response. Beyond $82^\circ$ no auto-oscillations were found for this sample.

In the case of sample 2, the onset frequency of the second finger first increases then drops dramatically and splits into two low frequency parts typical of the hidden mode interactions seen in samples 1 and 3. Finger four shows a gradual decrease in frequency and the loss of its high frequency component as the angle decreases. With the exception of the lower frequency component of the second finger found at the more oblique angles, the onset attenuation gradually decreases for both fingers. For this sample, the auto-oscillatory behavior found at $76^\circ$ was markedly different than that
Table 4.10: Auto-oscillation onset frequency (f) and attenuation (Att) as a function of the angle of the resonant field with respect to the film plane (θ) for the most prominent fingers of samples 1 and 2.

<table>
<thead>
<tr>
<th>Sample</th>
<th></th>
<th></th>
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<th></th>
<th></th>
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<tbody>
<tr>
<td>Finger</td>
<td>1</td>
<td>2</td>
<td>Finger</td>
<td>1</td>
<td>2</td>
<td>Finger</td>
<td>1</td>
<td>2</td>
<td>4</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>θ (deg)</td>
<td>f (MHz)</td>
<td>Att (db)</td>
<td>f (MHz)</td>
<td>Att (db)</td>
<td>f (MHz)</td>
<td>Att (dB)</td>
<td>f (MHz)</td>
<td>Att (dB)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>90</td>
<td>4.0</td>
<td>-12.0</td>
<td>4.0</td>
<td>-8.5</td>
<td>4.0</td>
<td>-10.0</td>
<td>6.8</td>
<td>-5.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>88</td>
<td>3.9</td>
<td>-12.0</td>
<td>4.1</td>
<td>-9.0</td>
<td>4.0</td>
<td>-10.0</td>
<td>6.7</td>
<td>-5.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
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<td>4.8</td>
<td>-10.5</td>
<td>4.1</td>
<td>-9.0</td>
<td>6.8</td>
<td>-5.0</td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>84</td>
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<td>-</td>
<td>-</td>
<td>4.4</td>
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<td>-5.0</td>
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<td></td>
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<td></td>
</tr>
<tr>
<td>82</td>
<td>0.4</td>
<td>-14.5</td>
<td>-</td>
<td>-</td>
<td>5.2</td>
<td>-7.0</td>
<td>6.1</td>
<td>-5.0</td>
<td></td>
<td></td>
<td></td>
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<td>-</td>
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<td>-</td>
<td>-</td>
<td>2.1</td>
<td>-7.5</td>
<td>-</td>
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<td></td>
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<tr>
<td>78</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>1.8</td>
<td>-7.5</td>
<td>-</td>
<td>-</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
previously recorded. At 78° the auto-oscillation map consists of just two small regions of rather weak oscillations attributed to the second finger. Rotation of the bias field by an additional 2° produced a much stronger oscillatory signal which mapped as a large, single finger ranging from 1 to 2 G wide and extending from 0 to -6 dB attenuation. As the bias field was swept to higher values the oscillation would first appear as a weak kilohertz excitation and would rapidly progress to a very well-defined 1 MHz signal (the first directly measurable frequency was 1.3 MHz). It would then continue to roughly 2 MHz where it would weaken and vanish. This finger exhibited very little variation over the entire range of attenuation. The two most striking details of this behavior are the increasing frequency as the bias field is increased and the gradual, rather than abrupt, onset. Both of these features are in opposition to the behavior seen when the bias field is closer to the perpendicular orientation. As the bias field was rotated further away from 90° this finger persisted with almost no variation in the first measurable frequency even though the onset attenuation was found to decrease somewhat. Finally at an angle of 66° the auto-oscillations either ceased to exist or at least ceased to be strong enough to measure.

The auto-oscillatory behavior of samples 3 and 4 is summarized in Table 4.11, using the same conventions already noted for Table 4.10, while graphical results are again shown in Figures 4.6 and 4.7. For the low-frequency component of the first finger of sample 3 the onset frequency was found to fluctuate with no apparent trend, while the high-frequency component gradually decreased in frequency. For the second finger a two-part finger emerged at 84°. The overall trend for both parts was found to
be toward lower frequencies at more oblique angles. For the low-frequency component of the first finger the attenuation clearly increased with angle, indicating the need for less power to excite the interaction. Unfortunately, no such clear behavior was found in the attenuation measurements for the other part of finger one or in either part of finger two. Just as with sample 2, a dramatic change in the observed auto-oscillations occurred, in this case as the bias field was rotated from 76° to 74°. Again a strong, single finger was born with the same characteristics found in that of sample 2. The first measurable frequency was 1.3 MHz at an attenuation of -8.0 dB. The last angle at which any auto-oscillations could be tracked was 66°.

In contrast to the mixed trends found in all of the other samples, those for sample 4 are clear. For finger one the onset frequency was found to decrease and the onset attenuation increased as the bias field was rotated away from the film normal. The onset frequency for finger three likewise decreased, but in this case the attenuation decreased as the field was rotated. The small regions denoted as fingers two and four in the analysis of the room temperature results could not be tracked as the angle of the bias field was varied due to their rapid disappearance. Sample 4 was actually the first sample in which the transition to a very different finger of auto-oscillation was found. In this case the transition was noted at 72°, but because it was the first sample found to exhibit this behavior an additional data point was taken at 73° where the transition was also found. Its general behavior is the same as that already documented for samples 2 and 3. The first measurable frequency was 1.4 MHz at -8.0 dB attenuation and the last angle where oscillations could be tracked was 65°.
Table 4.11: Auto-oscillation onset frequency ($f$) and attenuation ($A_{tt}$) as a function of the angle of the resonant field with respect to the film plane ($\theta$) for the most prominent fingers of samples 3 and 4.

<table>
<thead>
<tr>
<th>$\theta$ (deg)</th>
<th>Sample 3 Finger 1</th>
<th>Sample 3 Finger 2</th>
<th>Sample 4 Finger 1</th>
<th>Sample 4 Finger 3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$f$ (MHz)</td>
<td>$A_{tt}$ (dB)</td>
<td>$f$ (MHz)</td>
<td>$A_{tt}$ (dB)</td>
</tr>
<tr>
<td>90</td>
<td>2.5</td>
<td>-8.0</td>
<td>6.4</td>
<td>-7.0</td>
</tr>
<tr>
<td>88</td>
<td>2.4</td>
<td>-10.0</td>
<td>6.4</td>
<td>-8.0</td>
</tr>
<tr>
<td>86</td>
<td>2.7</td>
<td>-10.5</td>
<td>6.5</td>
<td>-7.5</td>
</tr>
<tr>
<td>84</td>
<td>2.8</td>
<td>-11.0</td>
<td>6.0</td>
<td>-6.0</td>
</tr>
<tr>
<td>82</td>
<td>2.6</td>
<td>-12.0</td>
<td>5.6</td>
<td>-6.5</td>
</tr>
<tr>
<td>80</td>
<td>2.8</td>
<td>-12.5</td>
<td>5.0</td>
<td>-6.5</td>
</tr>
<tr>
<td>78</td>
<td>2.6</td>
<td>-13.5</td>
<td>4.8</td>
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<td>-7.5</td>
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<tr>
<td>74</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>
Figure 4.6: Angular dependence of the onset attenuation for the most prominent auto-oscillation finger of each sample. No consistent trend is apparent from this data.
Figure 4.7: Angular dependence of the onset frequency for the most prominent auto-oscillation finger of each sample. The angular effect is clearly not significant within 4° of perpendicular.
From all of this data general conclusions about the behavior of the auto-oscillations as the bias field is rotated away from the film normal indicate that for the low frequency part of the first finger the onset frequency will decrease accompanied by an increase in attenuation. For the higher order fingers a more oblique orientation again leads to lower onset frequencies but the data for onset attenuation is inconclusive. The results for frequency and the trend to increases attenuation for the low frequency part of the first finger are consistent with what would be expected on the basis of the decreasing mode spacing. The effect of rotating the bias field appears minimal within 4° of the perpendicular orientation. This is clearly good news for experiments which are performed in the perpendicular orientation since it is doubtful that the alignment of the bias field is ever better than ±1°. Beyond 86° the influence of the angular effects becomes quite noticeable as the frequencies begin to deviate significantly from the values at 90°. It is apparently in the vicinity of 85° that the increased coupling to other spinwaves begins to strongly influence the behavior of the system.

As for the transition to a region with fundamentally different auto-oscillatory behavior, it appears that the nature of the underlying bifurcation has changed at these angles. At perpendicular the auto-oscillations are well modeled by the generation of a Hopf bifurcation in the equations of motion. It awaits the development of a numerically viable set of equations of motion at oblique angles to test whether the underlying bifurcation has indeed changed.

In a recent work by Marcelli and Slavin [18] the threshold for nonlinear behavior was investigated for the case of parallel pumping as the bias field was rotated
relative to the film normal. In this case the highest threshold power for the onset of nonlinearities was found to occur at about 73° for room temperature YIG. While not directly applicable to the data presented in this dissertation, it is significant that the same fundamental interactions underlie both systems and in the case of perpendicular pumping the highest threshold can be expected to occur roughly around 60 to 65°. This would correlate well with the experimental observations of where the auto-oscillations cease.

A summary of the characteristics of the transition region for each of the three samples in which it was found is presented in Table 4.12. Why no such region was found in sample 1 may be due to the large number of competing interactions from the hidden modes and the presence of the second exchange branch. More than just the presence of the hidden modes must be at work however, because sample 3 was also shown to have hidden mode interactions yet it still produced a transition region. Recall that sample 1 is also the least truly circular sample. Perhaps this aspect contributes significantly to the absence of the transition region.
Table 4.12: Summary of the auto-oscillation transition region: angle, measured from the film plane, at which the transition region starts ($\theta_{\text{start}}$) and ends ($\theta_{\text{end}}$), the onset frequency ($f$), and the onset attenuation ($\text{Att}$).

<table>
<thead>
<tr>
<th>Sample</th>
<th>$\theta_{\text{start}}$ (deg)</th>
<th>$\theta_{\text{end}}$ (deg)</th>
<th>$f$ (MHz)</th>
<th>$\text{Att}$ (dB)</th>
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<tr>
<td>1</td>
<td>-</td>
<td>-</td>
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<tr>
<td>2</td>
<td>76</td>
<td>66</td>
<td>1.3</td>
<td>-6.0</td>
</tr>
<tr>
<td>3</td>
<td>74</td>
<td>66</td>
<td>1.3</td>
<td>-8.0</td>
</tr>
<tr>
<td>4</td>
<td>73</td>
<td>65</td>
<td>1.4</td>
<td>-8.0</td>
</tr>
</tbody>
</table>
CHAPTER V
Model Results

5.1 General Features

Before presenting the numerical results for comparison with the experimentally observed auto-oscillation maps, there are some general features of the model which must be discussed. The model has two primary modes of operation labeled "single" and "sweep". In the "single" mode, data is generated for just one point in the attenuation-bias field variable space. The output data which results includes the simulated signal and its Fourier transform as well as a time series of the individual mode amplitudes and phases. Initial conditions for the mode amplitudes may be input directly by the user or they may be generated internally. When run with internal generation the option exists to assume that all the initial mode amplitudes are zero. A more realistic option, designed to simulate experimental practices, is to generate initial mode amplitudes by approaching the point of interest either from above or below in either bias field or attenuation. This is accomplished, for the case of approaching the point from a lower bias field, by assuming zero mode amplitudes at a point 10 G below the point of interest then incrementally sweeping the system up to the intended field. At each intermediate field value the equations of motion are integrated long enough for
the system to adapt to the new field value. Upon reaching the intended bias field, the current mode amplitudes are then used as the initial mode amplitudes and the single point analysis proceeds. A similar procedure is followed for the case of approaching the point from above in bias field as well as for both possible approaches in attenuation. This approach has been quite successful, providing amplitudes representative of both the low and the high amplitude states of the system. The time span and the time increment are both established by the user, although a minimum of 2048 data points are generated for producing the FFT of the simulated signal.

The "sweep" mode of operation is intended to simulate the process of taking an auto-oscillation map. The user establishes upper and lower limits for both the attenuation and the bias field then specifies an increment for each. This establishes a grid of points in the variable space, each of which is then examined for auto-oscillatory behavior. The order in which points are checked can be either upfield from the lower bias field limit or downfield from the upper limit, the typical experimental approaches. Initial values for the mode amplitudes are assumed to be zero at the starting point of a sweep for each value of the attenuation. It is thus important that the starting limit be a few gauss away from where the nearest auto-oscillatory point is expected to occur. As the process moves along the bias field at fixed attenuation the initial mode amplitudes for successive points are taken to be the final values associated with the previous point. In order for the system to settle into amplitudes appropriate for the new coordinates, the equations of motion are integrated for a brief time. The length of the integration may be extended if certain conditions indicate the solution is
numerically unstable. At this junction the stationary state solution to the equations of motion are obtained, the Jacobian is evaluated based on that solution, and the eigenvalues and eigenvectors of the Jacobian are determined. If any complex pair of eigenvalues has a positive real part then the point is labeled as auto-oscillatory, with the frequency given by the magnitude of the imaginary part of the eigenvalues. While generally quite accurate at predicting onset values, this method of establishing the auto-oscillation frequency is not reliable where more complex interactions exist, such as those which occur where different fingers merge. In such instances the "single" mode should be used to reliably identify the frequency. In addition, there has been one instance in this work where the strongest frequency found by using the "single" mode to reproduce a time series was actually the second harmonic of the frequency derived from the imaginary part of the eigenvalues. These caveats aside it is still the most efficient method of re-creating experimental auto-oscillation maps. The output from this operating mode includes the bias field, attenuation, number of eigenvalues with positive real parts, auto-oscillation frequency, and initial mode amplitudes for each auto-oscillatory point found. Once the sweep is completed a summary file is written and a simulation of the low power (-30 dB) signal, extending over the total range of the bias field, is produced.

No matter which mode of operation is being used, there are several input variables that the user needs to specify. The most important, of course, is which modes to include and what their resonant fields are at low power. The choice of which modes is entirely dependent upon what has been observed experimentally, though typically the
first five direct modes are a good starting point. The direct mode locations should be input based entirely upon their locations as measured at low power experimentally. Relative values are perfectly acceptable since only the differences between the bias field and location of the resonance enter the equations of motion. The usual procedure is to shift the (0,1) resonance to 20 G and then record the other mode locations relative to that value. The hidden modes are typically responsible for the low frequency (0.5 to about 2 MHz) fingers and may need to be included if such fingers have been seen in the experimental data. Of course they are hidden in the low power experimental spectra, so the locations of these modes should be based upon a linear fit of the locations of the direct modes to the Bessel function zeros. While the true dipole moment, \( J^* \), of a hidden mode is zero, it is set to a value of about 2% of the dipole moment of the (0,1) mode in the model. This small value has been found necessary for the appearance of the low frequency parts of the first finger.

The user must also input the linewidth, a value which should come from the low power experimental observations. Before modeling a particular sample it is also necessary to determine if the observed modes are associated with a uniform magnetization across the thickness of the film or one of the higher exchange branches. This is an important option which the user must specify because for an exchange branch the interaction parameters, \( A_{ijkl} \) are 1.5 times larger than those associated with uniform magnetization while the dipole moments, \( J^*_j \), are reduced by a factor of \( \frac{2\sqrt{2}}{n\pi} \) where \( n \) is the order of the exchange branch (0.9 for \( n = 1 \)). A number of other inputs exist which are designed for flexibility in the use of the model. These include, with
typical values at room temperature given in parentheses: the saturation magnetization, $4\pi M_s$ (1760 G); the microwave power at 0 dB, $P_0$ (50 mW); the frequency width of the cavity, $\Delta f$ (4 MHz); and a number of limits associated with the IMSL mathematical routines used in the program.

Before comparing any results from the simulation to experimental observations, it is important to note the possible difference in sensitivity which exists between the two methods. Experimentally a strong auto-oscillation produces an amplitude of about 15 mV which is rather easy to detect and identify. Unfortunately not all of the observed oscillations are this strong. The noise level of the electronics is roughly 1 mV, which presents no problem for strong oscillations but certainly obscures the weakest ones. If the initial onset consists of a relatively weak oscillation, then it may not be detectable within the limitations of the experimental apparatus. No such limitation exists within the simulation. The criteria for the presence of an auto-oscillation is simply having a complex pair of eigenvalues with a positive real part. There is no assessment of the relative strength of the oscillation, nor is it apparent how a lower limit could be established to provide one. It is therefore important to remember when comparing model results to those of the experiments that the model may very well predict auto-oscillations which are too weak to be recorded.

5.2 Room Temperature Results

Using the low power experimental measurements summarized in Tables 3.2 and 4.1 as input data, numerical results were generated for each of the samples at room temperature. Samples 1, 2, and 3 were modeled as first exchange branches, while
sample 4 was assumed to have uniform magnetization across the sample thickness. Since both samples 1 and 3 produced two-part first fingers experimentally, hidden modes were included in their models. Only direct modes were used for samples 2 and 4 because the inclusion of hidden modes produces finger structures not seen experimentally.

The most extensively studied sample was number 1. Starting with a five mode model using the (0,1), (0,2), and (0,3) direct modes coupled with the (1,1) and (2,1) hidden modes, results were generated for a variety of linewidths. Placing the (0,1) mode at 20 G, the (1,1) mode resides at 18.7 G while the (2,1) is at 17.6 G. Except for the largest linewidth where only a single first finger exists, this choice of modes produces a two-part first finger and a third finger. Results summarizing the onset frequency, attenuation, and bias field separation between the onset point and the associated low power resonance are provided in Table 5.1.

The trend in attenuation is obvious: as the linewidth increases the power required for onset increases so the attenuation is seen to decrease. Similarly the trend that larger linewidth produces an increased field separation between the onset and the associated low power resonance is clearly evident, and is an effect tied closely to the required increase in power. From an examination of direct absorption spectra it is possible to track where the system jumps from a low to a high amplitude state (the foldover point). As the power to the sample is increased, experimental observations show that these points always move to lower bias fields. Since the onset of auto-oscillatory behavior is generally associated with where these jumps take place, it
Table 5.1: Numerical predictions of the onset frequency (f), attenuation (Att), and field separation between the onset and the associated low power resonance (ΔH) for the two-part first finger and the third finger of sample 1 as a function of linewidth (Γ).

<table>
<thead>
<tr>
<th>Γ (G)</th>
<th>f (MHz)</th>
<th>Att (dB)</th>
<th>ΔH (G)</th>
<th>f (MHz)</th>
<th>Att (dB)</th>
<th>ΔH (G)</th>
<th>f (MHz)</th>
<th>Att (dB)</th>
<th>ΔH (G)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.3</td>
<td>1.6</td>
<td>-16.6</td>
<td>2.1</td>
<td>3.7</td>
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<td>5.2</td>
<td>-11.6</td>
<td>1.2</td>
</tr>
<tr>
<td>0.5</td>
<td>1.0</td>
<td>-14.0</td>
<td>2.2</td>
<td>3.7</td>
<td>-13.0</td>
<td>2.8</td>
<td>5.6</td>
<td>-8.8</td>
<td>1.5</td>
</tr>
<tr>
<td>0.7</td>
<td>0.7</td>
<td>-11.6</td>
<td>2.6</td>
<td>3.6</td>
<td>-10.4</td>
<td>3.2</td>
<td>5.9</td>
<td>-6.2</td>
<td>1.6</td>
</tr>
<tr>
<td>0.9</td>
<td>0.7</td>
<td>-9.0</td>
<td>3.2</td>
<td>3.7</td>
<td>-8.4</td>
<td>3.7</td>
<td>7.2</td>
<td>-3.4</td>
<td>2.3</td>
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<td>-</td>
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<td>-6.8</td>
<td>4.0</td>
<td>8.7</td>
<td>-0.6</td>
<td>2.3</td>
</tr>
</tbody>
</table>

follows that when they move to a lower field value the separation from the resonance associated with an auto-oscillation onset will increase.

The onset frequency, however, is a curious beast. For the first part of finger one it is observed to decrease with increasing linewidth while at the same time the frequency for finger three is found to increase. To make matters more confusing the onset frequency of the second part of the first finger remains constant throughout the process. No obvious explanation for the frequency observations suggests itself, but it would be very interesting to examine experimentally the effect which increasing linewidth on identical size samples would produce.

The experimental linewidth for sample 1 at room temperature is 0.7 G. Results from the five mode model used in the linewidth study are not very impressive when
compared with the experimental observations. The onset frequencies for finger one differ by 0.7 (50%) and 0.5 MHz (12%) respectively, while that for finger three is off by 2.5 MHz (74%). Onset attenuations fare no better, with variations of 3.4 (23%), 2.6 (20%), and 4.8 dB (44%) for each of the fingers. The field separation does best, being off by only 0.3 (13%), 0.1 (3%), and 0.4 G (33%). Finally, there is the experimentally observed second finger which the model completely fails to reproduce.

Ignoring the last point for the moment, what happens if the results from the model using a linewidth of 0.5 G are compared to the experimental observations? For the onset frequency the differences are now off by 0.4 (29%), 0.4 (10%), and 2.2 MHz (65%) for the two parts of the first finger and the third finger respectively. This is a slight improvement, but still not terribly impressive. Things look a lot better for the attenuation values though with variations of only 1.0 (7%), 0, and 2.2 dB (20%). Field separation still does quite well with differences of 0.1 (4%), 0.5 (15%), and 0.3 (25%) for each of the fingers. A substantial improvement in the results for the low frequency part of the first finger is possible if the initial onset is disregarded and the next lower value of the attenuation is examined. Rather than the -14.0 dB results quoted above, at -13.8 dB the onset frequency is 1.4 MHz with a field separation of 2.4 G. These differ from the experimental values by 1.2 dB (8%), 0 MHz, and 0.1 G (4%). This is not an unreasonable suggestion since it may well be that the model is more sensitive than the experimental apparatus, making it capable of predicting some parts of fingers which may be too weak to detect.
On the basis of the improvement in attenuation and the knowledge that the models for the other samples all performed reasonably well in predicting onset attenuation, the smaller linewidth is a more appropriate choice for modeling sample 1. It may well be that the experimental value is too large, since the effects of the sweep rate and the settings of the lock-in amplifier have been found to produce artificially large linewidths.

There is still the problem of the missing second finger. In an attempt to produce one, the capacity of the computer model was expanded from its original upper limit of five modes to its present capacity of seven modes. The five mode model used in the linewidth study, with a linewidth of 0.5 G, was then expanded to include the (0,4) direct mode and the (3,1) hidden mode which is located at 16.6 G. It was a limited success in that a second finger was indeed born at -11.0 dB, a difference of 2.0 dB (15%) from the experimental value, with a mode spacing of 1.7 G which is 0.3 G (15%) off, but unfortunately it has a frequency of 2.6 MHz which differs by 1.9 MHz (42%) from the experimental value. Evaluation of a point in the interior of this finger using the “single” mode of operation revealed that from the generated time series the strongest frequency is in fact the second harmonic of the eigenvalue predicted frequency. At a value of 5.1 MHz such a result differs by only 0.6 MHz (13%) from the experimental value. Alternatively, following up along this finger as the attenuation is decreased, the eigenvalue predicted frequency shifts abruptly at -10.4 dB, near where the first and second fingers converge. At this point the frequency is 4.7 MHz, a difference of only 0.2 MHz (4%) from the experimental value.
As for the variation in attenuation, that increases to 2.6 dB (20%) while the difference in field separation decreases to 0.1 G (5%). Either of these approaches yields results which do a very good job of replicating the experimental observations of a second finger. Figure 5.1 shows a comparison of the experimentally observed map of the first and second fingers with that generated by the seven mode model. While specific characteristics require careful analysis, the overall structure of the simulation map replicates the experimental observation beautifully. As for the behavior of the other fingers in going from the five to the seven mode model, the first changed only slightly while the third and fourth exhibited dramatically different characteristics.

Numerous other models for sample 1 have been examined, but none have produced any better results than the seven mode model just discussed. Substitution of the (1,2) hidden mode for the (2,1) mode failed to produce the low frequency component of the first finger. Likewise, eliminating either the (1,1) or the (2,1) mode prevented the model from producing a low frequency part to the first finger. Models based solely on direct modes failed to produce any better results than the mixed models, and often times were worse depending on which modes were missing from the model. No doubt part of the difficulty in modeling sample 1 stems from the influence of the second exchange branch and the many hidden mode interactions which seem to be present. Taking all of this into account, the results of the seven mode model using a 0.5 G linewidth are summarized in Tables 5.2 and 5.3 along with the best model estimates of the room temperature results for the other samples.

For sample 2 five direct modes were used: (0,1), (0,2), (0,3), (0,4) and (0,5). No
Figure 5.1: An expanded view of the first and second fingers of Sample 1 as mapped (A) experimentally and (B) by the seven mode model.
Table 5.2: Numerical predictions of the onset frequency ($f$), attenuation ($A_{tt}$), and field separation between the onset and the associated low power resonance ($\Delta H$) for fingers 1 and 2 of the room temperature auto-oscillation maps.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Finger</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$f$ (MHz)</td>
<td>$A_{tt}$ (dB)</td>
<td>$\Delta H$ (G)</td>
</tr>
<tr>
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<td>2.2</td>
</tr>
<tr>
<td></td>
<td>3.6</td>
<td>-12.8</td>
<td>2.8</td>
</tr>
<tr>
<td>2</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
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<td>-8.2</td>
<td>3.4</td>
</tr>
<tr>
<td></td>
<td>5.7</td>
<td>-7.0</td>
<td>4.3</td>
</tr>
<tr>
<td>4</td>
<td>5.9</td>
<td>-8.2</td>
<td>3.8</td>
</tr>
</tbody>
</table>

Table 5.3: Numerical predictions of the onset frequency ($f$), attenuation ($A_{tt}$), and field separation between the onset and the associated low power resonance ($\Delta H$) for fingers 3 and 4 of the room temperature auto-oscillation maps.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Finger</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>3</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$f$ (MHz)</td>
<td>$A_{tt}$ (dB)</td>
<td>$\Delta H$ (G)</td>
</tr>
<tr>
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<td>5.5</td>
<td>-5.4</td>
<td>2.6</td>
</tr>
<tr>
<td></td>
<td>13.1</td>
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</tr>
<tr>
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<td>6.1</td>
<td>-4.4</td>
<td>3.8</td>
</tr>
<tr>
<td>4</td>
<td>20.0</td>
<td>-3.2</td>
<td>2.6</td>
</tr>
</tbody>
</table>
first finger was produced by this model, an observation which agrees with experiment. The results for finger 2 are reasonably good, differing from the experimental values by 0.8 MHz (20%) in frequency, 0.2 dB (2%) in attenuation, and 0.3 G (27%) in field separation. Unfortunately a third finger shows up in the simulation which is not seen experimentally. Just as in those results however, the fourth finger exhibits a two-part presence in the model, although only the high frequency component is well modeled, differing from experiment by 0.2 MHz (2%), 1.8 dB (45%), and 0.1 G (5%).

The model was also run with the linewidth reduced from 0.8 to 0.6 G. There was no significant change in the onset frequencies, the onset attenuations were further degraded from the experimental values, and the low frequency portion of the fourth finger vanished. Unlike sample 1, it appears that based upon these observations the experimentally measured linewidth is quite good. Alternatively, this particular model may just be insensitive to small variations in linewidth since no hidden modes are included.

The initial model for sample 3 used the (0,1), (0,2), and (0,3) direct modes with the (1,1) and (2,1) hidden modes located at 18.0 and 16.4 G, relative to the 20.0 G location of the (0,1) mode, respectively. Just as in the experimental map, a two-part first finger appears along with a third finger. Just as in the case of sample 1, the model produces no second finger even though one is observed experimentally. As for the specific results, the onset attenuation results are superb, differing by 3, 0 and 7% for the two parts of the first finger and the third finger respectively. Unfortunately the frequency results are not as good. They vary by 1.4 (56%) and 0.7 MHz (11%) for finger one.
and by 2.4 MHz (22%) for finger three. Recall from the discussion of the experimental results that the experimental measurements of $\Delta H$ for this sample are not reliable due to drift of the klystron frequency. Therefore, there is no point in attempting a comparison between those and the model values. While the onset frequency for the first part of finger one is quite poor in comparison with the experimental value, it is interesting to note that at the next lower power level, -8.0 dB, the observed frequency is 1.9 MHz, a 0.6 MHz (24%) difference, which is quite an improvement. Just as with sample 1, this may be an indication that in some ways the simulation is more sensitive than the experimental apparatus.

To test whether these results could be improved by changing the linewidth, it was reduced from 0.8 to 0.6 G. Doing so reduces the onset power thereby degrading the previous results for onset attenuation. The onset frequency for the first part of finger one improves to 2.2 MHz, a difference of 0.3 (12%) with experiment, while the second part remains unchanged. As for the third finger, its onset is reduced to 8.4 MHz, a 2.7 (24%) difference, which is worse. Just as with sample 2 it appears that the linewidth measurement for this sample is quite good.

In an attempt to generate a second finger for this sample the seven mode model was tried just as it was for sample 1. In this case the (3,1) mode is located at 14.9 G. What resulted was a two part first finger, along with fingers two and four but not three. The onset frequency for the second finger is 3.7 MHz which is quite poor when compared with the experimental value. However, a mere 0.2 dB less attenuation and the predicted frequency doubles to 7.3 MHz which matches the experimental value.
perfectly! As for the attenuation value of -4.8 dB, that differs by only 0.2 dB (4%) from that of the experiment. Since no fourth finger was found experimentally, the model either fails in this regard or is perhaps too sensitive. Results for the first finger improve slightly for the low frequency portion and do not differ substantially for the higher frequency component when compared to what the initial five mode model predicts. The values quoted in Tables 5.2 and 5.3 combine the second and fourth finger results from this model with those from the initial model for fingers one and three.

Experimentally sample 4 exhibited a single part first finger and a third finger, consequently it was modeled by the (0,1), (0,2), (0,3), and (0,4) direct modes. The simulation results produced a single first finger with a two part third finger. Comparison with the experimental data shows that the first finger is very well modeled. The onset frequency differs by 0.5 MHz (8%), attenuation is off by 0.2 dB (3%), while field separation is 1.0 G (21%) different. Similar agreement does not exist for the third finger results unless it can be assumed that what was observed experimentally was actually the second harmonic of the onset frequency. If that is true then the model frequency provides a good replication of the underlying dynamics. Experimentally, at a power level 3 dB higher than the onset both 12.2 and 6.1 MHz peaks appear, with the 12.2 MHz peak still the stronger of the two. It would be nice to interpret this as evidence supporting the model data, but more likely it represents a period-doubling bifurcation as the system moves along the path to chaotic behavior. As for the other two characteristics, the model differs by 0.2 dB (5%) in attenuation and 0.2 G (6%)
in field separation from the experimental observations. With the initial linewidth already at 0.6 G, no attempt was made at modeling this sample with a smaller value.

In order to better assess the capabilities of the numerical model to quantitatively simulate the auto-oscillatory behavior of the system, Figures 5.2, 5.3 and 5.4 have been generated and Tables 5.4 and 5.5 have been constructed. Using the experimental results presented in Tables 4.2 and 4.3 and the numerical results given in Tables 5.2 and 5.3, comparisons are shown only for those fingers where both experimental and model results exist. The percentage differences between the two results were computed for all of the onset characteristics common to both data sets. These results indicate that even for the higher order fingers the model does an excellent job of predicting the onset attenuation and field separation. The prediction of onset frequency appears to be the more challenging aspect, though at least in some cases the differences in frequency can be greatly reduced by assuming that the model predicts onsets at lower attenuations than can be seen experimentally.

5.3 Temperature Dependent Results

The temperature dependent behavior of samples 1 and 2 was modeled using the information contained in Table 4.4. Based upon its performance in the modeling of the room temperature results, a seven mode model was used for sample 1. It consisted of the (0,1), (0,2), (0,3) and (0,4) driven modes coupled with the (1,1), (2,1) and (3,1) hidden modes. The locations of the hidden modes were calculated from linear fits to the positions of the driven modes for each temperature. It was hoped that this model would produce the second finger seen experimentally, but with
Figure 5.2: Comparison of the experimental and simulation onset attenuations for all fingers common to both. Samples are labeled “S_” below the finger labels.
Figure 5.3: Comparison of the experimental and simulation onset field separations for all fingers common to both. Samples are labeled "S_" below the finger labels.
Figure 5.4: Comparison of the experimental and simulation onset frequencies for all fingers common to both. Samples are labeled “S_” below the finger labels.
Table 5.4: Percent differences between the experimental results and the numerical predictions for the onset frequency (f), attenuation (Att), and field separation ($\Delta H$) for fingers 1 and 2 of the room temperature auto-oscillation maps.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Finger</th>
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</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>f</td>
<td>Att</td>
</tr>
<tr>
<td></td>
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<td>-</td>
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<td>4</td>
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<td>11</td>
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</table>

Table 5.5: Percent differences between the experimental results and the numerical predictions for the onset frequency (f), attenuation (Att), and field separation ($\Delta H$) for fingers 3 and 4 of the room temperature auto-oscillation maps.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Finger</th>
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</tr>
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<tbody>
<tr>
<td></td>
<td></td>
<td>f</td>
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<td></td>
<td></td>
<td>(%)</td>
<td>(%)</td>
</tr>
<tr>
<td>1</td>
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</tr>
<tr>
<td>4</td>
<td></td>
<td>50</td>
<td>-5</td>
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the increased linewidth associated with decreasing temperature it failed to appear. As noted in the last section the experimental linewidth for sample 1 is larger than the model would indicate. For the case of a single temperature it was quite reasonable to run the seven mode model for multiple linewidths in an effort to better model the system. Rather than repeat that exercise for an additional eight temperatures, the experimental linewidth was used for each temperature in anticipation of tracking overall trends which could then be compared to the experimental results without optimizing the modeling of any one temperature. Table 5.6 summarizes the results of these simulations while Figures 5.5, 5.6, and 5.7 display them graphically.

As expected on the basis of its performance at room temperature, this model produced a two-part first finger, a third finger, and a two-part fourth finger. Only the lack of a second finger and the presence of a second part in the fourth finger differ from the experimental results. From Figure 5.5 it can readily be seen that as the temperature decreases the onset attenuation decreases for all of the fingers. This is a trend which agrees well with the experiment. The onset spacing in the model results tends to increase for all but finger three, where the data is inconclusive. Unfortunately the experimental data was too erratic to allow any comparison of trends. As for the onset frequency, the model results indicate a gradual increase with decreasing temperature for the high frequency part of finger 1 and for finger 3 which is just as was seen experimentally. The model results for the low frequency part of finger 1 and for finger 4 show a fair amount of fluctuation, but no significant trend with temperature.
Table 5.6: Numerical predictions of the onset frequency (f), attenuation (Att), and field separation between the onset and the associated low power resonance (ΔH) for the first, third and fourth fingers of sample 1 as a function of the sample temperature.

<table>
<thead>
<tr>
<th>T (K)</th>
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<th>3</th>
<th>4</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>f (MHz)</td>
<td>Att (dB)</td>
<td>ΔH (G)</td>
<td>f (MHz)</td>
</tr>
<tr>
<td>290</td>
<td>0.8</td>
<td>-11.6</td>
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<td>3.6</td>
</tr>
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<td>270</td>
<td>0.5</td>
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<td>2.6</td>
<td>3.9</td>
</tr>
<tr>
<td>250</td>
<td>0.6</td>
<td>-11.2</td>
<td>2.8</td>
<td>4.1</td>
</tr>
<tr>
<td>230</td>
<td>0.9</td>
<td>-11.0</td>
<td>2.9</td>
<td>4.3</td>
</tr>
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<td>-10.2</td>
<td>3.1</td>
<td>4.5</td>
</tr>
<tr>
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<td>-9.4</td>
<td>3.3</td>
<td>4.6</td>
</tr>
<tr>
<td>170</td>
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<td>-9.0</td>
<td>3.4</td>
<td>4.7</td>
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<td>-7.6</td>
<td>3.8</td>
<td>5.0</td>
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<tr>
<td>130</td>
<td>0.6</td>
<td>-6.2</td>
<td>4.3</td>
<td>4.8</td>
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</table>
Figure 5.5: Temperature dependent model predictions of the onset attenuation for the first four fingers of sample 1. These results reproduce quite nicely the experimental trend toward lower attenuation as the temperature decreases.
Figure 5.6: Temperature dependent model predictions of the onset field separation for the first four fingers of sample 1. No experimental data is available for comparison.
Figure 5.7: Temperature dependent model predictions of the onset frequency for the first four fingers of sample 1. The high frequency part of finger 1 and finger 3 model the experimental trend toward higher frequencies at lower temperatures, but the low frequency part of finger 1 and finger 4 are not consistent with experimental observations.
In order to model the temperature behavior of sample 2 the first five direct modes were used just as in the room temperature study. The results are given in Table 5.7 for the second and fourth finger. Just as in the room temperature model, a third finger appears in the model map which is not seen experimentally. The results for this finger were not tabulated since no comparison with experiment was possible. The fourth finger is comprised of two parts at room temperature, but at 250 and 200 K the model no longer produces a lower frequency component. At 150 K the low frequency part of finger four reappears, but now the high frequency part has been relegated to power levels above the maximum experimental level which actually agrees with the lack of a fourth finger in the experimental observations at this temperature.

For both the second and fourth fingers the model indicates that onset attenuation decreases with decreasing temperature. The onset frequency shows an increase with decreasing temperature for both finger two and the high frequency component of finger four. Likewise the onset spacing was found to increase with decreasing temperature, but only for finger two with the data for finger four being quite inconclusive. All of these general trends agree with both the experimental observations and the model results for sample 1.

These simulation results indicate that whatever causes the experimentally observed trends as a function of temperature is well modeled. So what changes in the numerical model account for the observed behavior? There are three inputs which vary with temperature: the low power spacing of the magnetostatic modes, the linewidth, and the saturation magnetization. Based upon the data given in Table 4.4
Table 5.7: Numerical predictions of the onset frequency (f), attenuation (Att), and field separation between the onset and the associated low power resonance (ΔH) for the first and fourth fingers of sample 2 as a function of the sample temperature.

<table>
<thead>
<tr>
<th>T (K)</th>
<th>f (MHz)</th>
<th>Att (dB)</th>
<th>ΔH (G)</th>
<th>f (MHz)</th>
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<td>1.9</td>
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</table>

All of these values increase with decreasing temperature. According to the dispersion relations given in Section 2.3, the increase in saturation magnetization produces the increase in mode spacing. From a comparison of the room temperature results for the four samples, it is apparent that an increase in mode separation yields higher onset frequencies and lower attenuations. Increasing the linewidth surely leads to lower attenuations, as was indicated by the various model runs for sample 1 given in Table 5.1. These same results indicate that the increasing linewidth may also contribute to the observed increase in onset frequency. According to the equations of motion, increasing the saturation magnetization also increases the strength of the nonlinear coupling. It would be interesting to experimentally investigate the influence of changing the saturation magnetization while maintaining the same mode separation. This could be accomplished by selectively doping the YIG and then carefully sizing it.
Using four circular, thin film samples of YIG, this work has investigated the influence of sample size, sample temperature, and the orientation of the bias field upon the observed auto-oscillatory behavior. Data taking consisted of mapping the regions in attenuation - bias field variable space where auto-oscillations were found and noting their frequency. The resulting maps consist of various fingers which can be associated with particular resonances on the basis of their onset location. The characteristics used to evaluate and compare the auto-oscillatory behavior of the different samples under different conditions were the onset frequency, onset attenuation, and the onset location (field separation) relative to the position of the associated resonance as measured at low power.

The spacing of the magnetostatic modes at low power depends upon the ratio of a sample's thickness to its diameter. Because of this relationship the four samples conveniently split into two groups of two which exhibit similar ratios and might therefore be expected to produce similar nonlinear behavior. Comparisons of the room temperature data confirmed this expectation as the results for the larger samples, 1 and 2, were quite similar as were those for the smaller pair, 3 and 4. Furthermore it was shown that the larger spacing associated with the smaller samples produced
higher onset frequencies and required higher power (lower attenuation) to excite auto-
oscillations.

The effects of reducing the sample temperature were investigated for two of the
samples. The reason for interest in this behavior stems from the observation that the
strength of the nonlinear coupling of the system is directly proportional to the mag-
nitude of the saturation magnetization, a quantity known to increase with decreasing
temperature. Furthermore the system damping is given by the linewidth which is also
expected to vary with sample temperature. For each sample the lower temperature
produced an increase in the linewidth and an increase in the spacing of the magne-
tostatic modes, though there appeared to be an upper limit to the increase in mode
separation. The overall trend in onset frequency was to slightly higher frequencies at
lower temperatures. Onset attenuation was found to decrease, indicating an increase
in onset power, as the temperature was lowered. Both of these trends are consistent
with the sample size effects noted at room temperature in that the increased mode
separation led to higher frequencies and lower attenuations. Measurements of the
onset field separation were too varied to provide useful generalizations. For one of
the samples an abrupt jump in the onset frequency of the third finger was attributed
to the influence of a shift in the position of the second exchange branch.

Changing the orientation of the bias field from normal to the film plane to oblique
angles destroys the symmetry which makes it possible to derive computationally at-
tractive equations of motion. An increased coupling to additional spinwaves can be
expected to influence the nonlinear behavior of the system in as yet unknown ways.
This possibility was investigated for all four samples by examining auto-oscillation maps at oblique angles. Low power observations of the magnetostatic mode spacings indicate that they tend to decrease as the angle of the bias field is rotated further away from the film plane normal. The trend for the first auto-oscillation finger was found to be that a more oblique angle for the bias field produced a decrease in onset frequency and an increase in attenuation. Based upon the room temperature investigations into the influence of sample size, these trends are consistent with the observed decrease in mode spacing. Higher order fingers were also found to produce lower onset frequencies with increasingly oblique fields, but in these cases the onset attenuation was too erratic to allow for any definitive conclusion about its behavior. A review of both the onset attenuation and frequency results indicates that the orientation effects do not become significant until the bias field is more than $4^\circ$ away from the film plane normal.

In three of the four samples a most interesting region of auto-oscillations was found when the bias field was rotated about $15^\circ$ away from the film plane normal. The behavior of the auto-oscillations in this region was found to be fundamentally different from the behavior typical of those found with the bias field nearer to the film plane normal. The map reduced to a single, strong finger. No hysterisis exists as the bias field is first increased from below the auto-oscillation onset and then reduced from above the onset. The frequency and amplitude of the oscillation remained quite uniform over the entire extent of the finger, exhibiting an onset frequency of about $1.3 \text{ MHz}$ for all three samples despite their different sizes. Further rotation of the bias
field led to a point beyond which no auto-oscillations were found. This orientation
may be explicable on the basis of the work of Slavin [18], but his work is based upon
the parallel pumping configuration so further theoretical development needs to be
done.

Using a numerical simulation developed from the equations of motion for the
case of the bias field normal to the film plane, model results were generated in an
attempt to replicate the experimental observations at room temperature for all four
samples and for the temperature dependent observations. Varying which modes were
included in the model and examining the amplitudes of those modes allowed the
identification of hidden mode interactions influencing the experimental observations
for two of the samples. Overall results for the four samples indicated that the model
does an excellent job of predicting the onset attenuation and field separation. While
not as adept at matching the onset frequencies, considerable improvement is possible,
without seriously degrading the attenuation and field separation results, by assuming
that the noise level of the experiment is such that the simulation is more sensitive
to the onset of auto-oscillations. The experimental trends found by decreasing the
sample temperature were well reproduced by the simulation.

These results naturally lead to suggestions for further study. Both the room
temperature, sample size dependent results and those of the temperature dependent
study were limited by the power output of the klystron. It would be very interesting
to observe what additional changes occur at higher power levels in both instances.
In part the temperature dependent study illustrated the influence of the saturation
magnetization on the strength of the nonlinear coupling, but it was confounded by an accompanying increase in the linewidth. Perhaps it would be instructive to examine similar circumstances from an entirely different set of material parameters. This could be achieved by producing a set of selectively doped samples which would again yield a variation in both the saturation magnetization and the linewidth. It would likewise be interesting to check the behavior of such samples as the orientation of the bias field is varied. Would they likewise exhibit a transition region such as that seen in three of the films used in this work? What about the temperature dependent behavior of the transition region? Would the onset frequency change? Would it still be the same for all three samples? As with most studies of this nature, the process of uncovering answers to one set of questions produces any number of subsequent questions. While much has been learned about auto-oscillatory phenomena during the past decade, a great deal more remains for future investigation.
Appendix A

Magnet Controller Program

QuickBASIC Controlling Routine for Magnet Controller M596A

Local variables:
- bas% - an output controller address
- bas1% - an output controller address
- bas2% - an output controller address
- bas4% - an input controller address
- bas7% - an output controller address
- centerfield% - the actual center field requested
- choice$ - the command hot-key corresponding to the user's menu choice
- delaycounter% - the scaled counter to be sent to the I/O board to produce the delay required for a given sweep time
- direction$ - the present direction of the sweep
- halfrange! - half of the sweep range
- inchar$ - the name of the function key entered
- maxfield% - the maximum value for the magnetic field as determined by the pole cap configuration
- mode$ - the command hot-key corresponding to the user's choice of mode
- pole$ - a flag to identify the pole cap configuration
- presentfield% - the present value of the magnetic field
- sweepinterrupt$ - an interrupt flag used to stop a sweep or change its direction
- sweeprange% - the total sweep range
sweeptime% - the total sweep time in minutes
( "0" = 30 secs )
vernier% - a fine-tuning adjustment to the
center field

Routines called:
BlankMenuSpace GoToCenter
DefineFunctionKeys GoToTop
DefineMenu ManualSweep
DisplayMenu SawtoothSweep
F9EnableOptions SetCenterField
F10EnableOptions SetSweepRange
F11EnableOptions SetVernierField
GetFunctionKey SingleStepSweep
GetMenuChoice StaticDisplay
GoToBottom TriangularSweep

Notes: All fields are in Gauss. The center field must be
positive and less than the maxfield value fixed by the
pole cap configuration. The identification of the
maximum allowable field by pole cap configuration is
meant to reduce the frequency of tripping the circuit
breaker for the magnet power supply. The sweep range is
restricted so that the bottom field is positive and the
top field is less than the maxfield value. The sweep
range must be larger than 2 Gauss or it scales to zero.
The vernier field is meant to allow the fine-tuning of
the center field, but has not been verified. Contact the
electronics shop if you need to implement it. The delay
timer is run off of the I/O board ( originally in hope
of eliminating machine dependence ) and a brief delay
has been included in the code as well because of some
communications timing problems that arose. The delay
times are calibrated only for the program loaded as a
stand-alone executable. The sweep counter is used to
indicate where in the sweep the field is located. The
top has a value of 47, the center value is 2047, and
the bottom corresponds to 4047. GPIB interfacing with
another computer has not been implemented in this
version of the routine. It is my intent that such an
interface would link-up with this routine through the
subroutine F11EnableOptions. Finally, the liberal use
of routines from the QuickBASIC book are explicitly granted by the author of the text in the introduction.

DECLARE SUB BlankMenuSpace (menu AS ANY)
DECLARE SUB BlankSweepMessage ()
DECLARE SUB DefineFunctionKeys (functionkeys() AS ANY)
DECLARE SUB DefineMenu (menuindex%, menu AS ANY, items() AS ANY)
DECLARE SUB DisplayBox (topline%, bottomline%, leftcol%, rightcol%)
DECLARE SUB DisplayDoubleBox (topline%, bottomline%, leftcol%, rightcol%)
DECLARE SUB DisplayMenu (menu AS ANY, items() AS ANY)
DECLARE SUB F9EnableOption (choice$, centerfield%, sweeprange%, sweeppcounter%, vernier%, maxfield%, pole$)
DECLARE SUB F10EnableOption (choice$, delaycounter%, sweeptime%)
DECLARE SUB F11EnableOption (choice$, mode$)
DECLARE SUB GetFunctionKey (inchar$)
DECLARE SUB GetInput (instring$, maxlength%, escapeflag%)
DECLARE SUB GetInteger (integerinput%, maxlength%, escapeflag%)
DECLARE SUB GetMenuChoice (menu AS ANY, items() AS ANY, choice$)
DECLARE SUB GoToBottom (sweeppcounter%)
DECLARE SUB GoToCenter (sweeppcounter%)
DECLARE SUB GoToTop (sweeppcounter%)
DECLARE SUB LoadSweep (highbyte%, lowbyte%)
DECLARE SUB ManualSweep (centerfield%, direction$, sweeppcounter%, sweeprange%)
DECLARE SUB SawtoothSweep (centerfield%, direction$, sweeppcounter%, sweeprange%)
DECLARE SUB SetCenterField (centerfield%)
DECLARE SUB SetSweepRange (sweeppcounter%, sweeprange%)
DECLARE SUB SetVernierField (vernier%)
DECLARE SUB SingleStepSweep (centerfield%, direction$, sweeppcounter%, sweeprange%)
DECLARE SUB StaticDisplay (functionkeys() AS ANY)
DECLARE SUB StringToInteger (anystring$, integerout%, badnumber%)
DECLARE SUB SweepDelay ()
DECLARE SUB SweepMessage ()
DECLARE SUB TriangularSweep (centerfield%, direction$, sweeppcounter%, sweeprange%)

TYPE FunctionKeyDisplay
title AS STRING * 6
use AS STRING * 6
leftcol AS INTEGER
END TYPE

TYPE MenusRec
  title AS STRING * 15
  numitems AS INTEGER
  topline AS INTEGER
  bottomline AS INTEGER
  leftcol AS INTEGER
  rightcol AS INTEGER
END TYPE

TYPE MenuItemsRec
  iname AS STRING * 15
  cmdkey AS STRING * 1
  cmdcol AS INTEGER
END TYPE

DIM functionkeys(10) AS FunctionKeyDisplay

DIM menus(3) AS MenusRec

DIM f9menu(6) AS MenuItemsRec
DIM f10menu(7) AS MenuItemsRec
DIM f11menu(5) AS MenuItemsRec

'Initialize function keys and menus
CALL DefineFunctionKeys(functionkeys())
CALL DefineMenu(9, menus(1), f9menu())
CALL DefineMenu(10, menus(2), f10menu())
CALL DefineMenu(11, menus(3), f11menu())

'Initialize input and output controller addresses
bas% = &H2A0
bas1% = bas% + 1
bas2% = bas% + 2
bas4% = bas% + 4
bas7% = bas% + 7
'Initialize variables, fields, and display

centerfield% = 5000
delaycounter% = 330
maxfield% = 23000
mode$ = "M"
pole$ = "On"
sweeprange% = 0
sweeptime% = 0
vernier% = 0

CALL SetCenterField(centerfield%)
CALL SetSweepRange(sweepcounter%, sweeprange%)
CALL SetVernierField(vernier%)
CALL GoToCenter(sweepcounter%)
CALL StaticDisplay(functionkeys())

LOCATE 13, 17
PRINT USING "#####"; centerfield%;
LOCATE 13, 41
PRINT USING "#####"; centerfield%;
LOCATE 17, 17
PRINT USING "#####"; sweeprange%;
LOCATE 19, 15
PRINT "30";
LOCATE 19, 18
PRINT "secs";
LOCATE 17, 32
PRINT "Manual";
LOCATE 19, 37
PRINT "On"
LOCATE 21, 35
PRINT USING "+###"; vernier%;

'Loop until the user requests to exit to DOS

DO

'Wait for the user to request an action

CALL GetFunctionKey(inchar$)
'Respond to the requested action, if ESC is returned from a menu it 
closes and the user is returned to the GetFunctionKey wait cycle.

IF inchar$ = "F1" THEN

direction$ = "Down"

IF mode$ = "M" THEN
    CALL ManualSweep(centerfield%, direction$, sweepcounter%,
                     sweeprange%)
ELSEIF mode$ = "S" THEN
    CALL SingleStepSweep(centerfield%, direction$, sweepcounter%,
                         sweeprange%)
ELSEIF mode$ = "T" THEN
    CALL TriangularSweep(centerfield%, direction$, sweepcounter%,
                          sweeprange%)
ELSEIF mode$ = "D" THEN
    CALL SawtoothSweep(centerfield%, direction$, sweepcounter%,
                        sweeprange%)
ELSE
    BEEP
END IF

ELSEIF inchar$ = "F3" THEN

direction$ = "Up"

IF mode$ = "M" THEN
    CALL ManualSweep(centerfield%, direction$, sweepcounter%,
                     sweeprange%)
ELSEIF mode$ = "S" THEN
    CALL SingleStepSweep(centerfield%, direction$, sweepcounter%,
                         sweeprange%)
ELSEIF mode$ = "T" THEN
    CALL TriangularSweep(centerfield%, direction$, sweepcounter%,
                          sweeprange%)
ELSEIF mode$ = "U" THEN
    CALL SawtoothSweep(centerfield%, direction$, sweepcounter%,
                        sweeprange%)
ELSE
    BEEP
END IF
ELSEIF inchar$ = "F5" THEN

    CALL GoToBottom(sweepcounter%)
    halfrange! = sweprange% / 2!
    presentfield% = centerfield% - halfrange!
    LOCATE 13, 41
    PRINT USING "#####"; presentfield%;

ELSEIF inchar$ = "F6" THEN

    CALL GoToCenter(sweepcounter%)
    LOCATE 13, 41
    PRINT USING "#####"; centerfield%;

ELSEIF inchar$ = "F7" THEN

    CALL GoToTop(sweepcounter%)
    halfrange! = sweprange% / 2!
    presentfield% = centerfield% + halfrange!
    LOCATE 13, 41
    PRINT USING "#####"; presentfield%;

ELSEIF inchar$ = "F9" THEN

    CALL DisplayMenu(menus(1), f9menu())
    CALL GetMenuChoice(menus(1), f9menu(), choice$)
    IF choice$ <> CHR$(27) THEN
        CALL F9Enable0ption(choice$, centerfield%, sweprange%, sweepcounter, vernier%, maxfield%, pole$)
    END IF
    CALL BlankMenuSpace(menus(1))

ELSEIF inchar$ = "F10" THEN

    CALL DisplayMenu(menus(2), f10menu())
    CALL GetMenuChoice(menus(2), f10menu(), choice$)
    IF choice$ <> CHR$(27) THEN
        CALL F10Enable0ption(choice$, delaycounter%, sweptime%)
    END IF
    CALL BlankMenuSpace(menus(2))
ELSEIF inchar$ = "F11" THEN

    CALL DisplayMenu(menus(3), f11menu())
    CALL GetMenuChoice(menus(3), f11menu(), choice$)
    IF choice$ <> CHR$(27) THEN
        CALL F11EnableOption(choice$, mode$)
    END IF
    CALL BlankMenuSpace(menus(3))

END IF

LOOP UNTIL inchar$ = "F12"

GOTO ExitMagnetController

'Handle interrupts that arise during field sweeps

Down:
    sweepinterrupt$ = "Down"
    RETURN

Hold:
    sweepinterrupt$ = "Hold"
    RETURN

Up:
    sweepinterrupt$ = "Up"
    RETURN

ExitMagnetController:
    CLS

END

SUB BlankMenuSpace (menu AS MenusRec)

';';';';';';';';';';';';';';';';';';';';';';';';';';';';';';';';';';';';';'
' Purpose: To blank that portion of the screen used to
' display a menu and obtain input from the user.
'
Parameters:
menu (input) - contains the menu title, number of items, and on-screen dimensions

Local variables:

cnt% - a counter for the menu height
menuheight% - the height of the menu
menuwidth% - the width of the menu

'Clear the space occupied by the menu

menuwidth% = menu.rightcol - menu.leftcol + 1
menuheight% = menu.bottomline - menu.topline + 1

FOR cnt% = 0 TO menuheight%
  LOCATE menu.topline + cnt%, menu.leftcol
  PRINT STRINGS(menuwidth%, " ");
NEXT cnt%

'Clear the space for user input

LOCATE 23, 50
PRINT SPACE$(30);
LOCATE 24, 50
PRINT SPACE$(30);

END SUB

SUB BlankSweepMessage

Purpose: To blank the area of the screen used to display the sweep message.

LOCATE 11, 51
PRINT SPACE$(25);
LOCATE 12, 51
PRINT SPACE$(25);
SUB DefineFunctionKeys (functionkeys() AS FunctionKeyDisplay)

' Purpose: To define the display parameters
' for the special function keys.

' Parameters:
' functionkeys (output) - contains the on-screen menu
' location, title, and use of
' the special function keys

'Define the on-screen location of the special function keys

functionkeys(1).leftcol = 2
functionkeys(2).leftcol = 9
functionkeys(3).leftcol = 16
functionkeys(4).leftcol = 27
functionkeys(5).leftcol = 34
functionkeys(6).leftcol = 41
functionkeys(7).leftcol = 52
functionkeys(8).leftcol = 59
functionkeys(9).leftcol = 66
functionkeys(10).leftcol = 73

'Define the title used to label the key display

functionkeys(1).title = " F1 
functionkeys(2).title = " F2 
functionkeys(3).title = " F3 
functionkeys(4).title = " F5 

functionkeys(5).title = "F6"
functionkeys(6).title = "F7"
functionkeys(7).title = "F9"
functionkeys(8).title = "F10"
functionkeys(9).title = "F11"
functionkeys(10).title = "F12"

'Define the purpose of the key as it is to be displayed

functionkeys(1).use = "DOWN"
functionkeys(2).use = "HOLD"
functionkeys(3).use = "UP"
functionkeys(4).use = "BOTTOM"
functionkeys(5).use = "CENTER"
functionkeys(6).use = "TOP"
functionkeys(7).use = "FIELDS"
functionkeys(8).use = "RATE"
functionkeys(9).use = "MODE"
functionkeys(10).use = "DOS"

END SUB

SUB DefineMenu (menuindex%, menu AS MenusRec, items() AS MenuItemsRec)

' Define the menu records for the F9, F10, and F11 menus
IF menuindex% = 9 THEN

    menu.title = "Set:"
    menu.numitems = 6
    menu.topline = 11
    menu.bottomline = 20
    menu.leftcol = 58
    menu.rightcol = 76

ELSEIF menuindex% = 10 THEN

    menu.title = "Set Sweep Time:"
    menu.numitems = 7
    menu.topline = 11
    menu.bottomline = 21
    menu.leftcol = 58
    menu.rightcol = 76

ELSE

    menu.title = "Choose Mode:"
    menu.numitems = 5
    menu.topline = 11
    menu.bottomline = 19
    menu.leftcol = 58
    menu.rightcol = 76

END IF

'Define the individual menu items

IF menuindex% = 9 THEN

    items(1).iname = "Sweep range"
    items(1).cmdkey = "S"
    items(1).cmdcol = 1
    items(2).iname = "Center field"
    items(2).cmdkey = "C"
    items(2).cmdcol = 1
    items(3).iname = "Vernier field"
    items(3).cmdkey = "V"
    items(3).cmdcol = 1
items(4).iname = ""
items(4).cmdkey = ""
items(4).cmdcol = 0
items(5).iname = "Pole caps: ON"
items(5).cmdkey = "N"
items(5).cmdcol = 14
items(6).iname = "OFF"
items(6).cmdkey = "F"
items(6).cmdcol = 14

ELSEIF menuindex% = 10 THEN

items(1).iname = "0:30"
items(1).cmdkey = "0"
items(1).cmdcol = 6
items(2).iname = "1:00"
items(2).cmdkey = "1"
items(2).cmdcol = 6
items(3).iname = "2:00"
items(3).cmdkey = "2"
items(3).cmdcol = 6
items(4).iname = "3:00"
items(4).cmdkey = "3"
items(4).cmdcol = 6
items(5).iname = "4:00"
items(5).cmdkey = "4"
items(5).cmdcol = 6
items(6).iname = "5:00"
items(6).cmdkey = "5"
items(6).cmdcol = 6
items(7).iname = "Other"
items(7).cmdkey = "O"
items(7).cmdcol = 6

ELSE

items(1).iname = "Manual"
items(1).cmdkey = "M"
items(1).cmdcol = 1
items(2).iname = "Triangle"
items(2).cmdkey = "T"
items(2).cmdcol = 1
items(3).iname = "Single Step"
items(3).cmdkey = "S"
items(3).cmdcol = 1
items(4).iname = "Sawtooth Up"
items(4).cmdkey = "U"
items(4).cmdcol = 10
items(5).iname = "Sawtooth Down"
items(5).cmdkey = "D"
items(5).cmdcol = 10

END IF

END SUB

SUB DisplayBox (topline%, bottomline%, leftcol%, rightcol%)

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'Draw the top line

LOCATE topline%, leftcol%
PRINT CHR$(218); STRING$(innerwidth%, CHR$(196)); CHR$(191);
'Draw the sides

FOR midline% = topline% + 1 TO bottomline% - 1
    LOCATE midline%, leftcol%
    PRINT CHR$(179);
    LOCATE midline%, rightcol%
    PRINT CHR$(179);
NEXT midline%

'Draw the bottom line

LOCATE bottomline%, leftcol%
PRINT CHR$(192); STRING$(innerwidth%, CHR$(196)); CHR$(217);

END SUB

SUB DisplayDoubleBox (topline%, bottomline%, leftcol%, rightcol%)

    Purpose: To draw a double box using the current colors.
    Parameters:
        bottomline% (input) - the bottom line of the box
        leftcol% (input) - the left column of the box
        rightcol% (input) - the right column of the box
        topline% (input) - the top line of the box
    Local variables:
        innerwidth% - the inner width of the box
        midline% - a counter for the middle lines of the box
    Adapted from: "QuickBASIC: The Complete Reference",
    Steven Nameroff, Osborne McGraw-Hill,
    1989, pg. 463.

        innerwidth% = rightcol% - leftcol% - 1

'Draw the top line
LOCATE topline%, leftcol%
PRINT CHR$(201); STRING$(innerwidth%, CHR$(205)); CHR$(187);

'Draw the sides

FOR midline% = topline% + 1 TO bottomline% - 1
  LOCATE midline%, leftcol%
  PRINT CHR$(186);
  LOCATE midline%, rightcol%
  PRINT CHR$(186);
NEXT midline%

'Draw the bottom line

LOCATE bottomline%, leftcol%
PRINT CHR$(200); STRING$(innerwidth%, CHR$(205)); CHR$(188);

END SUB

SUB DisplayMenu (menu AS MenusRec, items() AS MenuItemsRec)

' Purpose: To display an on-screen menu.

' Parameters:
' items (input) - contains the individual item name, the command hot-key, and the location of the hot-key relative to the first letter of the item name
' menu (input) - contains the menu title, number of items, and on-screen dimensions

' Local variables:
' cnt% - a counter for the number of menu items
' innerwidth% - the inner width of the menu

' Other routine called:
' DisplayBox

' Adapted from: "QuickBASIC: The Complete Reference", 
INNERWIDTH% = MENU.RIGHTCOL - MENU.LEFTCOL - 1

'Draw the menu box

CALL DisplayBox(MENU.TOPLINE, MENU.BOTTOMLINE, MENU.LEFTCOL, MENU.RIGHTCOL)

'Display the title

LOCATE MENU.TOPLINE + 1, MENU.LEFTCOL + 2
PRINT RTRIM$(MENU.TITLE);

'Draw a line to separate the title from the menu items

LOCATE MENU.TOPLINE + 2, MENU.LEFTCOL
PRINT CHR$(195); STRING$(INNERWIDTH%, CHR$(196)); CHR$(180);

'Display the menu items

FOR CNT% = 1 TO MENU.NUMITEMS

'Display the item name

LOCATE MENU.TOPLINE + 2 + CNT%, MENU.LEFTCOL + 2
PRINT RTRIM$(ITEMS(CNT%).INAME);

'Hilight the command hot-key in reverse video

IF LEFT$(ITEMS(CNT%).INAME, 1) <> "" THEN
    LOCATE MENU.TOPLINE + 2 + CNT%, MENU.LEFTCOL+1+ITEMS(CNT%).CMDCOL
    COLOR 0, 7
    PRINT RTRIM$(ITEMS(CNT%).CMDKEY);
END IF

'Return the color scheme to normal

COLOR 7, 0
SUB F10EnableOption (choice$, delaycounter%, sweeptime%)
IF choice$ = "0" THEN
  sweeptime% = 0
  delaycounter% = 330
ELSEIF choice$ = "1" THEN
  sweeptime% = 1
  delaycounter% = 1145
ELSEIF choice$ = "2" THEN
  sweeptime% = 2
  delaycounter% = 2630
ELSEIF choice$ = "3" THEN
  sweeptime% = 3
  delaycounter% = 4125
ELSEIF choice$ = "4" THEN
  sweeptime% = 4
  delaycounter% = 5660
ELSEIF choice$ = "5" THEN
  sweeptime% = 5
  delaycounter% = 7190
ELSE

  'Get a user requested value for the sleep time

  validnumber% = 1

DO

  LOCATE 23, 50
  PRINT "Enter sleep time (mins): ";
  CALL GetInteger(sweeptime%, 2, escapeflag%)

  'Check for ESC key entry and if found exit the menu sequence

  IF escapeflag% = 1 THEN
    EXIT SUB
  END IF

  'Verify that the requested value is acceptable

  IF sweeptime% > 0 AND sweeptime% < 21 THEN
    validnumber% = 0
  ELSE
    BEEP
LOCATE 24, 50
PRINT "Enter a value > 0 and < 21.";
END IF

LOOP WHILE validnumber% = 1
  'A valid entry has been received, compute the appropriate delay
  delaycounter% = 25 * 60 * sweeptime% - 348
END IF

'Update the sweeptime in the controller status display

LOCATE 19, 15
IF sweeptime% = 0 THEN
  PRINT "30";
  LOCATE 19, 18
  PRINT "secs";
ELSE
  PRINT USING "##"; sweeptime%;
  LOCATE 19, 18
  IF sweeptime% = 1 THEN
    PRINT "min ";
  ELSE
    PRINT "mins";
  END IF
END IF
END SUB

SUB F11EnableOption (choice$, mode$)
  Purpose: To enable the switching of operational modes.
  Parameters:
  choice$ (input) - the command hot-key corresponding to the user's menu choice
  mode$ (output) - the command hot-key corresponding to the user's choice of mode
mode$ = choice$

' Update the mode in the controller status display

LOCATE 17, 32

IF mode$ = "M" THEN
    PRINT "Manual"
ELSEIF mode$ = "T" THEN
    PRINT "Triangle"
ELSEIF mode$ = "S" THEN
    PRINT "Single Step"
ELSEIF mode$ = "U" THEN
    PRINT "Sawtooth up"
ELSE
    PRINT "Sawtooth down"
END IF
END SUB

SUB F9EnableOption (choice$, centerfield%, sweeprange%, sweepcounter%, vernier%, maxfield%, pole$)

Purpose: To enable the setting of the center field, the sweep range, the vernier field, and the pole cap configuration.

Parameters:
- centerfield% (both) - the actual center field requested
- choice$ (input) - the command hot-key corresponding to the user's menu choice
- maxfield% (both) - the maximum value for the magnetic field as determined by the pole cap
pole$ (both) - a flag to identify the pole cap configuration
sweepcounter% (both) - identifies where in the sweep range the field is presently located
sweeprange% (both) - the total range of the sweep
vernier% (both) - a fine-tuning adjustment to the center field

Local variables:
escapeflag% - a flag set to 1 if the user presses the ESC key instead of entering a field
halfrange! - half of the sweep range
killtime% - a counter used as a delay timer to produce a pause in execution
outerloop% - a loop used in conjunction with killtime% to do the equivalent of a pause while the user reads a displayed error message
presentfield% - the present value of the magnetic field

Other routines called:
GetInteger
SetCenterField
SetSweepRange
SetVernierField

Note: Most of the parameters in this routine are both input and output because of the multiple use of this routine to set the various fields. In most cases some of the fields will already have been set when this routine is called.

IF choice$ = "S" THEN

'Set the sweep range

EnterSweep:

LOCATE 23, 50
PRINT "Enter the sweep range: ";
CALL GetInteger(sweeprange%, 5, escapeflag%)
halfrange! = sweeprange% / 2!

'Check for ESC key entry and if found exit the menu sequence

IF escapeflag% = 1 THEN
    EXIT SUB
END IF

'Check that lower limit will not result in a negative field

IF centerfield% - halfrange! < 0 THEN
    COLOR 0, 7
    LOCATE 22, 50
    PRINT "  Bottom of sweep < 0!  ";
    LOCATE 23, 50
    PRINT " Please make another entry. ";
    BEEP
    outerloop% = 0
    DO WHILE outerloop% < 5
        killtime% = 0
        DO WHILE killtime% < 30000
            killtime% = killtime% + 1
        LOOP
        outerloop% = outerloop% + 1
    LOOP
    COLOR 7, 0
    LOCATE 22, 50
    PRINT "  ";
    LOCATE 23, 50
    PRINT "  ";
    GOTO EnterSweep
END IF

'All's well so go ahead and set the sweep range.

CALL SetSweepRange(sweepcounter%, sweeprange%)
LOCATE 17, 17
PRINT USING "#####"; sweeprange%;
presentfield% = centerfield% + (((2047 - sweepcounter%) / 2000) * halfrange!)
LOCATE 13, 41
PRINT USING "#####"; presentfield%;

ELSEIF choice$ = "C" THEN

'Set the center field

EnterCenter:

LOCATE 23, 50
PRINT "Enter the center field: ";
CALL GetInteger(centerfield%, 5, escapeflag%)

'Check for ESC key entry and if found exit the menu sequence

IF escapeflag% = 1 THEN
  EXIT SUB
END IF

'Check that the maximum field allowed by the magnet
'configuration (pole caps on or off) is not exceeded.

IF centerfield% > maxfield% THEN
  COLOR 0, 7
  LOCATE 22, 50
  PRINT " Entered value is too large. ";
  LOCATE 23, 50
  PRINT " Please enter a new value. ";
  BEEP
  outerloop% = 0
  DO WHILE outerloop% < 5
    killtime% = 0
    DO WHILE killtime% < 30000
      killtime% = killtime% + 1
    LOOP
    outerloop% = outerloop% + 1
  LOOP
  COLOR 7, 0
  LOCATE 22, 50
  PRINT " ";
  LOCATE 23, 50
  PRINT " ";
  GOTO EnterCenter

'Check that the new center field will not result in
'a lower sweep limit that is < 0.

halfrange! = sweeprange% / 2!
IF centerfield% - halfrange! < 0 THEN
  COLOR 0, 7
  LOCATE 22, 50
  PRINT " Bottom of sweep < 0!  ";
  LOCATE 23, 50
  PRINT " Please make another entry, ";
  LOCATE 24, 50
  PRINT " or change the sweep field. ";
  BEEP
  outerloop%= 0
  DO WHILE outerloop% < 5
    killtime% = 0
    DO WHILE killtime% < 30000
      killtime% = killtime% + 1
    LOOP
    outerloop% = outerloop% + 1
  LOOP
  COLOR 7, 0
  LOCATE 22, 50
  PRINT " ";
  LOCATE 23, 50
  PRINT " ";
  LOCATE 24, 50
  PRINT " ";
  GOTO EnterCenter
END IF

'All's well so go ahead and set the center field.

CALL SetCenterField(centerfield%)
LOCATE 13, 17
PRINT USING "#####"; centerfield%
presentfield% = centerfield% + (((2047 - sweepcounter%) / 2000) * halfrange!)
LOCATE 13, 41
PRINT USING "#####"; presentfield%;
ELSEIF choice$ = "V" THEN

'Set the vernier field adjustment

LOCATE 23, 50
PRINT "Enter vernier(0 to 200): ";
LOCATE 24, 50
PRINT " (0 to 10 Gauss)";
LOCATE 23, 75
CALL GetInteger(vernier%, 4, escapeflag%)

'Check for ESC key entry and if found exit the menu sequence

IF escapeflag% = 1 THEN
   EXIT SUB
END IF

CALL SetVernierField(vernier%)
LOCATE 21, 35
PRINT USING "+###": vernier%;

ELSEIF choice$ = "H" THEN

'Set the maximum field for pole caps on

maxfield% = 23000
pole$ = "On"
LOCATE 19, 37
PRINT "On ";

ELSE

'Set the maximum field for pole caps off

maxfield% = 16000
pole$ = "Off"
LOCATE 19, 37
PRINT "Off ";

END IF
Purpose: To await and then process a special function key entry.

Parameter:

inchar$ (output) - the name of the function key entered

Note: In its present form the controller does not use keys F4 and F8, hence they are not accepted as valid input.

inchar$ = ""

'Loop until a valid key has been entered

DO

'Wait for a keystroke

DO
  inchar$ = INKEY$
LOOP WHILE inchar$ = ""

'Check that it was a function key

IF LEFT$(inchar$, 1) = CHR$(0) THEN

  'Process the key; do not accept F4 or F8

  IF RIGHT$(inchar$, 1) = CHR$(59) THEN
    inchar$ = "F1"
  ELSEIF RIGHT$(inchar$, 1) = CHR$(60) THEN
    inchar$ = "F2"
  ELSEIF RIGHT$(inchar$, 1) = CHR$(61) THEN
    inchar$ = "F3"
  ELSEIF RIGHT$(inchar$, 1) = CHR$(62) THEN
    BEEP
inchar$ = ""
ELSEIF RIGHT$(inchar$, 1) = CHR$(63) THEN
  inchar$ = "F5"
ELSEIF RIGHT$(inchar$, 1) = CHR$(64) THEN
  inchar$ = "F6"
ELSEIF RIGHT$(inchar$, 1) = CHR$(65) THEN
  inchar$ = "F7"
ELSEIF RIGHT$(inchar$, 1) = CHR$(66) THEN
  BEEP
  inchar$ = ""
ELSEIF RIGHT$(inchar$, 1) = CHR$(67) THEN
  inchar$ = "F9"
ELSEIF RIGHT$(inchar$, 1) = CHR$(68) THEN
  inchar$ = "F10"
ELSEIF RIGHT$(inchar$, 1) = CHR$(133) THEN
  inchar$ = "F11"
ELSEIF RIGHT$(inchar$, 1) = CHR$(134) THEN
  inchar$ = "F12"
ELSE
  BEEP
  inchar$ = ""
END IF

ELSE

  'Beep because it was an inappropriate entry
  BEEP
  inchar$ = ""
END IF

LOOP WHILE inchar$ = ""

END SUB

SUB GetInput (instring$, maxlen%, escapeflag%)

  'Purpose: To allow the user to enter a string of fixed length.

Parameters:
- escapeflag% (output) - a flag set to 1 if the user enters the ESC key
- instring$ (output) - a string entered by the user
- maxlen% (input) - the maximum allowed length of the input string

Local variables:
- curpos% - the cursor position relative to the allowed length of the string
- firstcol% - the on-screen column of the first entry of the string
- insert% - a constant, used to toggle insertmode%
- insertmode% - a flag used to toggle between the insert and overstrike modes
- onechar$ - a single input character
- overstrike% - a constant, used to toggle insertmode%

Note: Most cursor movements are handled by this routine. The available length for the string is shown by underscoring. The cursor position is noted in reverse video with blinking text.

Adapted from: "QuickBASIC: The Complete Reference"

CONST insert% = 1, overstrike% = 2
firstcol% = POS(0)
insertmode% = overstrike%
curpos% = 1
onechar$ = ""
escapeflag% = 0

'Display available length with underscore
PRINT instring$;
PRINT STRING$(maxlen% - LEN(instring$), CHR$(95));
LOCATE , firstcol%

'Blink the cursor

COLOR 23, 0
IF LEN(instring$) = 0 THEN
    PRINT CHR$(95); CHR$(29);
ELSE
    PRINT LEFT$(instring$, 1); CHR$(29);
END IF
COLOR 7, 0

'Get the first character

DO
    onechar$ = INKEY$
LOOP WHILE onechar$ = ""

'Check for ESC key and if pressed back out of
'the menu selection by returning escapeflag%=1

IF LEFT$(onechar$, 1) = CHR$(27) THEN
    escapeflag% = 1
    COLOR 7, 0
    EXIT SUB
END IF

'Process the characters one at a time until Enter is received

DO UNTIL onechar$ = CHR$(13)

'Remove the highlight from the current character

    IF curpos% > maxlen% THEN
        PRINT " "; CHR$(29);
    ELSEIF curpos% > LEN(instring$) THEN
        PRINT CHR$(95); CHR$(29);
    ELSE
        PRINT MID$(instring$, curpos%, 1); CHR$(29);
    END IF

'Check for special characters
IF LEFT$(onechar$, 1) = CHR$(0) THEN

'Check for <Right>

IF RIGHTS(onechar$, 1) = CHR$(77) THEN

'If before last character, move right one space

IF curpos% <= LEN(instring$) THEN
    curpos% = curpos% + 1
END IF

'Check for <Left>

ELSEIF RIGHTS(onechar$, 1) = CHR$(75) THEN

'If past first character, move left one space

IF curpos% > 1 THEN
    curpos% = curpos% - 1
END IF

'Check for <Del>

ELSEIF RIGHTS(onechar$, 1) = CHR$(83) THEN

'If before last character, remove one

IF curpos% <= LEN(instring$) THEN
    instring$ = LEFT$(instring$, curpos% - 1) + MID$(instring$, curpos% + 1)
    PRINT MID$(instring$, curpos%); CHR$(95);
END IF

'Check for <Ins>

ELSEIF RIGHTS(onechar$, 1) = CHR$(82) THEN

'Toggle the insert mode

IF insertmode% = overstrike% THEN
insertmode% = insert%
ELSE
    insertmode% = overstrike%
END IF

ELSE IF onechar$ = CHR$(8) THEN

'if past first character, remove one
IF curpos% > 1 THEN
    IF curpos% > LEN(instring$) THEN
        PRINT CHR$(29); CHR$(95);
    ELSE
        PRINT CHR$(29); MID$(instring$, curpos%); CHR$(95);
    END IF
    instring$ = LEFT$(instring$, curpos% - 2) + MID$(instring$, curpos%)
    curpos% = curpos% - 1
END IF

'No special character, check for overstrike mode
ELSEIF insertmode% = overstrike% THEN

'if overstrike, replace that character or add it to the end
IF curpos% <= LEN(instring$) THEN
    MID$(instring$, curpos%, 1) = onechar$
    PRINT onechar$;
    curpos% = curpos% + 1
ELSEIF curpos% <= maxlength% THEN
    instring$ = instring$ + onechar$
    PRINT onechar$;
    curpos% = curpos% + 1
ELSE
    BEEP
END IF

'Insert mode
ELSEIF curpos% <= maxlength% THEN

'Insert character, move rest of string over

instring$ = LEFT$(instring$, curpos% - 1) + onechar$ +
MID$(instring$, curpos%, maxlength% - curpos%)
PRINT MID$(instring$, curpos%);
curpos% = curpos% + 1

ELSE
BEEP
END IF

'Hightlight the cursor position

LOCATE , firstcol% + curpos% - 1
IF curpos% > maxlength% THEN
COLOR 0, 7
PRINT " "; CHR$(29);
ELSEIF curpos% > LEN(instring$) THEN
COLOR 23, 0
PRINT CHR$(95); CHR$(29);
ELSE
COLOR 23, 0
PRINT MID$(instring$, curpos%, 1); CHR$(29);
END IF
COLOR 7, 0

'Get another character

onechar$ = ""
DO
onechar$ = INKEY$
LOOP WHILE onechar$ = ""

LOOP

'Redisplay the string without the length display

LOCATE , firstcol%
PRINT instring$; SPACE$(maxlength% - LEN(instring$))
SUB GetInteger (integerinput%, maxlenlength%, escapeflag%) 

Purpose: To obtain an integer input from the user.

Parameters:
- escapeflag% (output) - a flag set to 1 if the user enters the ESC key
- integerinput% (input) - an integer input by the user
- maxlenlength% (input) - the maximum allowed length of the input number

Local variables:
- colnum% - the on-screen column location of the cursor at the start of user input
- instring$ - a string containing the user input as a string rather than a number to facilitate error checking
- linenumber% - the on-screen line location of the cursor at the start of user input
- validnumber% - a flag set to 0 when a valid integer has been entered

Other routines called:
- GetInput
- StringToInteger


'Record the current cursor position

linenumber% = CSRLIN
colnumber% = POS(0)
'Loop until a valid integer has been input

DO
  validnumber% = 1

  'Get a number as string input from the user

  LOCATE linenum%, colnum%
  instring$ = ""
  CALL GetInput(instring$, maxlength%, escapeflag%)

  'Check for ESC key as input and if received back out of the menu

  IF escapeflag% = 1 THEN
    EXIT SUB
  END IF

  'Convert the string to integer format

  IF instring$ <> "" THEN
    CALL StringToInteger(instring$, integerinput%, validnumber%)
    IF validnumber% = 1 THEN BEEP
  END IF

LOOP WHILE validnumber% = 1

END SUB

SUB GetMenuChoice (menu AS MenusRec, items() AS MenuItemRec, choice$)

  'Purpose: To get a menu entry from the user.
  'Params:
  '  choice$ (output) - the command hot-key corresponding
  '    to the user’s menu choice
  '  items   (input) - contains the individual item name,
  '    the command hot-key, and the location
  '    of the hot-key relative to the first
  '    letter of the item name
  '  menu    (input) - contains the menu title, number of


Local variables:
' choiceindex% - the current menu array index
' choiceline% - the currently highlighted line
' cnt% - a loop counter for the menu items
' inchar$ - the key pressed by the user

Adapted from: "QuickBASIC: The Complete Reference",
Steven Nameroff, Osborne McGraw-Hill,
1989, pg. 467.

'Set the default choice

choiceline% = menu.topline + 3
choiceindex% = 1
choice$ = ""

'Highlight the current choice

COLOR 0, 7
LOCATE choiceline%, menu.leftcol + 2
PRINT items(choiceindex%).iname
COLOR 16, 7
LOCATE choiceline%, menu.leftcol + 1 + items(choiceindex%).cmdcol
PRINT items(choiceindex%).cmdkey

'Loop until a choice is selected

DO

'Get a key

inchar$ = ""
DO
    inchar$ = INKEY$
LOOP WHILE inchar$ = ""

'Check for ESC key, if pressed close the menu and return
IF LEFT$(inchar$, 1) = CHR$(27) THEN
    choice$ = inchar$
    COLOR 7, 0
    EXIT SUB
END IF

' Remove current choice highlight
COLOR 7, 0
LOCATE choiceline%, menu.leftcol + 2
PRINT items(choiceindex%).iname
COLOR 0, 7
LOCATE choiceline%, menu.leftcol + 1 + items(choiceindex%).cmdcol
PRINT items(choiceindex%).cmdkey

' Check for special keys
IF LEFT$(inchar$, 1) = CHR$(0) THEN

' Process up arrow
    IF RIGHT$(inchar$, 1) = CHR$(72) THEN
        IF choiceindex% > 1 THEN
            choiceindex% = choiceindex% - 1
        ELSE
            choiceindex% = menu.numitems
        END IF
        DO UNTIL (items(choiceindex%).cmdcol > 0) OR (choiceindex% = 1)
            choiceindex% = choiceindex% - 1
        LOOP
        choiceline% = menu.topline + 2 + choiceindex%

' Process down arrow
ELSEIF RIGHT$(inchar$, 1) = CHR$(80) THEN
    IF choiceindex% < menu.numitems THEN
        choiceindex% = choiceindex% + 1
    ELSE
        choiceindex% = 1
    END IF
    DO UNTIL (items(choiceindex%).cmdcol > 0) OR (choiceindex% = menu.numitems)
choiceindex% = choiceindex% + 1
LOOP
choicecline% = menu.topline + 2 + choiceindex%

'Otherwise beep because of an unacceptable special character
ELSE
BEEP
END IF

'Check for valid characters
ELSE

'Process ENTER
IF inchar$ = CHR$(13) THEN
choice$ = items(choiceindex%).cmdkey
ELSE

'Process command keys
inchar$ = UCase$(inchar$)
FOR cnt% = 1 TO menu.numitems
IF items(cnt%).cmdcol > 0 THEN
IF inchar$ = items(cnt%).cmdkey THEN
choiceindex% = cnt%
choicecline% = menu.topline + 2 + cnt%
choice$ = inchar$
EXIT FOR
END IF
END IF
NEXT cnt%

'Otherwise beep because of an unacceptable key input
IF choice$ = "" THEN BEEP
END IF
'Re-highlight the current choice

COLOR 0, 7
LOCATE choiceline%, menu.leftcol + 2
PRINT items(choiceindex%).iname
COLOR 16, 7
LOCATE choiceline%, menu.leftcol + 1 + items(choiceindex%).cmdcol
PRINT items(choiceindex%).cmdkey

LOOP UNTIL choice$ <> ""

'Stop blinking the choice command key

COLOR 0, 7
LOCATE choiceline%, menu.leftcol + 1 + items(choiceindex%).cmdcol
PRINT items(choiceindex%).cmdkey

'Return color scheme to normal

COLOR 7, 0

END SUB

SUB GoToBottom (sweepcounter%)

-----------------------------
' Purpose: To set the magnetic field to the bottom of the sweep.
' Parameter:
' sweepcounter% (output) - identifies where in the sweep range
' the field is presently located
' Local variables:
' highbyte% - the high byte of sweepcounter%
' lowbyte% - the low byte of sweepcounter%
' Other routine called:
' LoadSweep
-----------------------------
sweepcounter% = 4047

highbyte% = INT(sweepcounter% / 256)
lowbyte% = sweepcounter% - 256 * highbyte

CALL LoadSweep(highbyte%, lowbyte%)

END SUB

SUB GoToCenter (sweepcounter%)

     ,...........................................................................................................................................
     ,
     , Purpose: To set the magnetic field to the center field.
     ,
     , Parameter:
     ,   sweepcounter% (output) - identifies where in the sweep range
     ,   the field is presently located
     ,
     , Local variables:
     ,   highbyte% - the high byte of sweepcounter%
     ,   lowbyte% - the low byte of sweepcounter%
     ,
     , Other routine called:
     ,   LoadSweep
     ,

sweepcounter% = 2047

highbyte% = INT(sweepcounter% / 256)
lowbyte% = sweepcounter% - 256 * highbyte%

CALL LoadSweep(highbyte%, lowbyte%)

END SUB

SUB GoToTop (sweepcounter%)

     ,...........................................................................................................................................
     ,
     , Purpose: To set the magnetic field to the top of the sweep.   }


Parameter:

- `sweepcounter%` (output) - identifies where in the sweep range the field is presently located

Local variables:

- `highbyte%` - the high byte of `sweepcounter%`
- `lowbyte%` - the low byte of `sweepcounter%`

Other routine called:

- `LoadSweep`

```fortran
sweepcounter% = 47

highbyte% = INT(sweepcounter% / 256)
lowbyte% = sweepcounter% - 256 * highbyte%

CALL LoadSweep(highbyte%, lowbyte%)

END SUB

SUB LoadSweep (highbyte%, lowbyte%)

Purpose: To load a sweep location into the controller.

Parameters:

- `highbyte%` (input) - the high byte of the sweep location
- `lowbyte%` (input) - the low byte of the sweep location

Shared variables:

- bas% - an output controller address
- bas1% - an output controller address
- bas2% - an output controller address

SHARED bas%, bas1%, bas2%
```
SUB ManualSweep (centerfield%, direction$, sweepcounter%, sweeprange%)

Purpose: To facilitate a manually controlled sweep of
the magnetic field through the sweep range.

Parameters:
centerfield% (input) - the actual center field
direction$ (input) - the present direction of the sweep
sweepcounter% (both) - identifies where in the sweep range
the field is presently located
sweeprange% (input) - the total sweep range

Shared variable:
sweepinterrupt$ - an interrupt flag used to stop
a sweep or change its direction

Local variables:
ahalfrange! - half of the sweep range
highbyte% - the high byte of sweepcounter%
lowbyte% - the low byte of sweepcounter%
presentfield% - the present value of the magnetic field

Other routines called:
BlankSweepMessage
LoadSweep
SweepDelay
SweepMessage

END SUB
SHARED sweepinterrupt$

'Define the acceptable interrupt keys

ON KEY(1) GOSUB Down
ON KEY(2) GOSUB Hold
ON KEY(3) GOSUB Up

CALL SweepMessage
halfrange! = sweeprange% / 2!

StartSweep:

'Handle a downfield sweep

IF direction$ = "Down" THEN

'Turn on the appropriate interrupt keys

KEY(1) OFF
KEY(2) ON
KEY(3) ON

'Cycle the field from where it is to the bottom of the sweep

DO WHILE sweepcounter% < 4047

'Increment and load the sweep counter

sweepcounter% = sweepcounter% + 1
highbyte% = INT(sweepcounter% / 256)
lowbyte% = sweepcounter% - 256 * highbyte%
CALL LoadSweep(highbyte%, lowbyte%)

'Update the display

presentfield% = centerfield% + (((2047 - sweepcounter%) / 2000) * halfrange!)

LOCATE 13, 41
PRINT USING "#####"; presentfield%;
'Delay the sweep cycle to match the sweep time

CALL SweepDelay

'Check for an interrupt and respond accordingly

IF sweepinterrupt$ <> "" THEN
    IF sweepinterrupt$ = "Up" THEN
        direction$ = "Up"
        sweepinterrupt$ = ""
        GOTO StartSweep
    ELSE
        GOTO ExitSweep
    END IF
END IF

LOOP

ELSE

'Handle an upfield sweep

'Turn on the appropriate interrupt keys

KEY(1) ON
KEY(2) ON
KEY(3) OFF

'Cycle the field from where it is to the top of the sweep

DO WHILE sweepcounter% > 47

'Decrement and load the sweep counter

sweepcounter% = sweepcounter% - 1
highbyte% = INT(sweepcounter% / 256)
lowbyte% = sweepcounter% - 256 * highbyte%
CALL LoadSweep(highbyte%, lowbyte%)

'Update the display

presentfield% = centerfield% + ((2047 - sweepcounter%) / 2000) *
halfrange!)

LOCATE 13, 41
PRINT USING "#####": presentfield%

'Delay the sweep cycle to match the sweep time
CALL SweepDelay

'Check for an interrupt and respond accordingly

IF sweepinterrupt$ <> "" THEN
  IF sweepinterrupt$ = "Down" THEN
    direction$ = "Down"
    sweepinterrupt$ = ""
    GOTO StartSweep
  ELSE
    GOTO ExitSweep
  END IF
END IF

LOOP

END IF

ExitSweep:

'Turn off the interrupt key checking

KEY(1) OFF
KEY(2) OFF
KEY(3) OFF

sweepinterrupt$ = ""
CALL BlankSweepMessage

END SUB

SUB SawtoothSweep (centerfield%, direction$, sweepcounter%, sweeprange%)

' Purpose: To produce a sawtooth sweep of the magnetic field. '
Parameters:

- `centerfield%` (input) - the actual center field requested
- `direction$` (input) - the present direction of the sweep
- `sweepcounter%` (output) - identifies where in the sweep range the field is presently located
- `sweeprange%` (input) - the total sweep range

Shared variable:

- `sweepinterrupt$` - an interrupt flag used to stop a sweep or change its direction

Local variables:

- `halfrange!` - half of the sweep range
- `highbyte%` - the high byte of `sweepcounter%`
- `lowbyte%` - the low byte of `sweepcounter%`
- `presentfield%` - the present value of the magnetic field

Other routines called:

- `BlankSweepMessage`
- `LoadSweep`
- `SweepDelay`
- `SweepMessage`

```plaintext
SHARED sweepinterrupt$

halfrange! = sweeprange% / 2!

CALL SweepMessage

'Define and turn on the acceptable interrupt key

ON KEY(2) GOSUB Hold
KEY(2) ON

StartSawtooth:

'Handle a downfield sawtooth sweep

IF direction$ = "Down" THEN
'Cycle the field from where it is to the bottom of the sweep

DO WHILE sweepcounter% < 4047

'Increment and load the sweep counter

sweepcounter% = sweepcounter% + 1
highbyte% = INT(sweepcounter% / 256)
lowbyte% = sweepcounter% - 256 * highbyte%
CALL LoadSweep(highbyte%, lowbyte%)

'Update the display

presentfield% = centerfield% + (((2047 - sweepcounter%) / 2000) * halfrange!)
LOCATE 13, 41
PRINT USING "#####"; presentfield%;

'Delay the sweep cycle to match the sweep time

CALL SweepDelay

'Check for an interrupt and respond accordingly

IF sweepinterrupt$ <> "" THEN
  GOTO ExitSawtooth
END IF

LOOP

'Set the field to the top of the sweep and begin again

CALL GoToTop(sweepcounter%)
GOTO StartSawtooth

ELSE

'Handle an upfield sawtooth sweep

'Cycle the field from where it is to the top of the sweep

DO WHILE sweepcounter% > 47
'Decrement and load the sweep counter

sweepcounter% = sweepcounter% - 1
highbyte% = INT(sweepcounter% / 256)
lowbyte% = sweepcounter% - 256 * highbyte%
CALL LoadSweep(highbyte%, lowbyte%)

'Update the display

presentfield% = centerfield% + (((2047 - sweepcounter%) / 2000) * halfrange!)
LOCATE 13, 41
PRINT USING "#####"; presentfield%;

'Delay the sweep cycle to match the sweep time

CALL SweepDelay

'Check for an interrupt and respond accordingly

IF sweepinterrupt$ <> "" THEN
    GOTO ExitSawtooth
END IF

LOOP

'Set the field to the bottom of the sweep and begin again

CALL GoToBottom(sweepcounter%)
GOTO StartSawtooth

END IF

ExitSawtooth:

'Turn off the interrupt key checking

KEY(2) OFF

sweepinterrupt$ = ""
CALL BlankSweepMessage
END SUB

SUB SetCenterField (centerfield%)

Purpose: To set the center field.

Parameter:
  centerfield% (input) - the actual center field requested

Shared variables:
  bas% - an output controller address
  bas1% - an output controller address
  bas2% - an output controller address

Local variables:
  highbyte% - the high byte of scaledfield%
  lowbyte% - the low byte of scaledfield%
  scaledfield% - the scaled field based upon the NMR calibration of the controller
  scaledfield! - the real variable value of the scaled field
  x! - centerfield% as a real variable
  x2! - the square of x!

Note: This routine does not set the magnetic field to the center field value. It merely changes the center field value in the controller, which in turn adjusts the magnetic field based upon the value of sweepcounter%.

SHARED bas%, bas1%, bas2%

x! = centerfield%
x2! = x! * x!

'Compute the scaled field based upon a piecewise quadratic fit to the NMR data of 3/11/92

IF centerfield% < 2000 THEN
scaledfield! = -3.14E-06 * x2! + .698 * x! + 8!
ELSEIF centerfield% < 6000 THEN
  scaledfield! = -1.89E-06 * x2! + .696 * x! + 6!
ELSEIF centerfield% < 10000 THEN
  scaledfield! = -3.23E-06 * x2! + .711 * x! - 38!
ELSEIF centerfield% < 12500 THEN
  scaledfield! = -4.77E-06 * x2! + .743 * x! - 203
ELSE
  scaledfield! = -3.81E-06 * x2! + .719 * x! - 51!
END IF

'Convert the scaled field to an integer and
'insure that it is either positive or zero

scaledfield% = CINT(scaledfield!)

IF scaledfield% < 0 THEN
  scaledfield% = 0
END IF

'Load the scaled center field

highbyte% = INT(scaledfield% / 256)
lowbyte% = scaledfield% - (256 * highbyte%)

OUT bas%, highbyte%
OUT bas1%, &H15
OUT bas2%, &H1
OUT bas2%, &H0
OUT bas%, lowbyte%
OUT bas1%, &H16
OUT bas2%, &H1
OUT bas2%, &H0

END SUB

SUB SetSweepRange (sweepcounter%, sweeprange%)
  
  Purpose: To set the sweep range.
  
END SUB
Parameters:

- sweepcounter% (input) - identifies where in the sweep range the field is presently located
- sweeprange% (input) - the total sweep range

Shared variables:

- bas% - an output controller code
- bas1% - an output controller code
- bas2% - an output controller code

Local variables:

- highbyte% - the high byte of scaledrange%
- lowbyte% - the low byte of scaledrange%
- scaledrange% - the scaled sweep range based upon the NMR calibration of the controller
- scaledrange! - the real variable value of the scaled sweep range
- sweeprange! - the real variable value of sweeprange%

Other routine called:

- GoToCenter

SHARED bas%, bas1%, bas2%

sweeprange! = sweeprange%

'Scale the sweep range based upon the NMR data of 3/19/92

scaledrange! = .339 * sweeprange! - .488
scaledrange% = CINT(scaledrange!)

'Insure that the scaled range is either positive or zero

IF scaledrange% < 0 THEN
  scaledrange% = 0
END IF

'Load the scaled sweep range

highbyte% = INT(scaledrange% / 256)
lowbyte% = scaledrange% - (256 * highbyte)
OUT bas%, highbyte%
OUT bas1%, &H13
OUT bas2%, &H1
OUT bas2%, &H0
OUT bas%, lowbyte%
OUT bas1%, &H14
OUT bas2%, &H1
OUT bas2%, &H0

'If the scaled range is zero, then set the magnet at the center field

IF scaledrange% = 0 THEN
    CALL GoToCenter(sweepcounter%)
END IF

END SUB

SUB SetVernierField (vernier%)

',
', Purpose: To set the vernier field.
',
', Parameter:
', vernier% (input) - a fine-tuning adjustment to
', the center field
',
', Shared variables:
', bas% - an output controller address
', bas1% - an output controller address
', bas2% - an output controller address
',

SHARED bas%, bas1%, bas2%

OUT bas%, vernier%
OUT bas1%, &H12
OUT bas2%, &H1
OUT bas2%, &H0
SUB SingleStepSweep (centerfield%, direction$, sweepcounter%, sweeprange%)

Purpose: To allow the user to step through a
sweep one field increment at a time.

Parameters:

- centerfield% (input) - the actual center field requested
- direction$ (input) - the present direction of the sweep
- sweepcounter% (both) - identifies where in the sweep range
  the field is presently located
- sweeprange% (input) - the total sweep range

Local variables:

- halfrange! - half of the total sweep range
- highbyte% - the high byte of sweepcounter%
- lowbyte% - the low byte of sweepcounter%
- presentfield% - the present value of the magnetic field

Other routines called:

LoadSweep

halfrange! = sweeprange% / 2!

'Handle a downfield sweep

IF direction$ = "Down" THEN

'Cycle the field from where it is to the next lower increment

IF sweepcounter% < 4047 THEN

'Increment and load the sweep counter

sweepcounter% = sweepcounter% + 1
highbyte% = INT(sweepcounter% / 256)
lowbyte% = sweepcounter% - 256 * highbyte%
CALL LoadSweep(highbyte%, lowbyte%)

'Update the display

presentfield% = centerfield% + (((2047 - sweepcounter%) / 2000) * halfrange!)

LOCATE 13, 41
PRINT USING "#####"; presentfield%;

ELSE

'Notify the user that the field is already at the bottom of the sweep

BEEP

END IF

ELSE

'Handle an upfield sweep

'Cycle the field from where it is to the next higher increment

IF sweepcounter% > 47 THEN

'Decrement and load the sweep counter

sweepcounter% = sweepcounter% - 1
highbyte% = INT(sweepcounter% / 256)
lowbyte% = sweepcounter% - 256 * highbyte%
CALL LoadSweep(highbyte%, lowbyte%)

'Update the display

presentfield% = centerfield% + (((2047 - sweepcounter%) / 2000) * halfrange!)

LOCATE 13, 41
PRINT USING "#####"; presentfield%;

ELSE

'Notify the user that the field is already at the top of the sweep
SUB StaticDisplay (functionkeys() AS FunctionKeyDisplay)

' Clear the screen
CLS

'Draw the menu title
CALL DisplayDoubleBox(1, 3, 22, 57)
LOCATE 2, 24
PRINT CHR$(176); CHR$(177); CHR$(178);
LOCATE 2, 28
PRINT "Magnet Controller M596A";
LOCATE 2, 53
PRINT CHR$(178); CHR$(177); CHR$(176);

'Draw the display boxes for the menu keys

CALL DisplayBox(5, 8, 1, 22)
CALL DisplayBox(5, 8, 26, 47)
CALL DisplayBox(5, 8, 51, 79)

'Insert the vertical dividers

LOCATE 5, 8
PRINT CHR$(194);
LOCATE , 15
PRINT CHR$(194);
LOCATE , 33
PRINT CHR$(194);
LOCATE , 40
PRINT CHR$(194);
LOCATE , 58
PRINT CHR$(194);
LOCATE , 65
PRINT CHR$(194);
LOCATE , 72
PRINT CHR$(194);
LOCATE 8, 8
PRINT CHR$(193);
LOCATE , 15
PRINT CHR$(193);
LOCATE , 33
PRINT CHR$(193);
LOCATE , 40
PRINT CHR$(193);
LOCATE , 58
PRINT CHR$(193);
LOCATE , 65
PRINT CHR$(193);
LOCATE , 72
PRINT CHR$(193);
LOCATE 6, 8
PRINT CHR$(179);
LOCATE , 15
PRINT CHR$(179);
LOCATE , 33
PRINT CHR$(179);
LOCATE , 40
PRINT CHR$(179);
LOCATE , 58
PRINT CHR$(179);
LOCATE , 65
PRINT CHR$(179);
LOCATE , 72
PRINT CHR$(179);
LOCATE 7, 8
PRINT CHR$(179);
LOCATE , 15
PRINT CHR$(179);
LOCATE , 33
PRINT CHR$(179);
LOCATE , 40
PRINT CHR$(179);
LOCATE , 58
PRINT CHR$(179);
LOCATE , 65
PRINT CHR$(179);
LOCATE , 72
PRINT CHR$(179);

'Add the key labels and their function

FOR cnt% = 1 TO 10
   LOCATE 6, functionkeys(cnt%).leftcol
   PRINT functionkeys(cnt%).title;
   LOCATE 7, functionkeys(cnt%).leftcol
   PRINT functionkeys(cnt%).use;
NEXT cnt%

'Draw the magnet status display
CALL DisplayDoubleBox(11, 23, 1, 47)

'Insert the vertical divider

LOCATE 11, 24
PRINT CHR$(203);
FOR midline% = 12 TO 23
    LOCATE midline%, 24
    PRINT CHR$(186);
NEXT midline%
LOCATE 23, 24
PRINT CHR$(202);

'Insert the horizontal divider

LOCATE 15, 1
PRINT CHR$(204); STRING$(45, CHR$(205)); CHR$(185);
LOCATE 15, 24
PRINT CHR$(206);

'Insert the labels

LOCATE 13, 3
PRINT "Center Field:";
LOCATE 13, 26
PRINT "Present Field:";
LOCATE 17, 3
PRINT "Sweep Range:";
LOCATE 17, 26
PRINT "Mode:";
LOCATE 19, 3
PRINT "Sweep Time:";
LOCATE 19, 26
PRINT "Pole caps:";
LOCATE 21, 4
PRINT "(Fields in Gauss)";
LOCATE 21, 26
PRINT "Vernier:";

END SUB

SUB StringToInteger (anystring$, integerout%, validnumber%)

Purpose: To convert a number input as a string variable to an integer variable.

Parameters:
- anystring$ (input) - the string to convert
- integerout% (output) - the resulting integer
- validnumber% (output) - a flag set to 0 when a valid integer has been processed

Local variables:
- cnt% - a counter for the string length
- digit% - one converted digit of the input
- negative% - a flag set to 1 for a negative number
- onechar$ - one character of the input string


integerout% = 0
negative% = 1
anystring$ = LTRIM$(RTRIM$(anystring$))

'Loop through each character in the string

FOR cnt% = 1 TO LEN(anystring$)
    onechar$ = MID$(anystring$, cnt%, 1)
    'Check for negative numbers
    IF cnt% = 1 AND onechar$ = "-" THEN
        negative% = 0
    'Check for invalid characters
    ELSEIF onechar$ < "0" OR onechar$ > "9" THEN
        validnumber% = 1
EXIT SUB

ELSE

'Do the conversion

digit% = VAL(onechar$)

'Check for too large or too small a number

IF integerout% > 3276 OR integerout% < -3276 THEN
    validnumber% = 1
    EXIT SUB
ELSEIF integerout% = 3276 AND digit% > 7 THEN
    validnumber% = 1
    EXIT SUB
ELSEIF integerout% = -3276 AND digit% = 9 THEN
    validnumber% = 1
    EXIT SUB

'Add the current digit to the number

ELSEIF negative% = 0 THEN
    integerout% = integerout% * 10 - digit%
ELSE
    integerout% = integerout% * 10 + digit%
END IF

END IF

EXIT cnt%

validnumber% = 0

END SUB

SUB SweepDelay

' Purpose: To effect a delay so that the timing of a sweep matches the user's request.

'
Shared variables:

bas4% - an input controller code
bas7% - an output controller code
delaycounter% - the scaled counter to be sent to
the I/O board to produce the delay
required for a given sweep time

Local variables:

counter% - the value of the count-down timer as
read from the I/O board
countup% - a count-up delay counter
highbyte% - the high byte of delaycounter%
lowbyte% - the low byte of delaycounter%

Note: An additional delay loop has been included within this
routine in order to keep the I/O board, computer, and
controller from tripping over themselves.

```
SHARED bas4%, bas7%, delaycounter%

'Load the delay counter to the I/O board

highbyte% = INT(delaycounter% / 256)
lowbyte% = delaycounter% - 256 * highbyte%

OUT bas7%, &H30
OUT bas4%, lowbyte%
OUT bas4%, highbyte%

'Wait for the delay time to expire

DO

'Delay the loop cycle so that communications do not get jumbled

countup% = 0
DO WHILE countup% < 100
    countup% = countup% + 1
LOOP
```
'Read the counter from the I/O board

lowbyte& = INP(bas4%)
highbyte& = INP(bas4%)
counter& = lowbyte& + 256 * highbyte&

'Check the counter against the intended delay

LOOP WHILE counter& < delaycounter%

END SUB

SUB SweepMessage

';);LOCATE 13, 53 PRINT " sweep and regain ";LOCATE 14, 53 PRINT " access to F5 - F12 ";

END SUB

SUB TriangularSweep (centerfield%, direction$, sweepcounter%, sweeprange%)

';);LOCATE 12, 53 PRINT "Press F2 to stop the";

CALL DisplayBox(11, 15, 51, 75)

LOCATE 12, 53 PRINT "Press F2 to stop the";
LOCATE 13, 53 PRINT " sweep and regain ";
LOCATE 14, 53 PRINT " access to F5 - F12 ";
Parameters:

centerfield% - the actual center field requested
direction% - the present direction of the sweep
sweepcounter% - identifies where in the sweep range
the field is presently located
sweeprange% - the total sweep range

Shared variable:
sweepinterrupt% - an interrupt flag used to stop
a sweep or change its direction

Local variables:
halfrange! - half of the total sweep range
highbyte% - the high byte of sweepcounter%
lowbyte% - the low byte of sweepcounter%
presentfield% - the present value of the magnetic field

Other routines called:
BlankSweepMessage
LoadSweep
SweepDelay
SweepMessage

SHARED sweepinterrupt$

'Define the acceptable interrupt keys

ON KEY(1) GOSUB Down
ON KEY(2) GOSUB Hold
ON KEY(3) GOSUB Up

CALL SweepMessage

halfrange! = sweeprange% / 2!

StartTriangle:

'Handle the downfield side of the triangular sweep

IF direction$ = "Down" THEN
'Turn on the appropriate interrupt keys

KEY(1) OFF
KEY(2) ON
KEY(3) ON

'Cycle the field from where it is to the bottom of the sweep

DO WHILE sweepcounter% < 4047

'Increment and load the sweep counter

sweepcounter% = sweepcounter% + 1
highbyte% = INT(sweepcounter% / 256)
lowbyte% = sweepcounter% - 256 * highbyte%
CALL LoadSweep(highbyte%, lowbyte%)

'Update the display

presentfield% = centerfield% + (((2047 - sweepcounter%) / 2000) * halfrange!)
LOCATE 13, 41
PRINT USING "#####"; presentfield%;

'Delay the sweep cycle to match the sweep time

CALL SweepDelay

'Check for an interrupt and respond accordingly

IF sweepinterrupt$ <> "" THEN
    IF sweepinterrupt$ = "Up" THEN
        direction$ = "Up"
        sweepinterrupt$ = ""
        GOTO StartTriangle
    ELSE
        GOTO ExitTriangle
    END IF
END IF
END IF

LOOP
'Switch the direction of the sweep and continue

direction$ = "Up"
GOTO StartTriangle

ELSE

'Handle the upfield side of the triangular sweep
'Turn on the appropriate interrupt keys

KEY(1) ON
KEY(2) ON
KEY(3) OFF

'Cycle the field from where it is to the top of the sweep

DO WHILE sweepcounter% > 47

'Decrement and load the sweep counter

sweepcounter% = sweepcounter% - 1
highbyte% = INT(sweepcounter% / 256)
lowbyte% = sweepcounter% - 256 * highbyte%
cALL LoadSweep(highbyte%, lowbyte%)

'Update the display

presentfield% = centerfield% + (((2047 - sweepcounter%) / 2000) * halfrange!)
LOCATE 13, 41
PRINT USING "#####"; presentfield%;

'Delay the sweep cycle to match the sweep time

cALL SweepDelay

'Check for an interrupt and respond accordingly

IF sweepinterrupt$ <> "" THEN
    IF sweepinterrupt$ = "Down" THEN
direction$ = "Down"
sweepinterrupt$ = ""
GOTO StartTriangle
ELSE
    GOTO ExitTriangle
END IF
END IF

LOOP

'Switch the direction of the sweep and continue

direction$ = "Down"
GOTO StartTriangle

END IF

ExitTriangle:

'Turn off the interrupt key checking

KEY(1) OFF
KEY(2) OFF
KEY(3) OFF

sweepinterrupt$ = ""
CALL BlankSweepMessage

END SUB
Appendix B

LeCroy Transfer Routine

\ ******************************** Definitions ********************************

\ dim[ 150 ] integer array signal.desc
\ dim[ 28 ] integer array desc.data
\ dim[ 32000 ] integer array signal
\ dim[ 16003 ] dma.array raw.signal

\ integer scalar filenum
\ integer scalar flag
\ integer scalar limit
\ integer scalar narrays
\ integer scalar scratch

2 string channel
30 string dummy
50 string filename
50 string lastfile

dim[ 2 , 64 ] string.array info
\ dim[ 17 , 20 ] string.array state

13 3 22 76 window {prompts}
18 3 22 76 window {fprompt}

\ ******************************** Set-up GPIB Interface ********************************

24 gpib.device lecroy.scope \ 9400A oscilloscope address
\ eoi.on \ turn on the End of Information
\ eos.on \ turn on the End of String

182
10 eos.character \ line feed = End Of String

05 gpib.device plotter \ 7470A plotter address
eos.on \ turn on the End of Information
eos.on \ turn on the End of String
10 eos.character \ line feed = End Of String

bus.init
send.interface.clear
remote.enable.on
lecroy.scope

\ ********** I/O Routines ( from applic.dmo ASYST program ) **********

: #enter&check \ numeric I/O
begin
?rel.col ?rel.row
#input
not
while
  bell
  ?rel.col 3 pick - 1 +
  3 pick 3 pick goto.xy
  spaces
  goto.xy
repeat
unrot 2 *drop
;

: "input&check \ string I/O
begin
"input
"len 0 =
while
  bell
"drop
repeat
;

: get.y/n \ Y/N input
begin
?rel.col ?rel.row
pckey not
if
  dup 90 > if 32 - then
  dup 89 = not
  dup 78 = not and
else
  true
then
while
  bell
drop
." Y or N"
1000 msec.delay
?rel.col 3 pick - 1 +
3 pick 3 pick goto.xy
spaces
goto.xy
repeat
unrot 2 *drop
89 =
;
\ **************************** Main Menu Display ****************************

: main.menu
  normal.display
  green inten mix foreground
  186 205 201 200 188 187 border.chars {border} " Signal Transfer Routine for the LeCroy 9400A"
  filename ":=
  filename "len 2 / 40 - neg 0 goto.xy
  inverse.on "type inverse.off
  red green inten mix foreground
  " F1 - Transfer Channel 1 "
  "len 2 / 40 - neg 2 goto.xy "type
  " F2 - Transfer Channel 2 "
  "len 2 / 40 - neg 3 goto.xy "type
  " F3 - Transfer Memory C "
  "len 2 / 40 - neg 4 goto.xy "type
  " F4 - Transfer Memory D "
  "len 2 / 40 - neg 5 goto.xy "type
  " F5 - Disable remote control "
"len 2 / 40 - neg 6 goto.xy "type
" F6 - Screen dump to the 7470A "
"len 2 / 40 - neg 7 goto.xy "type
" F8 - Save data in an ASCII file "
"len 2 / 40 - neg 8 goto.xy "type
" F9 - Review an old ASYST data file"
"len 2 / 40 - neg 9 goto.xy "type
" F10 - Exit to ASYST "
"len 2 / 40 - neg 10 goto.xy "type

; 

\ ************** Acquisition parameters menu **************

: acq.menu

normal.display
blue green mix foreground
186 205 201 200 188 187 border.chars {border}
filename "len 2 / 40 - neg 0 goto.xy
inverse.on "type inverse.off
red green inten mix foreground
3 1 goto.xy ." Comments:
6 2 goto.xy ." 1) " info ": [ 1 ] "type
6 3 goto.xy ." 2) " info ": [ 2 ] "type
40 5 goto.xy ." Vertical gain: " state ": [ 1 ] "type
3 7 goto.xy ." Trigger: 
40 10 goto.xy ." Level: " state ": [ 8 ] "type
3 12 goto.xy ." Vert. offset: " state ": [ 14 ] "type
40 13 goto.xy ." Last pt. rel. add.: " state ": [ 16 ] "type
40 14 goto.xy ." Points/division: " state ": [ 17 ] "type
3 15 goto.xy ." Coupling: " state ": [ 10 ] "type
3 16 goto.xy ." Record type:  " state "[ 9 ] "type

; 

\  ********************************** Comment modification routine  **********************************

: modify.comment

begin

{fprompt} screen.clear
red inten mix foreground {border}
white inten mix foreground

" Modify comment number (0 to exit): "
"len 2 / 38 - neg 0 goto.xy "type
#enter&check
false

false case

0 of
not
endof

1 of

2 2 goto.xy ." Enter new comment line ( < 64 characters ):" 1
2 3 goto.xy "input&check info "[ 1 ] ":=
{def} 6 2 goto.xy ." 1) info "[ 1 ] "type
endof

2 of

2 2 goto.xy ." Enter new comment line ( < 64 characters ):"
2 3 goto.xy "input&check info "[ 2 ] ":=
{def} 6 3 goto.xy ." 2) info "[ 2 ] "type
endof

screen.clear
" INVALID SELECTION!"
"len 2 / 38 - neg 0 goto.xy "type
500 msec.delay
" Try to pay attention this time!"
"len 2 / 38 - neg 2 goto.xy "type
1000 msec.delay
" Ready?"
\"len 2 / 38 - neg 3 goto.xy \"type
1500 msec.delay
endcase
until
;
\ *************** File naming routine ******************
: get.name

{prompts} screen.clear
red inten mix foreground \{border\}
red green inten mix foreground
\ get the filename
begin

\ " Enter the filename: 
\"len 2 / 34 - neg 1 goto.xy \"type
\input&check
filename :=
filename defer> file.sizes
0 = 0 = and

if
   file.template
     19 comments
end

?file.open
if
   file.close
then
filename defer> file.create
filename defer> file.open
true
else
    screen.clear
    " A file by that name already exits."
    "len 2 / 38 - neg 1 goto.xy "type
    500 msec.delay
    white inten mix foreground
    " Be more careful next time or the"
    "len 2 / 38 - neg 3 goto.xy "type
    " computer gods will have your data for lunch!"
    "len 2 / 38 - neg 4 goto.xy "type
    2500 msec.delay
    screen.clear
false
then
until
" The munchkins are working furiously!"
"len 2 / 38 - neg 2 goto.xy "type
;

\ *********************** Data taking routine **************************
: take.data

    stack.clear
    stack.reset

    0 signal.desc :=
    0 raw.signal :=

    " dcl" gpib.write

lecroy.scope listener

\ Read the data descriptor

    signal.desc []gpib.buffer
    gpib.buffer.reset
" READ,"
channel
"cat
" .DE"
"cat
gpib.write
me listener
lecroy.scope talker
buffer.listen

\ Read the waveform limit

" INS,"
channel
"cat
" .LI"
"cat
gpib.write
dummy gpib.read
dummy
ascii , "number
limit :=
limit "."
state "[ 15 ] " :=

\ Read the raw data

lecroy.scope
eos.off
raw.signal dma.gpib.buffer
gpib.buffer.reset

" READ,"
channel
"cat
" .DA,"
"cat
" 1,32000,"
"cat
state "[ 15 ]
"cat
gpib.write
me listener
lecroy.scope talker
dma.listen
eos.on

stack.clear
stack.reset

; \\
********************** Data conversion routine **********************

: convert.data

    stack.clear
    stack.reset

    0 signal :=

    \ Unpack the signal

    raw.signal
    sub[ 3 , 4000 ]
    unpack
    signal
    sub[ 1 , 8000 ] :=
    raw.signal
    sub[ 4003 , 4000 ]
    unpack
    signal
    sub[ 8001 , 8000 ] :=
    raw.signal
    sub[ 8003 , 4000 ]
    unpack
    signal
    sub[ 16001 , 8000 ] :=
    raw.signal
    sub[ 12003 , 4000 ]
    unpack
    signal
    sub[ 24001 , 8000 ] :=
stack.clear
stack.reset

\ Unpack the signal description

signal.desc unpack
sub[ 5 , 28 ]
desc.data :=

\ Define the fixed vertical gain (volts/division) (state "[ 1 ]")

desc.data [ 1 ]
  22 - false
  case
    0 of
      .005
      endof
    1 of
      .01
      endof
    2 of
      .02
      endof
    3 of
      .05
      endof
    4 of
      .1
      endof
    5 of
      .2
      endof
    6 of
      .5
      endof
    7 of
      1.
      endof
    8 of
\ Define the variable vertical gain (state "[ 13 ])

desc.data [ 2 ]
0.005 *
0.4 +
"."
state "[ 13 ]" :=

\ Define the vertical offset (state "[ 14 ])

desc.data [ 5 ]
256 *
desc.data [ 6 ] +
0.04 *
8.0 -
"."
" div "
"cat
state "[ 14 ]" :=

\ Define the input channel coupling (state "[ 10 ])

desc.data [ 7 ]
false
case
  0 of
    " dc, 50 "
  endof
  1 of
  " Ground "
  endof
Determine the status of the bw limiting option (state "[ 11 ]")

desc.data [ 9 ]
false
case
  0 of
    " off "
    endof
  1 of
    " on "
    endof
endcase
state "[ 11 ] ":=

\ Determine the time base (microseconds/division) (state "[ 2 ]")

desc.data [ 10 ]
false
case
  4 of
    .002
    endof
  5 of
    .005
    endof
  6 of
    .01
    endof
  7 of
    .02
endof
8 of
  .05
endof
9 of
  .1
endof
10 of
  .2
endof
11 of
  .5
endof
12 of
  1
endof
13 of
  2
endof
14 of
  5
endof
15 of
  10
endof
16 of
  20
endof
17 of
  50
endof
18 of
  100
endof
19 of
  200
endof
20 of
  500
endof
21 of
  1000
endof
22 of
  2000
endof
23 of
  5000
endof
24 of
  10000
endof
25 of
  20000
endof
26 of
  50000
endof
27 of
  100000
endof
28 of
  200000
endof
29 of
  500000
endof
30 of
  1000000
endof
31 of
  2000000
endof
32 of
  5000000
endof
33 of
  10000000
endof
34 of
  20000000
endof
35 of
  50000000
Determine the sampling interval (microseconds) (state "[ 12 ]")

desc.data [ 11 ]
false
case
11 of
  .0002
  endof
12 of
  .0004
  endof
13 of
  .0008
  endof
16 of
  .01
  endof
17 of
  .02
  endof
18 of
  .04
  endof
19 of
  .08
  endof
20 of
  .2
  endof
21 of
  .4
  endof
22 of
  .8
  endof
23 of
  2.
  endof
24 of
  4.
  endof
25 of
  8.
  endof
26 of
  20.
  endof
27 of
  40.
  endof
28 of
  80.
  endof
29 of
  200.
  endof
30 of
  400.
  endof
31 of
  800.
  endof
32 of
  2000.
  endof
33 of
  4000.
  endof
34 of
  8000.
  endof
35 of
  20000.
  endof
I I I I
\ usec/div 
"cat
state "[ 12 ] ":=

\ Define the record type (state "[ 9 ]")

desc.data [ 12 ]
127 >
if
    desc.data [ 12 ]
    128 -
else
    desc.data [ 12 ]
then
false
case
0 of
    " non-interleaved "
endof
3 of
   " inter / 25 swps "
endof
4 of
   " inter / 50 swps "
endof
5 of
   " inter / 100 swps "
endof
-3 of
   " seqnce / 8 segs "
endof
-4 of
   " seqnce / 15 segs "
endof
-5 of
   " seqnce / 31 segs "
endof
-6 of
   " seqnce / 62 segs "
endof
-7 of
   " seqnce / 125 segs "
endof
-8 of
   " seqnce / 250 segs "
endof
endcase
state "[ 9 ] ":=

\ Determine the trigger coupling (state "[ 5 ]")

desc.data [ 13 ]
false
case
  0 of
    " dc "
endof
  1 of
    " hf rej "
endof
Determine the trigger mode (state "[ 6 ]")

desc.data [ 14 ]
false

case
0 of
" single "
endof
1 of
" normal "
endof
2 of
" auto "
endof
3 of
" sequence "
endof
endcase
state "[ 6 ]" :=

\ Determine the trigger source (state "[ 3 ]")

desc.data [ 15 ]
false

case
0 of
" ext/10 "
endof
1 of
" ext  "
endof
2 of
" line  "
endof
endof
3 of
  " chan 2"
endof
4 of
  " chan 1"
endof
endcase
state "[ 3 ]" :=
\ Determine the trigger slope (state "[ 4 ]")

desc.data [ 16 ]
false
case
  0 of
    " negative"
endof
  1 of
    " positive"
endof
  2 of
    " window"
endof
endcase
state "[ 4 ]" :=
\ Determine the trigger level (state "[ 8 ]")

desc.data [ 17 ]
256 *
desc.data [ 18 ] +
scratch :=
desc.data [ 16 ]
false
case
  2 of
    2 0 goto.xy." 1"
desc.data [ 15 ]
false
case
0 of
  scratch
  .08 *
  10 *
  "." " v " "cat
  endif
1 of
  scratch
  .08 *
  "." " v " "cat
  endif
  scratch
  .02 *
  "." " div " "cat
  endcase
desc.data [ 15 ]
false
case
  0 of
    scratch
    .016 *
    2 -
    10 *
    "." " v " "cat
    endif
  1 of
    scratch
    .016 *
    2 -
    "." " v " "cat
    endif
scratch
  .04 *
  5 -
  "."
  " div"
  "cat
  endcase
endcase
state "[ 8 ]":=
10000 msec.delay

\ Determine the trigger delay (state "[ 7 ]")

  desc.data [ 19 ]
  127 >
  if
  desc.data [ 19 ]
  256 -
  16777216 *
  desc.data [ 20 ]
  65536 * +
  desc.data [ 21 ]
  256 * +
  desc.data [ 22 ] +
else
  desc.data [ 21 ]
  256 *
  desc.data [ 22 ] +
then
  .02 *
  "."
  " div"
  "cat
state "[ 7 ]":=

\ Determine the number of data points/division (state "[ 17 ]")

  desc.data [ 23 ]
  127 >
  if
  desc.data [ 23 ]
  256 -
256 *
   desc.data [ 24 ] +
else
   desc.data [ 23 ]
   256 *
   desc.data [ 24 ] +
then
   "".
state "[ 17 ] " :=

\ Determine the relative address of the
\ first data point (state "[ 15 ]")

desc.data [ 25 ]
127 >
if
   desc.data [ 25 ]
   256 -
   256 *
   desc.data [ 26 ] +
else
   desc.data [ 25 ]
   256 *
   desc.data [ 26 ] +
then
   "".
state "[ 15 ] " :=

\ Determine the relative address of the
\ last data point (state "[ 16 ]")

desc.data [ 27 ]
127 >
if
   desc.data [ 27 ]
   256 -
   256 *
   desc.data [ 28 ] +
else
   desc.data [ 27 ]
   256 *
   desc.data [ 28 ] +
then
"."
state "[ 16 ] " :=

stack.clear
stack.reset

;

\ ******************** ASYST file generation *************************

: asyst.file

stack.clear
stack.reset

3 1 do
  info "[ I ] I >comment
loop
18 1 do
  state "[ I ] 2 I + >comment
loop

signal
append.array>file

stack.clear
stack.reset

;

\ ******************** Transfer Data **********************

: trans.dat

" " state " :=
" Signal Transfer Routine for the LeCroy 9400A"
filename " :=
acq.menu
modify.comment
get.name
take.data
convert.data
asyst.file
file.close
filename
lastfile "="

{prompts} screen.clear
red inten mix foreground {border}
red green inten mix foreground

;

\ **************************** Transfer Channel 1 ****************************

: trans.ch1

" C1"
channel "="

trans.dat

" Your data has been saved from channel 1."
"len 2 / 38 - neg 2 goto.xy "type
1500 msec.delay
white inten mix foreground
" Now offer an appropriate sacrifice to the computer gods!"
"len 2 / 38 - neg 4 goto.xy "type
3500 msec.delay

main.menu

;

\ **************************** Transfer Channel 2 ****************************

: trans.ch2

" C2"
channel "="

trans.dat
"Your data has been saved from channel 2."
"len 2 / 38 - neg 2 goto.xy "type
1500 msec.delay
white inten mix foreground
"Does the hard drive still eat files at random?"
"len 2 / 38 - neg 4 goto.xy "type
3500 msec.delay

main.menu

;

\ **************************** Transfer Memory C ****************************

: trans.memc

" MC"
channel ":=

trans.dat

"Your data has been saved from memory C."
"len 2 / 38 - neg 2 goto.xy "type
1500 msec.delay
white inten mix foreground
"A binary file, yea! Now we know what to have for lunch!"
"len 2 / 38 - neg 4 goto.xy "type
3500 msec.delay

main.menu

;

\ **************************** Transfer Memory D ****************************

: trans.memd

" MD"
channel ":=

trans.dat
"Your data has been saved from memory D."

"len 2 / 38 - neg 2 goto.xy "type
1500 msec.delay
white inten mix foreground
"At least we think it's saved, ... maybe, ... somewhere."
"len 2 / 38 - neg 4 goto.xy "type
3500 msec.delay

main.menu

;

\********************************************************************* Review old data *********************************************************************

: review.data

stack.clear
stack.reset

{prompts} screen.clear
red inten mix foreground {border}
red green inten mix foreground

"Do you wish to open a new file? (y/n)"
"len 2 / 34 - neg 1 goto.xy "type
get.y/n

if
  0 flag :=
else
  1 flag :=
then

flag 0 =

if

begin

screen.clear
"Enter the filename:"
"len 2 / 34 - neg 1 goto.xy "type
"input&check
filename " :=
filename defer> file.sizes
0 :=
not
if
  ?file.open
  if
    file.close
then
filename defer> file.open
file.contents
narrays :=
20 3 goto.xy ." There is "
narrays
29 3 goto.xy .
33 3 goto.xy ." data array in"
filename
49 3 goto.xy "type
20 5 goto.xy ." Which array do you wish to review?"
55 5 goto.xy #enter&check
filenum :=
3 1 do
  I comment> info "[ I ] " :=
loop
18 1 do
  2 I + comment> state "[ I ] " :=
loop

filenum subfile
signal
file>array
true
else
screen.clear
" I can't find that file, care to try again? (y/n) "
"len 2 / 38 - neg 2 goto.xy "type
get.y/n
not

then

until

else

lastfile
filename ":=
filename defer> file.open
1 filenum :=
file.contents
narrays :=

19 3 goto.xy ": There is"
narrays
28 3 goto.xy 
32 3 goto.xy ": data array in"
filename
48 3 goto.xy "type
19 5 goto.xy ": The last array you reviewed was number"
filenum
57 5 goto.xy 
19 7 goto.xy ": Which array do you now wish to review?"
58 7 goto.xy #enter&check
filenum :=

filenum subfile
signal
file>array

then

acq.menu
{fprompt} screen.clear
red inten mix foreground {border}
white inten mix foreground
" Press any key to return to the main menu."
"len 2 / 38 - neg 1 goto.xy "type
key

stack.clear
stack.reset
main.menu

;

\ ********************** ASCII file generation **********************

: ascii.file

stack.clear
stack.reset

{prompts} screen.clear
red inten mix foreground {border}
red green inten mix foreground

begin

" Enter the filename: "
"len 2 / 35 - neg 1 goto.xy "type
"input&check
filename ":=
filename defer> file.sizes
0 =

if

" The data gremlins are chomping at the bits!"
"len 2 / 38 - neg 3 goto.xy "type
filename defer> out>file
console.off

32001 + 1 do
 signal [ I ] . cr
loop
out>file.close
true
else
"A file by that name already exists."
"len 2 / 38 - neg 3 goto.xy "type
500 msec.delay
white inten mix foreground
"Such a lack of originality! Come on,"
"len 2 / 38 - neg 5 goto.xy "type
"put some thought into it this time!"
"len 2 / 38 - neg 6 goto.xy "type
2500 msec.delay
false
then
until
screen.clear
"The computer gods have smiled upon you!"
"len 2 / 38 - neg 1 goto.xy "type
"They have saved your data for all to see!"
"len 2 / 38 - neg 3 goto.xy "type
1000 msec.delay
white inten mix foreground
"A frightening thought, isn't it?"
"len 2 / 38 - neg 5 goto.xy "type
2500 msec.delay
main.menu
stack.clear
stack.reset

;\
\*************** Disable Remote Control ***********************
: rem.off
remote.enable.off

{prompts} screen.clear
red inten mix foreground {border}
red green inten mix foreground

" The Lecroy should now be in manual mode."
"len 2 / 38 - neg 1 goto.xy "type
" Hit any key to continue GPIB control."
"len 2 / 38 - neg 3 goto.xy "type

cpkey

send.interface.clear
remote.enable.on
lecroy.scope

main.menu

;

\\ *************** Screen dump to the 7470A ***************

: screen.dump

{prompts} screen.clear
red inten mix foreground {border}
red green inten mix foreground

" The plotter should be busy now, but the computer"
"len 2 / 38 - neg 1 goto.xy "type
" is resting for a fixed delay time. Don't bother"
"len 2 / 38 - neg 2 goto.xy "type
" it! When it's feeling better it'll return you to"
"len 2 / 38 - neg 3 goto.xy "type
" the main menu."
"len 2 / 38 - neg 4 goto.xy "type

" PT,HP,GP,NS,2" gpib.write
" SCR,RM" gpib.write
" PS,A4" gpib.write
" SD" gpib.write
lecroy.scope talker
plotter listener
go.to.standby
150000 msec.delay

untalk
send.interface.clear
remote.enable.on

screen.clear
main.menu

;

\ ******************** Exit to ASYST routine ********************

: >asyst
  remote.enable.off
  ?file.open if file.close then
  chdir \
asyst
  clear.function.keys
  line.edit
  white mix foreground
  normal.display
  quit
  ;

\ ******************** Set-up the function keys ********************

: fnc.keys
  clear.function.keys
  f1 function.key.does trans.ch1
  f2 function.key.does trans.ch2
  f3 function.key.does trans.memc
  f4 function.key.does trans.memd
  f5 function.key.does rem.off
  f6 function.key.does screen.dump
  f8 function.key.does ascii.file
  f9 function.key.does review.data
  f10 function.key.does >asyst
\ *************** Lecroy Driver ***************

: lecroy

" Signal Transfer Routine for the LeCroy 9400A"
filename ":=

chdir \lecroy \ default to the data directory
main.menu \ display the main menu
fnc.keys \ define the function keys
interpret.keys \ do as you’re told

onerr:
  stack.clear \ in case of an error
  ?file.open if file.close then \ close all open files
  normal.display \ and tell you about the error
{prompts} screen.clear {border}
" *** ERROR ***"
"len 2 / 38 - neg 1 goto.xy "type
?error# error.message error.trace
" Press any key to continue"
"len 2 / 55 - neg 5 goto.xy "type
key 0 = if key drop then
  myself

;
Appendix C

Numerical Simulation

PROGRAM DPFROG

* This program, written in double precision, is intended to be used
* to predict and examine the occurrence of auto-oscillations in
* circular YIG films. Information determined from the low power
* spectrum of the film is used to characterize the film properties
* and serves as the primary source of input to the program. There
* are three modes of operation: the interaction matrix $A(i,j,k,l)$
* can be calculated and printed, a single point in the bias field -
* attenuation variable space can be extensively analyzed, or a map
* of potential auto-oscillatory points can be generated.

INTEGER CIVFLAG, ERRFLAG, EXCFLAG, RUNFLAG
COMMON/FLAGS/ CIVFLAG, ERRFLAG, EXCFLAG, RUNFLAG
COMMON/WORKSP/ RWKSP(10000)

* Set the workspace needed by the IMSL FFT routine.

CALL IWKIN(10000)

* Read the input data.

CALL INPUT

* Initialize the zeroes of the Bessel functions.

CALL SETJZ

* Calculate the interaction matrix $A$.

CALL AIJKL
* If there's more to do, then do it!

IF ( RUNFLAG .EQ. 1 ) THEN

* Analyze a single point in the field-attenuation space.

CALL SINGLE

ELSEIF ( RUNFLAG .EQ. 2 ) THEN

* Generate a map of potential auto-oscillatory points.

CALL SWEEP

ELSE

* Emulate the direct spectrum output.

CALL DSPECTRUM

ENDIF

* That's a wrap!

END

**************************************************************************

SUBROUTINE INPUT

* Declare the arrays and variables which appear
* in the common blocks used by this subroutine.

COMPLEX*16 EVAL(14), EVEC(14,14)

INTEGER CIVFLAG, ERRFLAG, EXCFLAG, RUNFLAG, S(10)

REAL*8 C(20), ERREL, PFI, RFN
REAL*8 JZERO(0:8,9)
REAL*8 GAMMA, PI, SGAMMA
REAL*8 HO, HP, HRES(10), MS
REAL*8 PAR1, PAR3, PAR4, TOL
REAL*8 ATT, ATTINC, ATTSTRT, ATTEND, CIV(20),
1                 HMAX, HJOIN, HOSTRT, HOEND, TSPAN

* Declare the common blocks used in this subroutine.
COMMON/ANALYSIS/ C, ERREL, EVAL, EVEC, ITMAX, PFI, RFN
COMMON/BES/   NU(10), S, JZERO
COMMON/CONST/ GAMMA, PI, SGAMMA
COMMON/FIELDS/ HO, HP, HRES, MS
COMMON/FLAGS/ CIVFLAG, ERRFLAG, EXCFLAG, RUNFLAG
COMMON/INTEG/ PARI, PAR3, PAR4, TOL
COMMON/RUNDATA/ ATT, ATTINC, ATTSTRT, ATTEND, CIV,
1                 HMAX, HJOIN, HOSTRT, HOEND, NMODES,
2                 NPTS, TSPAN

* Declare the local variables.
REAL*8 DF, FMS, FOUR, ONE, PO, TWO, V, ZERO

* Initialize the numerical and physical constants.
FOUR  = 4.0D+00
ONE   = 1.0D+00
PI    = FOUR * DATANC(ONE)
SGAMMA = 17.6D+00
TWO   = 2.0D+00
ZERO  = 0.0D+00

* Read the initial input parameters.
READ *, RUNFLAG, EXCFLAG
READ *, NMODES, GAMMA, FMS

* If more than 7 modes are requested, stop the
* program and note on the *.LOG file that the
* ANALYSIS package is not set to handle more
* than 7 modes.
IF ( NMODES .GT. 7 ) THEN
  PRINT *, ' More than 7 modes requires modification'
  PRINT *, ' of the ANALYSIS subroutine.'
  STOP5
Define the saturation magnetization.

\[
MS = \frac{FMS}{(\text{FOUR} \times \text{PI})}
\]

Read the modes and their resonant fields.

\[
\text{DO 100 } I = 1, \text{ NMODES}
\]
\[
\text{READ *, NU(I), S(I), HRES(I)}
\]
\[
100 \text{ CONTINUE}
\]

Check the runflag to determine which type of execution is being requested.

\[
\text{IF ( RUNFLAG .EQ. 0 ) THEN}
\]

Only the values of the interaction matrix are required so there is nothing else to be input.

RETURN

\[
\text{ELSEIF ( RUNFLAG .EQ. 1 ) THEN}
\]

A single point analysis is to be performed.

Input the field, attenuation, initialization of the mode amplitudes, the number of data points to be generated, and the time span of the first 2048 signal data points.

\[
\text{READ *, HO, ATT}
\]
\[
\text{READ *, CIVFLAG}
\]
\[
\text{DO 200 } I = 1, \text{ NMODES}
\]
\[
\text{IF ( CIVFLAG .EQ. 5 ) THEN}
\]
\[
\text{READ *, CIV(2*I-1), CIV(2*I)}
\]
\[
\text{ELSE}
\]
\[
\text{CIV(2*I ) = ZERO}
\]
\[
\text{CIV(2*I-1) = ZERO}
\]
\[
\text{ENDIF}
\]
\[
200 \text{ CONTINUE}
\]
\[
\text{READ *, NPTS, TSPAN}
\]
ELSEIF ( RUNFLAG .EQ. 2 ) THEN

* A map has been requested. Input the starting and ending field and attenuation along with the increment for each.

READ *, HOSTRT, HOEND, HOINC
READ *, ATTSTRT, ATTEND, ATTINC

ELSE

* A direct spectrum has been requested. Input the starting and ending field, the field increment, and the attenuation.

READ *, HOSTRT, HOEND, HOINC
READ *, ATT

ENDIF

* Input the parameters for the IMSL integration routine DIVPRK, and for the IMSL nonlinear equation routine DNEQN. PAR1 is the initial integration time step, PAR3 is the maximum integration time step, PAR4 is the maximum number of integration steps, TOL is the integration error tolerance, ERREL is the error tolerance for computing the stationary state, and ITMAX is the maximum number of iterations allowed in the computation of the stationary state.

READ *, PAR1, PAR3, PAR4, TOL
IF ( RUNFLAG .EQ. 1 .OR. RUNFLAG .EQ. 2 ) THEN
  READ *, ERREL, ITMAX
ENDIF

* Input the 0 dB pumping power and the frequency half-width at half-maximum for the cavity, then compute the volume of the cavity and the maximum rf pumping field.

READ *, PO, DF
V = 4.5D+00 * 2.25D+00 * ONE
HPMAX = TWO * SQRT( TWO * PO / ( 100.0D+00 * DF * V ) )
* That's it for the easy part, now go do the real work!

RETURN

END

*************************************************************************

SUBROUTINE SINGLE

* Declare the arrays and variables which appear
* in the common blocks used in this subroutine.

COMPLEX*16 EVAL(14), EVEC(14,14)

INTEGER CIVFLAG, ERRFLAG, EXCFLAG, RUNFLAG, S(10), TOP10(10)

REAL*8 C(20), ERREL, PFI, RFN
REAL*8 JZERO(0:8,9)
REAL*8 GAMMA, PI, SGAMMA
REAL*8 FREQ(1024), FT(1024), SIGNAL(2048)
REAL*8 HO, HP, HRES(10), MS
REAL*8 PAR1, PAR3, PAR4, TOL
REAL*8 A(10,10,10,10), ISTAR(10)
REAL*8 ATT, ATTINC, ATTSTRT, ATTEND, CIV(20),
  1 HPMAX, HOINC, HOSTRT, HOEND, TSPAN
REAL*8 AMAX, AMIN, AVG

* Declare the common blocks used in this subroutine.

COMMON/ANALYSIS/ C, ERREL, EVAL, EVEC, ITMAX, PFI, RFN
COMMON/BES/ NU(10), S, JZERO
COMMON/CONST/ GAMMA, PI, SGAMMA
COMMON/FFT/ FREQ, FT, SIGNAL
COMMON/FIELDS/ HO, HP, HRES, MS
COMMON/FLAGS/ CIVFLAG, ERRFLAG, EXCFLAG, RUNFLAG
COMMON/INTEG/ PAR1, PAR3, PAR4, TOL
COMMON/INTER/ A, ISTAR, NZT, NZU
COMMON/NUDTA/ ATT, ATTINC, ATTSTRT, ATTEND, CIV,
  1 HPMAX, HOINC, HOSTRT, HOEND, NMDES,
  2 NPTS, TSPAN
* Declare the local arrays and variables.

CHARACTER*120 CIVLBL

REAL*8 AMP(10,2048), CDOT(20), PAR(50), PHASE(10,2048)
REAL*8 ATTREF, FIVE, HOREF, ONE, PTONE, RN, SIGNALX,
1 T, TEN, TEND, TINC, TWENTY, ZERO

* Declare as external the routine to be used by IMSL.

EXTERNAL FCDOT

* Initialize the mode amplitude initial value labels.

CIVLBL( 1:20   ) = 'zero initialization.'
CIVLBL( 21:40  ) = 'upfield sweep.'
CIVLBL( 41:60  ) = 'up-power sweep.'
CIVLBL( 61:80  ) = 'downfield sweep.'
CIVLBL( 81:100 ) = 'down-power sweep.'
CIVLBL( 101:120) = 'user entry.'

* Initialize the constants used in this subroutine.

FIVE  = 5.0D+00
ONE   = 1.0D+00
PTONE = 0.1D+00
TEN   = 10.0D+00
TWENTY = 20.0D+00
ZERO  = 0.0D+00

* Define the number of equations.

NEQ = 2 * NMODES

* Initialize the integration parameters for DIVPRK.

DO 100 I = 1, 50
   PAR(I) = ZERO
100    CONTINUE
PAR(1) = PAR1
PAR(3) = PAR3
PAR(4) = PAR4

* Initialize the mode amplitudes.

DO 150 I = 1, NEQ
   C(I) = CIV(I)
150 CONTINUE

* If the initial mode amplitudes were not initialized
* to zero or entered by the user, then determine them
* by sweeping either the attenuation or the field.

IF ( CIVFLAG .GT. 0 .AND. CIVFLAG .LT. 5 ) THEN

* Save the user input attenuation and field.

   ATTREF = ATT
   HOREF = HO

* Initialize the additional parameters for integration.

   IDO = 1
   T = ZERO
   TEND = ZERO

* Set the initial attenuation/field and increment.
* Insure that the starting attenuation is zero or less.

IF ( CIVFLAG .EQ. 1 ) THEN
   HO = HO - TEN
   HOINC = PTONE
   N = INT( ABS( HOREF - HO ) * TEN )
ELSEIF ( CIVFLAG .EQ. 2 ) THEN
   ATT = ATT - TEN
   ATTINC = PTONE
   N = INT( ABS( ATTREF - ATT ) * TEN )
ELSEIF ( CIVFLAG .EQ. 3 ) THEN
   HO = HO + 1.0D+00
   HOINC = -PTONE
   N = INT( ABS( HO - HOREF ) * TEN )
ELSE
ATT = ATT + TEN
ATTINC = -PTONE
IF ( ATT .GT. ZERO ) THEN
ATT = ZERO
ENDIF
N = INT( ABS( ATT - ATTREF ) * TEN )
ENDIF

* Integrate the system along the attenuation/field path to determine the initial mode amplitudes.

DO 200 I = 1, N
TEND = TEND + ONE
IF ( CIVFLAG .EQ. 1 .OR. CIVFLAG .EQ. 3 ) THEN
HO = HO + HOINC
ELSE
ATT = ATT + ATTINC
ENDIF
HP = HPMAX * TEN ** ( ATT / TWENTY )
CALL DIVPRK( IDO, NEQ, FCDOT, T, TEND, TOL, PAR, C )
200 CONTINUE

* Set the initial mode amplitudes.

DO 250 I = 1, NEQ
CIV(I) = C(I)
250 CONTINUE

* Restore the original attenuation and field values, then terminate the current integration sequence.

ATT = ATTREF
HO = HOREF
IDO = 3
CALL DIVPRK( IDO, NEQ, FCDOT, T, TEND, TOL, PAR, C )

ENDIF

* Record the summary of initial conditions.

IBOT = 20 * CIVFLAG + 1
ITOP = 20 * CIVFLAG + 20
WRITE(1,1000) HO, ATT, CIVLBL(IBOT:ITOP)
WRITE(1,1100)
DO 300 I = 1, NMODES
   WRITE(1,1200) NU(I), S(I), HRES(I), CIV(2*I-1), CIV(2*I)
300 CONTINUE
WRITE(1,1300) GAMMA, HPMAX
WRITE(1,1400) NZU, NWT

* Define the rf pumping field.
HP = HPMAX * TEN ** ( ATT / TWENTY )

* Perform a linear stability analysis.
CALL ANALYSIS

* Record the results of the linear stability analysis.
WRITE(1,1500) ( (C(2*I-1),C(2*I)), I=1,NMODES )
WRITE(1,1600) RFH
WRITE(1,1700) ( EVAL(I), I=1,NEQ )
WRITE(1,1800)
DO 400 J = 1, NMODES
   DO 350 I = 1, NEQ
      WRITE(1,1900) EVEC(I,2*J-1), EVEC(I,2*J)
350 CONTINUE
WRITE(1,2000)
400 CONTINUE
WRITE(1,2100) PFI

* Initialize the additional parameters for integration.
IDO = 1
N = 2048
RN = DBLE( N )
TINC = TSPAN / RN
T = -FIVE
TEND = ZERO

* Integrate the system for 5 microseconds
* in order to reduce/eliminate transients.
CALL DIVPRK( IDO,NEQ,FCDOT,T,TEND,TOL,PAR,C )

* Record the mode amplitudes after 5 microseconds.

WRITE(1,2200) ((C(2*I-1),C(2*I)),I=1,NMDES)

* Generate data files of the signal, mode amplitudes,
* and mode phases for N points over a time TSPAN.

DO 550 I = 1, N
   TEND = TEND + TINC
   CALL DIVPRK( IDO,NEQ,FCDOT,T,TEND,TOL,PAR,C )
   SIGNAL(I) = ZERO
   DO 450 J = 1, NMDES
      IF ( NU(J) .EQ. 0 ) THEN
         SIGNAL(I) = SIGNAL(I) + ISTAR(J) * C(2*J)
      ENDIF
   450 CONTINUE
   SIGNAL(I) = -SGAMMA * HP * SIGNAL(I)
   WRITE(2,2300) T, SIGNAL(I)
   DO 500 J = 1, NMDES
      K = 2*J
      AMP(J,I) = C(K-1) * C(K-1) + C(K) * C(K)
      IF ( C(K-1) .EQ. ZERO .AND. C(K) .EQ. ZERO ) THEN
         PHASE(J,I) = ZERO
      ELSE
         PHASE(J,I) = DATA2(C(K),C(K-1)) * 180.0D+00 / PI
         IF ( PHASE(J,I) .LT. ZERO ) THEN
            PHASE(J,I) = PHASE(J,I) + 360.0D+00
         ENDIF
      ENDIF
   500 CONTINUE
   WRITE(3,2400) T, ( AMP(J,I), J=1,NMDES )
   WRITE(4,2400) T, ( PHASE(J,I), J=1,NMDES )
550 CONTINUE

* Record the mode amplitudes after TSPAN microseconds.

WRITE(1,2500) ((C(2*I-1),C(2*I)),I=1,NMDES)

* Generate a data file of the power spectrum
* of the N point signal data set.
CALL SPECTRA
DO 600 I = 1, 1024
   WRITE(5,2300) FREQ(I), FT(I)
600    CONTINUE

*    Generate the statistics of the signal data.

CALL STAT( 2048, SIGNAL )
WRITE(1,2600) AMAX, AMIN, AVG

*    Generate the statistics of the power spectrum.

CALL STAT( 1024, FT )
WRITE(1,2700) ( (FREQ(TOP10(I)),FT(TOP10(I))), I=1,10 )

*    Generate the power spectrum and statistics
*    for each of the mode amplitudes and phases.

WRITE(1,2800)
DO 750 I = 1, NMODES
   DO 650 J = 1, 2048
      SIGNAL(J) = AMP(I,J)
   650    CONTINUE
   CALL SPECTRA
   CALL STAT( 2048, SIGNAL )
   WRITE(1,2900) I, AMAX, AMIN, AVG
   CALL STAT( 1024, FT )
   WRITE(1,3000) FREQ(TOP10(I)), FT(TOP10(I))
   DO 700 J = 1, 2048
      SIGNAL(J) = PHASE(I,J)
   700    CONTINUE
   CALL SPECTRA
   CALL STAT( 2048, SIGNAL )
   WRITE(1,3100) AMAX, AMIN, AVG
   CALL STAT( 1024, FT )
   WRITE(1,3200) FREQ(TOP10(I)), FT(TOP10(I))
750    CONTINUE

*    If more than 2048 signal data points were
requested, then generate the remainder.

IF ( NPTS .GT. 2048 ) THEN
  NMORE = NPTS - 2048
  DO 850 I = 1, NMORE
    TEND = TEND + TINC
    CALL DIVPRK( IDO, NEQ, FCDOT, T, TEND, TOL, PAR, C )
    SIGNALX = ZERO
    DO 800 J = 1, NMODES
      IF ( NU(J) .EQ. 0 ) THEN
        SIGNALX = SIGNALX + ISTAR(J) * C(2*J)
      ENDIF
    800 CONTINUE
    SIGNALX = -SGAMMA * HP * SIGNALX
     WRITE(2,2300) T, SIGNALX
  850 CONTINUE
ENDIF

* Game, set, match - hit the showers!

RETURN

1000 FORMAT( ' Single point analysis at ', F5.2,
  1         ' G and ', F6.2, ' dB attenuation.' //
  2         ' Initial mode amplitudes determined by ', A / )
1100 FORMAT( ' Modes', 3X, 'Res. Field(G)', 7X,
  1         ' Initial Amplitudes' / )
1200 FORMAT( 1X, 2I2, 5X, F7.2, 7X, 2(2X,E12.5) )
1300 FORMAT( / ' Linewidth:', F6.2, ' G', 7X,
  1         ' 0 dB pumping field: ', F8.5, ' G' / )
1400 FORMAT( ' There are ', I3, ' unique and ', I3,
  1         ' total nonzero elements in the A(ijkl) matrix.' / )
1500 FORMAT( ' Stationary solution: ', 2X, 2(2X,E12.5) /,
  1 9( 24X, 2(2X,E12.5) / ) )
1600 FORMAT( ' Residual function norm: ', E12.5 / )
1700 FORMAT( ' Eigenvalues: ', 2(2X,E12.5) /,
            1 9( 14X, 2(2X,E12.5) / ) )

1800 FORMAT( ' Eigenvectors: ' )

1900 FORMAT( '+', 13X, 2(2X,E12.5), 4X, 2(2X,E12.5) / )

2000 FORMAT( ' ' )

2100 FORMAT( '+Performance index: ', E12.5 / )

2200 FORMAT( ' Mode amplitudes after 5 usec:', 2(1X,E12.5,1X) /,
            1 9( 29X, 2(2X, E12.5) / ) )

2300 FORMAT( 2( 2X, E15.8 ) )

2400 FORMAT( 6(1X,E12.5) / 13X, 5(1X,E12.5) )

2500 FORMAT( ' Mode amplitudes after TSPAN: ', 2(1X,E12.5,1X) /,
            1 9( 29X, 2(2X, E12.5) / ) )

2600 FORMAT( ' Max, min, & average signal: ',
            1 3(2X,E12.5) / )

2700 FORMAT( ' The top 10 freq. and amp.: ',

2800 FORMAT( ' Amplitude and phase summary by mode',
            1 ' ( amp. first line, phase second ): ' //,
            2 ' Mode', 3X, 'Maximum', 7X, 'Minimum', 6X,
            3 ' Average', 7X, 'Top Freq.', 4X,
            4 ' Freq. Amp.' / )

2900 FORMAT( 2X, I1, 3( 2X, E12.5 ) )

3000 FORMAT( '+', 45X, 2( 2X, E12.5 ) )

3100 FORMAT( / 3I , 3( 2X, E12.5 ) )

3200 FORMAT( '+', 45X, 2( 2X, E12.5 ) )

END
SUBROUTINE SWEEP

* Declare the arrays and variables which appear
* in the common blocks used in this subroutine.

COMPLEX*16 EVAL(14), EVEC(14,14)

INTEGER CIVFLAG, ERRFLAG, EXCFLAG, RUNFLAG , S(10)

REAL*8 C(20), ERREL, PFI, RFN
REAL*8 JZERO(0:8,9)
REAL*8 GAMMA, PI, SGAMMA
REAL*8 HO, HP, HRES(10), MS
REAL*8 PAR1, PAR3, PAR4, TOL
REAL*8 A(10,10,10,10), ISTAR(10)
REAL*8 ATT, ATTINC, ATTSTRT, ATTEND, CIV(20),
1 HPMAX, HOINC, HOSTRT, HOEND, TSPAN

* Declare the common blocks used in this subroutine.

COMMON/ANALYSIS/ C, ERREL, EVAL, EVEC, ITMAX, PFI, RFN
COMMON/BES/ NU(10), S, JZERO
COMMON/CONST/ GAMMA, PI, SGAMMA
COMMON/FIELDS/ HO, HP, HRES, MS
COMMON/FLAGS/ CIVFLAG, ERRFLAG, EXCFLAG, RUNFLAG
COMMON/INTEG/ PAR1, PAR3, PAR4, TOL
COMMON/INTER/ A, ISTAR, NZT, NZU
COMMON/RUNDATA/ ATT, ATTINC, ATTSTRT, ATTEND, CIV,
1 HPMAX, HOINC, HOSTRT, HOEND, NMODES,
2 NPTS, TSPAN

* Declare the local arrays and variables.

COMPLEX SPEVAL

REAL*8 FIVE, EVALFRQ(14), EVALPOS(14), EVALRP,
1 PAR(50), ONE, PTONE, PTFIVE,
2 SIGNAL, T, TEN, TEND,
3 TWENTY, TWO, TWOPI, ZERO
* Declare as external the routine to be used by IMSL.

EXTERNAL FCDOT

* Initialize the constants used in this subroutine.

FIVE    = 5.0D+00
ONE     = 1.0D+00
PTONE   = 0.1D+00
PTFIVE  = 0.5D+00
TEN     = 10.0D+00
TWENTY  = 20.0D+00
TWO     = 2.0D+00
TWOPI   = TWO * PI
ZERO    = 0.0D+00

* Record the summary of initial conditions.

WRITE(1,1000) HOSTRT, HOEND, ATTSTRT, ATTEND
WRITE(1,1100)
DO 100 I = 1, NHODES
     WRITE(1,1200) NU(I), S(I), HRES(I), CIV(2*I-1), CIV(2*I)
100 CONTINUE
WRITE(1,1300) GAMMA, HPMAX
WRITE(1,1400) NZU, NZT

* Initialize the integration parameters for DIVPRK.

DO 200 I = 1, 50
     PAR(I) = ZERO
200 CONTINUE
PAR(1) = PARI
PAR(3) = PAR3
PAR(4) = PAR4

* Initialize all other parameters for the sweep.

ATT     = ATTSTRT - ATTINC
IMSLTOT = 0
IWRITFLAG = 0
NEQ     = 2 * NMODES
NPTS = 0
NASTEPS = ( ABS(ATTSTRT - ATTEND) / ABS(ATTINC) ) + 1
NHSTEPS = ( ABS(HOSTRT - HOEND ) / ABS(HOINC ) ) + 1

* The outer loop sweeps through the attenuation values.

DO 700 I = 1, NASTEPS

* Initialize DIVPRK each time a new attenuation is begun.

IDO = 1
T = ZERO

* Initialize the mode amplitudes to zero.

DO 300 J = 1, NEQ
  C(J) = ZERO
300 CONTINUE

* Initialize the additional parameters for the field sweep.

ATT = ATT + ATTINC
HO = HOSTRT - HOINC
HP = HPMAX * TEN ** ( ATT / TWENTY )
NPTSA = 0

* The inner loop sweeps through the field values.

DO 600 J = 1, NHSTEPS

* Initialize the IMSL error counter.

IMSLCNT = 0

* Increment the field.

HO = HO + HOINC

* Check that the routine is progressing satisfactorily.

400 IF ( IMSLCNT .GT. 5 ) THEN
Reset the integration sequence.

IDO = 3
CALL DIVPRK( IDO, NEQ, FCDOT, T, TEND, TOL, PAR, C )

Integrate the system for 5 microseconds in an attempt to eliminate transients and perhaps reach a stable solution for the next field point.

IDO = 1
T = ZERO
TEND = FIVE
CALL DIVPRK( IDO, NEQ, FCDOT, T, TEND, TOL, PAR, C )

Identify the present point as potentially auto-oscillatory, but note its unstable character by listing the number of positive eigenvalues as -1.

NEVPOS = -1
WRITE(6,1500) HO, ATT, NEVPOS
WRITE(7,1600) HO, ATT, ((C(2*K-1),C(2*K)),K=1,NMDES)

Continue the field sweep.

GO TO 600
ENDIF

Increment the final time for the integration, using a larger increment if there has been an error trying to find a solution to the linear stability problem (IMSL error in DNEQNJ).

IF ( IMSLCNT .EQ. 0 .AND. NEVPOS .EQ. 0 ) THEN
TEND = T + PTONE
ELSE
TEND = T + TWO
ENDIF

Integrate the system forward in time from T to TEND.
CALL DIVPRK( IDO, NEQ, FCDOT, T, TEND, TOL, PAR, C )

* Perform a linear stability analysis.

CALL ANALYSIS

* Check for an IMSL error returned from ANALYSIS.

IF ( ERRFLAG .GT. 0 ) THEN
  IMSLCNT = IMSLCNT + 1
  IMSLTOT = IMSLTOT + 1
  GO TO 400
END IF

* Determine the number of eigenvalues with positive real parts
* or with real parts which are very nearly positive since they
* too are often found to produce auto-oscillations.

NEVPOS = 0
DO 500 K = 1, NEQ
  EVALRP = DBLE( EVAL(K) )
  IF ( EVALRP .GT. -0.25D+00 ) THEN
    NEVPOS = NEVPOS + 1
    EVALPOS( NEVPOS ) = EVALRP
    SPEVAL = EVAL(K)
    EVALFRQ( NEVPOS ) = AIMAG( SPEVAL ) / TWOPI
  END IF
500 CONTINUE

* If the point has two or more eigenvalues with positive real
* parts, then it is potentially unstable and may oscillate.
* Record it as an auto-oscillatory point and print the values
* of the mode amplitudes used in the calculation.

IF ( NEVPOS .GE. 2 ) THEN
  NPTSA = NPTSA + 1
  WRITE(6,1500) HO, ATT, NEVPOS, PFI
  WRITE(6,1550) ( EVALPOS(K), K=1,NEVPOS )
  WRITE(6,1550) ( EVALFRQ(K), K=1,NEVPOS )
  WRITE(7,1600) HO, ATT, ((C(2*K-1),C(2*K)),K=1,NM0DES)
END IF
* Continue the field sweep.

600 CONTINUE

* Record the number of potential auto-oscillatory points found at the present attenuation and update the total number of such points found thus far in the sweep.

IF ( NPTSA .GT. 0 ) THEN
   NPTS = NPTS + NPTSA
   IF ( IWRTFLAG .EQ. 0 ) THEN
      IWRTFLAG = 1
      WRITE(1,1700) ATT, NPTSA
   ELSE
      WRITE(1,1800) ATT, NPTSA
   ENDIF
ENDIF

* Terminate the current integration sequence.

IDO = 3
CALL DIVPRK( IDO,NEQ,FCDOT,T,TEND,TOL,PAR,C )

* Note on the *.LOG file that ATT is finished.

IF ( I .EQ. 1 ) THEN
   PRINT *, ' Potential auto-oscillatory points:'
   PRINT *, ' Attenuation:',
   1     Points found:'
   PRINT *, ATT, NPTSA
ELSE
   PRINT *, ATT, NPTSA
ENDIF

* Continue the attenuation sweep.

700 CONTINUE

* Record the total number of potential auto-oscillatory points.

WRITE(1,1900) NPTS
* Note on the *.LOG file the number of IMSL errors handled.

PRINT *, ' Total number of IMSL errors: ', IMSLTOT

* Wrap it up and go home!

RETURN

1000 FORMAT( ' Auto-oscillation map from ', F5.2, ' to ',
1 F5.2, ' G and from ', F6.2, ' to ', F6.2,
2 ' dB attenuation.' / )

1100 FORMAT( ' Modes', 3X, 'Res. Field(G)', 7X,
1 ' Initial Amplitudes' / )

1200 FORMAT( '+', 2I2, 5X, F7.2, 7X, 2(2X,E12.5) / )

1300 FORMAT( ' Linewidth:', F6.2, ' G', 7X,
1 ' 0 dB pumping field: ', F8.5, ' G' / )

1400 FORMAT( ' There are ', I3, ' unique and ', I3,
1 ' total nonzero elements in the A(ijkl) matrix.' / )

1500 FORMAT(/2(2X,F7.3),2X,I2,2X,F8.4)

1550 FORMAT(10(1X,F7.3))

1600 FORMAT(2(2X,F7.3),2(2X,E15.8),9(/18X,2(2X,E15.8)))

1700 FORMAT( ' Number of potential auto-osc. points at ',
1 F6.2, ' dB attenuation: ', I5 )

1800 FORMAT( 41X, F6.2, 17X, I5 )

1900 FORMAT( / ' Total number of potential',
1 ' auto-oscillatory points: ', I5 )

END

*******************************************************************************

SUBROUTINE DSPECTRUM
* Declare the arrays and variables which appear
* in the common blocks used in this subroutine.

INTEGER CIVFLAG, ERRFLAG, EXCFLAG, RUNFLAG, S(10)

REAL*8 JZERO(0:8,9)
REAL*8 GAMMA, PI, SGAMMA
REAL*8 HO, HP, HRES(10), MS
REAL*8 PAR1, PAR3, PAR4, TOL
REAL*8 A(10,10,10,10), ISTAR(10)
REAL*8 ATT, ATTINC, ATTSTRRT, ATTEND, CIV(20),
1 HPMAX, HOINC, HOSTRT, HOEND, TSPAN

* Declare the common blocks used in this subroutine.

COMMON/BES/ NU(10), S, JZERO
COMMON/CONST/ GAMMA, PI, SGAMMA
COMMON/FIELDS/ HO, HP, HRES, MS
COMMON/FLAGS/ CIVFLAG, ERRFLAG, EXCFLAG, RUNFLAG
COMMON/INTEG/ PAR1, PAR3, PAR4, TOL
COMMON/INTER/ A, ISTAR, NZT, NZU
COMMON/RUNDATA/ ATT, ATTINC, ATTSTRRT, ATTEND, CIV,
1 HPMAX, HOINC, HOSTRT, HOEND, NMODES,
2 NPTS, TSPAN

* Declare the local arrays and variables.

REAL*8 C(20), PAR(50), ONE, SIGNAL, T,
1 TEN, TEND, TWENTY, ZERO

* Declare as external the routine to be used by IMSL.

EXTERNAL FCDOT

* Initialize the constants used in this subroutine.

ONE = 1.0D+00
TEN = 1.0D+01
TWENTY = 2.0D+01
ZERO = 0.0D+00
* Initialize the integration parameters for DIVPRK.

DO 100 I = 1, 50
   PAR(I) = ZERO
100   CONTINUE
PAR(1) = PARI
PAR(3) = PAR3
PAR(4) = PAR4

IDO = 1
T = ZERO

* Initialize all other parameters for the sweep.

NEQ = 2 * NMODES
NHSTEPS = (ABS(HOSTRT - HOEND) / ABS(HOINC)) + 1
HP = HPMAX * TEN ** (ATT / TWENTY)
HO = HO - HOINC

* Generate a signal vs. field data file.

DO 300 I = 1, NHSTEPS
   HO = HO + HOINC
   TEND = T + ONE
   CALL DIVPRK(IDO,NEQ,FCDOT,T,TEND,TOL,PAR,C)
   SIGNAL = ZERO
   DO 200 J = 1, NMODES
      IF (NU(J) .EQ. 0) THEN
         SIGNAL = SIGNAL + ISTAR(J) * C(2*J)
      ENDIF
200 CONTINUE
   SIGNAL = -SGAMMA * HP * SIGNAL
   WRITE(8,1000) HO, SIGNAL
300 CONTINUE

RETURN

1000 FORMAT(2(2X,ES15.8))

END

**********************************************************************
SUBROUTINE ANALYSIS

* Declare the arrays and variables which appear
* in the common blocks used in this subroutine.

COMPLEX*16 EVAL(14), EVEC(14,14)

INTEGER CIVFLAG, ERRFLAG, EXCFLAG, RUNFLAG

REAL*8 C(20), ERREL, PFI, RFN
REAL*8 ATT, ATTINC, ATTSTRT, ATTEND, CIV(20),
1 HPMAX, HOINC, HOSTRT, HOEND, TSPAN

* Declare the common blocks used in this subroutine.

COMMON/ANALYSIS/ C, ERREL, EVAL, EVEC, ITMAX, PFI, RFN
COMMON/FLAGS/ CIVFLAG, ERRFLAG, EXCFLAG, RUNFLAG
COMMON/RUNDATA/ ATT, ATTINC, ATTSTRT, ATTEND, CIV,
1 HPMAX, HOINC, HOSTRT, HOEND, NMODES,
2 NPTS, TSPAN

* Declare the local arrays and variables.
* Note that the multiple declarations of similar arrays
* is the result of IMSL requiring exactly dimensioned
* arrays. The use of arrays with variable dimensions
* does not work, hence each possible number of modes
* requires its own set of arrays.

COMPLEX*16 EVAL2(4), EVEC2(4,4), EVAL3(6), EVEC3(6,6),
1 EVAL4(8), EVEC4(8,8), EVAL5(10), EVEC5(10,10),
2 EVAL6(12), EVEC6(12,12), EVAL7(14), EVEC7(14,14)

REAL*8 DFDC2(4,4), X2(4), XGUESS2(4),
1 DFDC3(6,6), X3(6), XGUESS3(6),
2 DFDC4(8,8), X4(8), XGUESS4(8),
3 DFDC5(10,10), X5(10), XGUESS5(10),
4 DFDC6(12,12), X6(12), XGUESS6(12),
5 DFDC7(14,14), X7(14), XGUESS7(14)

* Declare as external the routines to be used by IMSL.
EXTERNAL FCDOT2, JACOB

* Initialize the IMSL error flag, the number of equations,
* and the initial guess for the stationary state solution.

ERRFLAG = 0
NEQ = 2 * NMODES
DO 100 I = 1, NMODES
    IF ( NMODES .EQ. 2 ) THEN
        XGUESS2(2*I-1) = C(2*I-1)
        XGUESS2(2*I ) = C(2*I )
    ELSEIF ( NMODES .EQ. 3 ) THEN
        XGUESS3(2*I-1) = C(2*I-1)
        XGUESS3(2*I ) = C(2*I )
    ELSEIF ( NMODES .EQ. 4 ) THEN
        XGUESS4(2*I-1) = C(2*I-1)
        XGUESS4(2*I ) = C(2*I )
    ELSEIF ( NMODES .EQ. 5 ) THEN
        XGUESS5(2*I-1) = C(2*I-1)
        XGUESS5(2*I ) = C(2*I )
    ELSEIF ( NMODES .EQ. 6 ) THEN
        XGUESS6(2*I-1) = C(2*I-1)
        XGUESS6(2*I ) = C(2*I )
    ELSEIF ( NMODES .EQ. 7 ) THEN
        XGUESS7(2*I-1) = C(2*I-1)
        XGUESS7(2*I ) = C(2*I )
    ENDF
100 CONTINUE

* Set the IMSL error controller so that insufficient
* progress in DNEQNJ does not stop the program.

CALL ERSET( 3, 0, 0 )
CALL ERSET( 4, 0, 0 )

* Compute the stationary state solution.

IF ( NMODES .EQ. 2 ) THEN
    CALL DNEQNJ( FCDOT2, JACOB, ERREL, NEQ, ITMAX, XGUESS2, 12, RFN )
ELSEIF ( NMODES .EQ. 3 ) THEN
    CALL DNEQNJ( FCDOT2, JACOB, ERREL, NEQ, ITMAX, XGUESS3, 13, RFN )
ELSEIF ( NMODES .EQ. 4 ) THEN
    CALL DNEQNJ( FCDOT2, JACOB, ERREL, NEQ, ITMAX, XGUESS4, 14, RFN )
CALL DNEQNH( FCD0T2, JACOB, ERREL, NEQ, ITMAX, XGUESS4, X4, RFH )
ELSEIF ( WMODES .EQ. 5 ) THEN
  CALL DNEQNH( FCD0T2, JACOB, ERREL, NEQ, ITMAX, XGUESS5, X5, RFH )
ELSEIF ( WMODES .EQ. 6 ) THEN
  CALL DNEQNH( FCD0T2, JACOB, ERREL, HEQ, ITMAX, XGUESS6, X6, RFH )
ELSEIF ( WMODES .EQ. 7 ) THEN
  CALL DNEQNH( FCD0T2, JACOB, ERREL, NEQ, ITMAX, XGUESS7, X7, RFH )
ENDIF

* Check for an IMSL error returned from DNEQNH, reset the error
controller, and in the case of an error return to the calling
routine.

ERRFLAG = IERCD()
CALL ERSET( 3, 1, 2 )
CALL ERSET( 4, 1, 2 )
IF ( ERRFLAG .GT. 0 ) RETURN

* Since no error was forthcoming, compute the
* Jacobian using the stationary state solution.

IF ( WMODES .EQ. 2 ) THEN
  CALL JACOB( NEQ, X2, DFDC2 )
ELSEIF ( WMODES .EQ. 3 ) THEN
  CALL JACOB( NEQ, X3, DFDC3 )
ELSEIF ( WMODES .EQ. 4 ) THEN
  CALL JACOB( NEQ, X4, DFDC4 )
ELSEIF ( WMODES .EQ. 5 ) THEN
  CALL JACOB( NEQ, X5, DFDC5 )
ELSEIF ( WMODES .EQ. 6 ) THEN
  CALL JACOB( NEQ, X6, DFDC6 )
ELSEIF ( WMODES .EQ. 7 ) THEN
  CALL JACOB( NEQ, X7, DFDC7 )
ENDIF

* Determine the eigenvalues and eigenvectors of the system,
* then compute the performance index for those values.

IF ( WMODES .EQ. 2 ) THEN
  CALL DEVCRCG( NEQ, DFDC2, NEQ, EVAL2, EVEC2, NEQ )
PFI = DEPIRCG(NEQ, NEQ, DFDC2, NEQ, EVAL2, EVEC2, NEQ)
ELSEIF ( WMODES .EQ. 3 ) THEN
CALL DEVCRG( NEQ, DFDC3, NEQ, EVAL3, EVEC3, NEQ )
PFI = DEPIRG(NEQ, NEQ, DFDC3, NEQ, EVAL3, EVEC3, NEQ)
ELSEIF ( NMODES .EQ. 4 ) THEN
CALL DEVCRG( NEQ, DFDC4, NEQ, EVAL4, EVEC4, NEQ )
PFI = DEPIRG(NEQ, NEQ, DFDC4, NEQ, EVAL4, EVEC4, NEQ)
ELSEIF ( NMODES .EQ. 5 ) THEN
CALL DEVCRG( NEQ, DFDC5, NEQ, EVAL5, EVEC5, NEQ )
PFI = DEPIRG(NEQ, NEQ, DFDC5, NEQ, EVAL5, EVEC5, NEQ)
ELSEIF ( NMODES .EQ. 6 ) THEN
CALL DEVCRG( NEQ, DFDC6, NEQ, EVAL6, EVEC6, NEQ )
PFI = DEPIRG(NEQ, NEQ, DFDC6, NEQ, EVAL6, EVEC6, NEQ)
ELSEIF ( NMODES .EQ. 7 ) THEN
CALL DEVCRG( NEQ, DFDC7, NEQ, EVAL7, EVEC7, NEQ )
PFI = DEPIRG(NEQ, NEQ, DFDC7, NEQ, EVAL7, EVEC7, NEQ)
ENDIF

* Store the eigenvalues and eigenvectors
* in the appropriate common block elements.

DO 300 I = 1, NEQ
  IF ( NMODES .EQ. 2 ) THEN
    EVAL(I) = EVAL2(I)
  ELSEIF ( NMODES .EQ. 3 ) THEN
    EVAL(I) = EVAL3(I)
  ELSEIF ( NMODES .EQ. 4 ) THEN
    EVAL(I) = EVAL4(I)
  ELSEIF ( NMODES .EQ. 5 ) THEN
    EVAL(I) = EVAL5(I)
  ELSEIF ( NMODES .EQ. 6 ) THEN
    EVAL(I) = EVAL6(I)
  ELSEIF ( NMODES .EQ. 7 ) THEN
    EVAL(I) = EVAL7(I)
  ENDIF

DO 200 J = 1, NEQ
  IF ( NMODES .EQ. 2 ) THEN
    EVEC(I,J) = EVEC2(I,J)
  ELSEIF ( NMODES .EQ. 3 ) THEN
    EVEC(I,J) = EVEC3(I,J)
  ELSEIF ( NMODES .EQ. 4 ) THEN
    EVEC(I,J) = EVEC4(I,J)
  ELSEIF ( NMODES .EQ. 5 ) THEN
    EVEC(I,J) = EVEC5(I,J)
ELSEIF ( NMODES .EQ. 6 ) THEN
  EVEC(I,J) = EVEC6(I,J)
ENDIF
ELSEIF ( NMODES .EQ. 7 ) THEN
  EVEC(I,J) = EVEC7(I,J)
ENDIF

200  CONTINUE
300  CONTINUE

* Store the stationary state solution
* in the appropriate common block element.

DO 400 I = 1, NMODES
  IF ( NMODES .EQ. 2 ) THEN
    C(2*I-1) = X2(2*I-1)
    C(2*I ) = X2(2*I )
  ELSEIF ( NMODES .EQ. 3 ) THEN
    C(2*I-1) = X3(2*I-1)
    C(2*I ) = X3(2*I )
  ELSEIF ( NMODES .EQ. 4 ) THEN
    C(2*I-1) = X4(2*I-1)
    C(2*I ) = X4(2*I )
  ELSEIF ( NMODES .EQ. 5 ) THEN
    C(2*I-1) = X5(2*I-1)
    C(2*I ) = X5(2*I )
  ELSEIF ( NMODES .EQ. 6 ) THEN
    C(2*I-1) = X6(2*I-1)
    C(2*I ) = X6(2*I )
  ELSEIF ( NMODES .EQ. 7 ) THEN
    C(2*I-1) = X7(2*I-1)
    C(2*I ) = X7(2*I )
  ENDIF
400  CONTINUE

RETURN

END

******************************************************************************

SUBROUTINE FCDOT( NEQ, T, C, CDOT )

* Declare the arrays and variables which appear
* in the common blocks used in this subroutine.

REAL*8 GAMMA, PI, SGAMMA
REAL*8 HO, HP, HRES(10), MS
REAL*8 A(10,10,10,10), ISTAR(10)
REAL*8 ATT, ATTINC, ATTSTRT, ATTEND, CIV(20),
1 HPMAX, HOINC, HOSTRT, HOEND, TSPAN

* Declare the common blocks used by this subroutine.

COMMON/CONST/ GAMMA, PI, SGAMMA
COMMON/FIELDS/ HO, HP, HRES, MS
COMMON/INTER/ A, ISTAR, NZT, NZU
COMMON/RUNDATA/ ATT, ATTINC, ATTSTRT, ATTEND, CIV,
1 HPMAX, HOINC, HOSTRT, HOEND, NMODES,
2 NPTS, TSPAN

* Declare the local arrays and variables.

REAL*8 C(NEQ), CDOT(NEQ), HALF, T, Z, ZERO

* Initialize the constants used in this subroutine.

HALF = 0.5D+00
ZERO = 0.0D+00

* Cycle through each pair of mode amplitudes.

DO 400 I = 1, NMODES

* Compute the linear portion of the equations of motion.

CDOT(2*I-1) = SGAMMA * ( HO - HRES(I) ) * C(2*I )
1 - SGAMMA * GAMMA * C(2*I-1)
CDOT(2*I ) = - SGAMMA * ( HO - HRES(I) ) * C(2*I-1)
1 - SGAMMA * GAMMA * C(2*I )
2 - HALF * SGAMMA * HP * ISTAR(I)

* Compute the nonlinear contribution, taking full
* advantage of the symmetry of the summation and
* skipping any terms for which Aijkl is zero.
DO 300 J = 1, NMODES
  DO 200 K = 1, NMODES
    Z = C(2*J-1)*C(2*K-1) + C(2*J )*C(2*K )
  DO 100 L = 1, NMODES
    IF ( A(I,J,K,L) .EQ. ZERO ) THEN
      GO TO 100
    ELSE
      CDOT(2*I-1) = CDOT(2*I-1) + 1
      CDOT(2*I  ) = CDOT(2*I  ) - 1
      A(I,J,K,L) * Z * C(2*L )
      A(I,J,K,L) * Z * C(2*L-1)
    ENDIF
  100     CONTINUE
  200    CONTINUE
  300   CONTINUE
  400  CONTINUE
RETURN
END

***************************************************************************

SUBROUTINE FCDOT2( C, CDOT, NEQ )

* Declare the arrays and variables which appear
  in the common blocks used in this subroutine.

REAL*8 GAMMA, PI, SGAMMA
REAL*8 HO, HP, HRES(10), MS
REAL*8 A(10,10,10,10), ISTAR(10)
REAL*8 ATT, ATTINC, ATTSRT, ATTEND, CIV(20),
  1   HPMAX, HOINC, HOSTRT, HOEND, TSPAN

* Declare the common blocks used in this subroutine.

COMMON/CONST/  GAMMA, PI, SGAMMA
COMMON/FIELDS/  HO, HP, HRES, MS
COMMON/INTER/  A, ISTAR, NZT, NZU
COMMON/RUNDATA/ ATT, ATTINC, ATTSRT, ATTEND, CIV,
  1   HPMAX, HOINC, HOSTRT, HOEND, NMODES,
  2   NPTS, TSPAN
* Declare the local arrays and variables.

REAL*8 C(NEQ), CDOT(NEQ), HALF, Z, ZERO

* Initialize the constants used in this subroutine.

HALF = 5.0D-01
ZERO = 0.0D+00

* Cycle through each pair of mode amplitudes.

DO 400 I = 1, NMODES

* Compute the linear portion of the equations of motion.

| CDOT(2*I-1)                      | SGAMMA * ( HO - HRES(I) ) * C(2*I ) |
| 1                                | - SGAMMA * GAMMA * C(2*I-1)         |
| CDOT(2*I)                        | - SGAMMA * ( HO - HRES(I) ) * C(2*I-1) |
| 1                                | - SGAMMA * GAMMA * C(2*I )         |
| 2                                | - HALF * SGAMMA * HP * ISTAR(I)     |

* Compute the nonlinear contribution, taking full
* advantage of the symmetry of the summation and
* skipping any terms for which Aijkl is zero.

DO 300 J = 1, NMODES
  DO 200 K = 1, NMODES
    Z = C(2*J-1)*C(2*K-1) + C(2*J) * C(2*K)
  DO 100 L = 1, NMODES
    IF ( A(I,J,K,L) .EQ. ZERO ) THEN
      GO TO 100
    ELSE
      CDOT(2*I-1) = CDOT(2*I-1) +
      1 A(I,J,K,L) * Z * C(2*L )
      CDOT(2*I ) = CDOT(2*I ) -
      1 A(I,J,K,L) * Z * C(2*L-1)
    ENDFI
100 CONTINUE
200 CONTINUE
300 CONTINUE
400 CONTINUE
SUBROUTINE JACOB( NEQ, C, DFDC )

* Declare the arrays and variables which appear
* in the common blocks used in this subroutine.

REAL*8 GAMMA, PI, SGAMMA
REAL*8 HO, HP, HRES(IO), MS
REAL*8 A(10,10,10,10), ISTAR(IO)
REAL*8 ATT, ATTINC, ATTSTRT, ATTEND, CIV(20),
   1   HPMAX, HOINC, HOSTRT, HOEND, TSPAN

* Declare the common blocks used in this subroutine.

COMMON/CONST/   GAMMA, PI, SGAMMA
COMMON/FIELDS/  HO, HP, HRES, MS
COMMON/INTER/   A, ISTAR, NZT, NZU
COMMON/RUNDATA/ ATT, ATTINC, ATTSTRT, ATTEND, CIV,
   1   HPMAX, HOINC, HOSTRT, HOEND, NMODES,
   2   NPTS, TSPAN

* Declare the local arrays and variables.

REAL*8 C(NEQ), DFDC(NEQ, NEQ)
REAL*8 GG, GH, SUM1, SUM2, SUM3, THREE, TWO, X, Y, Z, ZERO

* Initialize the constants used in this subroutine.

GG = SGAMMA * GAMMA
THREE = 3.0D+00
TWO = 2.0D+00
ZERO = 0.0D+00

* Compute the Jacobian.

DO 400 I = 1, NMODES


```
GH = SGAMMA * ( HO - HRES(I) )
DO 300 M = 1, NModes
  SUM1 = ZERO
  SUM2 = ZERO
  SUM3 = ZERO
  DO 200 K = 1, NModes
    DO 100 L = 1, NModes
      IF ( A(I,M,K,L) .EQ. ZERO ) THEN
        GO TO 100
      ELSE
        X = C(2*K-1) * C(2*L-1)
        Y = C(2*K-1) * C(2*L)
        Z = C(2*K) * C(2*L)
        SUM1 = SUM1 + A(I,M,K,L) * X
        SUM2 = SUM2 + A(I,M,K,L) * Y
        SUM3 = SUM3 + A(I,M,K,L) * Z
      ENDIF
      100 CONTINUE
    200 CONTINUE
    DFDC(2*I-1, 2*M-1) = TWO * SUM2
    DFDC(2*I-1, 2*M)  = SUM1 + THREE * SUM3
    DFDC(2*I , 2*M-1) = -SUM3 - THREE * SUM1
    DFDC(2*I , 2*M)  = -TWO * SUM2
    IF ( M .EQ. I ) THEN
      DFDC(2*I-1, 2*M-1) = DFDC(2*I-1,2*M-1) - GG
      DFDC(2*I-1, 2*M)  = DFDC(2*I-1,2*M)  + GH
      DFDC(2*I , 2*M-1) = DFDC(2*I ,2*M-1) - GH
      DFDC(2*I , 2*M)  = DFDC(2*I ,2*M)  - GG
    ENDIF
  300 CONTINUE
400 CONTINUE
RETURN
END

*******************************************************************************

SUBROUTINE SPECTRA

* Declare the arrays and variables which appear
* in the common blocks used in this subroutine.
```
INTEGER CIVFLAG, ERRFLAG, EXCFLAG, RUNFLAG

REAL*8 GAMMA, PI, SGAMMA
REAL*8 FREQ(1024), FT(1024), SIGNAL(2048)
REAL*8 ATT, ATTINC, ATTSTRT, ATTEND, CIV(20),
1 HPMAX, HOINC, HOSTRT, HOEND, TSPAN

* Declare the common blocks used in this subroutine.

COMMON/CONST/ GAMMA , PI , SGAMMA
COMMON/FFT/ FREQ, FT, SIGNAL
COMMON/FLAGS/ CIVFLAG, ERRFLAG, EXCFLAG, RUNFLAG
COMMON/RUNDATA/ ATT, ATTINC, ATTSTRT, ATTEND, CIV,
1 HPMAX, HOINC, HOSTRT, HOEND, NMODES,
2 NPTS, TSPAN
COMMON/WORKSP/ RWKSP(10000)

* Declare the local arrays and variable.

REAL*8 FT1(2048), RN, SIG1(2048)

* Initialize the number of points to be analyzed.

N = 2048
RN = DBLE( N )

* Store the signal in the temporary array SIG1.

DO 100 I = 1, N
   SIG1(I) = SIGNAL(I)
100 CONTINUE

* Perform the fast-fourier transform.

CALL DFFTRF( N , SIG1 , FT1 )

* Convert the transform output into the power spectra and record the matching frequency.

M = N/2 + 1
DO 200 I = 2, M
FREQ(I-1) = FLOAT(I-1) / TSPAN
FT(I-1) = ( FT1(2*I-2)**2 + FT1(2*I-1)**2 ) / ( TSPAN * RN )
200 CONTINUE

RETURN

END

*******************************************************************************

SUBROUTINE AIJKL

* Declare the arrays and variables which appear
* in the common blocks used in this subroutine.

INTEGER CIVFLAG, ERRFLAG, EXCFLAG, RUNFLAG, S(10)
INTEGER ORD1, ORD2, ORD3, ORD4

REAL*8 JZERO(0:8,9)
REAL*8 X1, X2, X3, X4
REAL*8 GAMMA, PI, SGAMMA
REAL*8 HO, HP, HRES(10), MS
REAL*8 A(10,10,10,10), ISTAR(10)
REAL*8 ATT, ATTNIC, ATTNSTR, ATTEND, CIV(20),
1 HPMAX, HOINC, HOSTRT, HOEND, TSPAN

* Declare the common blocks used in this subroutine.

COMMON/BES/ NU(10), S, JZERO
COMMON/BESFNC/ ORD1, ORD2, ORD3, ORD4, X1, X2, X3, X4
COMMON/CONST/ GAMMA, PI, SGAMMA
COMMON/FIELDS/ HO, HP, HRES, MS
COMMON/FLAGS/ CIVFLAG, ERRFLAG, EXCFLAG, RUNFLAG
COMMON/INTER/ A, ISTAR, WZT, NZU
COMMON/RUNDATA/ ATT, ATTNIC, ATTNSTR, ATTEND, CIV,
1 HPMAX, HOINC, HOSTRT, HOEND, NMODES,
2 NPTS, TSPAN

* Declare the local arrays and variables.

INTEGER IN(4)
REAL*8 BS(20), ERL, ERS, ERT, ONE, RES1,
  1      RES2, TOL, TWO, SQTWO, TWOPI, ZERO,
  2       Z1, Z2, Z3, Z4, ZZ

* Declare as external the routines to be used by IMSL.

EXTERNAL FBES, FCOS

* Initialize constants and integration error limits.

ERL = 1.0D-04
ERS = 1.0D-04
HZU = 0
ONE = 1.0D+00
TOL = 1.0D-06
TWO = 2.0D+00
SQTWO = DSQRT( TWO )
TWOPI = TWO * PI
ZERO = 0.0D+00

* If runflag is set to zero then the A matrix
* is to be computed and output to unit 9. If
* that is true, write the number of modes.

IF ( RUNFLAG .EQ. 0 ) WRITE(9,* ) NModes

* The interaction matrix is symmetric, so the computation
* of the elements requires only the lower triangular portion.

DO 250 I = 1, NModes

* If needed, output the modes used in the calculation of A.

IF ( RUNFLAG .EQ. 0 ) WRITE(9,* ) NU(I), S(I)

DO 200 J = 1, I
   DO 150 K = 1, J
      DO 100 L = 1, K

* Set the order of the Bessel functions and the
* zeros associated with the element Aijkl.
ORD1 = NU(I)
ORD2 = NU(J)
ORD3 = NU(K)
ORD4 = NU(L)
X1 = JZERO( NU(I), S(I) )
X2 = JZERO( NU(J), S(J) )
X3 = JZERO( NU(K), S(K) )
X4 = JZERO( NU(L), S(L) )

* Perform the angular integration.

CALL DQDAGS( FCOS,ZERO,TWOPI,ERS,ERL,RES1,ERT )

* If the result of the integration is nearly zero,
  * attribute that to computational error and set the
  * associated element, Aijkl, to zero.

IF ( DABS(RES1) .LT. TOL ) THEN
  A(I,J,K,L) = ZERO
  GO TO 100
ELSE

* Set the normalization factors to one, which is the
  * correct value for zero order Bessel functions.

Z1 = ONE
Z2 = ONE
Z3 = ONE
Z4 = ONE

* If the order is non-zero the correct normalization
  * factor is the square-root of two.

IF ( ORD1 .GT. 0 ) Z1 = SQTWO
IF ( ORD2 .GT. 0 ) Z2 = SQTWO
IF ( ORD3 .GT. 0 ) Z3 = SQTWO
IF ( ORD4 .GT. 0 ) Z4 = SQTWO

* Normalize the result of the angular integration.

RES1 = Z1 * Z2 * Z3 * Z4 * RES1
ENDDIF

* Perform the radial integration.

CALL QDAGS( FBES,ZERO,ONE,ERS,ERL,RES2,ERT )

* If the result of the integration is nearly zero,
* then attribute that to numerical error and set
* the associated element, Aijkl, to zero.

IF ( ABS(RES2) .LT. TOL ) THEN
  A(I,J,K,L) = ZERO
  GO TO 100
ELSE

* Compute the radial normalization factors.

  CALL DBSJNSC XI, ORD1+2, BS )
  Z1 = BS( ORD1+2 )
  CALL DBSJNSC X2, ORD2+2, BS )
  Z2 = BS( ORD2+2 )
  CALL DBSJNSC X3, ORD3+2, BS )
  Z3 = BS( ORD3+2 )
  CALL DBSJNSC X4, ORD4+2, BS )
  Z4 = BS( ORD4+2 )

* Normalize the result of the radial integration.

  RES2 = RES2 / ( Z1 * Z2 * Z3 * Z4 )

ENDDIF

* Compute the element Aijkl, incorporating the
* prefactors which appear in the equations of
* motion. Since the element is nonzero, increment
* the unique nonzero counter.

  A(I,J,K,L) = TWO * MS * SGAMMA * RES1 * RES2
  IF ( EXCFLAG .GT. 0 ) THEN
    A(I,J,K,L) = 1.5D+00 * A(I,J,K,L)
  ENDDIF
  NZU = NZU + 1
If needed, write the number of unique elements and then list them labeled by their indices.

IF ( RUNFLAG .EQ. 0 ) THEN
   WRITE(9,*) NZU
   DO 450 I = 1, NModes
       DO 400 J = 1, I
           DO 350 K = 1, J
               DO 300 L = 1, K
                   IF ( A(I,J,K,L) .NE. ZERO ) THEN
                       ZZ = A(I,J,K,L)/SGAMMA
                       WRITE(9,*) I, J, K, L, ZZ
                   ENDIF
   ENDIF
   300 CONTINUE
   350 CONTINUE
   400 CONTINUE
   450 CONTINUE
ENDIF

* Initialize the number of indices to be sent to the sorting subroutine and the total number of nonzero elements in the interaction matrix.

N = 4
NZT = 0

* Cycle through the entire interaction matrix, setting all of the nonzero elements to their appropriate value. While doing this, evaluate the normalized dipole moment.

DO 650 I = 1, NModes

* Evaluate the dipole moment.

IF ( NU(I) .EQ. 0 ) THEN
   ISTAR(I) = TWO / JZERO( NU(I), S(I) )
ELSE
  ISTAR(I) = 0.0134D+00
ENDIF
IF ( EXCFLAG .GT. 0 ) THEN
  ISTAR(I) = TWO*SQTWO*ISTAR(I) / (DBLE(EXCFLAG)*PI)
ENDIF

DO 600 J = 1, NMODES
  DO 550 K = 1, NMODES
    DO 500 L = 1, NMODES

* Set and sort the current indicies.

  IN(1) = I
  IN(2) = J
  IN(3) = K
  IN(4) = L
  CALL SORT( H, IH )

* Set the current matrix element.

  A(I,J,K,L) = A(IN(4),IN(3),IN(2),IN(1))

* If the matrix element is nonzero then
* increment the total nonzero element counter.

  IF ( A(I,J,K,L) .EQ. ZERO ) THEN
      GO TO 500
  ELSE
      NZT = NZT + 1
  ENDIF

500        CONTINUE
550        CONTINUE
600        CONTINUE
650        CONTINUE

* Print to the log-file the number of unique and
* total nonzero elements in the interaction matrix.

PRINT *, ' Number of unique nonzero elements in A: ', NZU
PRINT *, ' Total number of nonzero elements in A: ', NZT
REAL*8 FUNCTION FBES( X )

* Declare the arrays and variables which appear
* in the common block used in this subroutine.

INTEGER ORD1, ORD2, ORD3, ORD4

REAL*8 BS(20), X, XI, X2, X3, X4, Z1, Z2, Z3, Z4

* Declare the common block used in this subroutine.

COMMON/BESFNC/ ORD1, ORD2, ORD3, ORD4, XI, X2, X3, X4

* Evaluate the Bessel function of order ORD1 at
* the point X times the Bessel function zero XI.

IF ( ORD1 .EQ. 0 ) THEN
    Z1 = DBSJO( XI*X )
ELSE IF ( ORD1 .EQ. 1 ) THEN
    Z1 = DBSJ1( XI*X )
ELSE
    CALL DBSJNSC( XI*X, ORD1+1, BS )
    Z1 = BS( ORD1+1 )
ENDIF

* Evaluate the Bessel function of order ORD2 at
* the point X times the Bessel function zero X2.

IF ( ORD2 .EQ. 0 ) THEN
    Z2 = DBSJO( X2*X )
ELSE IF ( ORD2 .EQ. 1 ) THEN
    Z2 = DBSJ1( X2*X )
ELSE
    CALL DBSJNSC( X2*X, ORD2+1, BS )
    Z2 = BS( ORD2+1 )
ENDIF
Evaluate the Bessel function of order \( \text{ORD3} \) at the point \( \times \) times the Bessel function zero \( \text{X3} \).

\[
\begin{align*}
\text{IF ( ORD3 .EQ. 0 ) THEN} \\
\text{Z3} &= \text{DBSJO}( \text{X3} \times \text{X} ) \\
\text{ELSE IF ( ORD3 .EQ. 1 ) THEN} \\
\text{Z3} &= \text{DBSJ1}( \text{X3} \times \text{X} ) \\
\text{ELSE} \\
\text{CALL DBSJNS}( \text{X3} \times \text{X}, \text{ORD3}+1, \text{BS} ) \\
\text{Z3} &= \text{BS}( \text{ORD3}+1 )
\end{align*}
\]

Evaluate the Bessel function of order \( \text{ORD4} \) at the point \( \times \) times the Bessel function zero \( \text{X4} \).

\[
\begin{align*}
\text{IF ( ORD4 .EQ. 0 ) THEN} \\
\text{Z4} &= \text{DBSJO}( \text{X4} \times \text{X} ) \\
\text{ELSE IF ( ORD4 .EQ. 1 ) THEN} \\
\text{Z4} &= \text{DBSJ1}( \text{X4} \times \text{X} ) \\
\text{ELSE} \\
\text{CALL DBSJNS}( \text{X4} \times \text{X}, \text{ORD4}+1, \text{BS} ) \\
\text{Z4} &= \text{BS}( \text{ORD4}+1 )
\end{align*}
\]

Return the value \( \times \) times the product of the previous four Bessel function evaluation.

\[
\text{FBES} = \times \text{Z1} \times \text{Z2} \times \text{Z3} \times \text{Z4}
\]

RETURN

END

REAL*8 FUNCTION FCOS( X )

* Declare the variables which appear in the common block used in this subroutine.
INTEGER ORD1, ORD2, ORD3, ORD4
REAL*8 X1, X2, X3, X4

* Declare the common block used in this subroutine.
COMMON/BESFNC/ ORD1, ORD2, ORD3, ORD4, X1, X2, X3, X4
* Declare the local variables.
REAL*8 C1, C2, C3, C4, X

* Initialize the coefficients to the Bessel function orders.
C1 = DBLE( ORD1 )
C2 = DBLE( ORD2 )
C3 = DBLE( ORD3 )
C4 = DBLE( ORD4 )

* Return the product of the four cosines evaluated
* at X times the order of the Bessel function associated
* with each term.
FCOS = DCOS(C1*X) * DCOS(C2*X) * DCOS(C3*X) * DCOS(C4*X)
RETURN
END

********************************************************************

SUBROUTINE SETJZ

* Declare the arrays which appear in the
* common block used in this subroutine.

INTEGER S(10)
REAL*8 JZERO(0:8, 9)

* Declare the common block used in this subroutine.
COMON/BES/ HW(10), S, JZERO

* Initialize the zeroes of the Bessel functions.

JZERO(0, 1) = 2.4048255577D+00
JZERO(0, 2) = 5.5200781103D+00
JZERO(0, 3) = 8.6537279129D+00
JZERO(0, 4) = 11.7915344391D+00
JZERO(0, 5) = 14.9309177086D+00
JZERO(0, 6) = 18.0710639679D+00
JZERO(0, 7) = 21.2116366299D+00
JZERO(0, 8) = 24.3524715308D+00
JZERO(0, 9) = 27.493479132D+00
JZERO(1, 1) = 3.83171D+00
JZERO(1, 2) = 7.01559D+00
JZERO(1, 3) = 10.17347D+00
JZERO(2, 1) = 5.13562D+00
JZERO(3, 1) = 6.38016D+00
JZERO(4, 1) = 7.58834D+00
JZERO(5, 1) = 8.77148D+00

* The capacity of the array JZERO is sufficient to allow entry
* of the Bessel function zeros up to and including (8,9). The
* user should enter them here as needed.

RETURN

END

******************************************************************************

SUBROUTINE SORT( N, A )
*
* This routine sorts a one-dimensional array (A) of length N
* into ascending numerical order using the Heapsort algorithm.
* It is copied from the book "Numerical Recipes" by W.H. Press,
* et. al., Cambridge University Press, 1986.
*
INTEGER A(N), B

L = N/2 + 1
M = N
100 CONTINUE

IF ( L .GT. 1 ) THEN
   L = L-1
   B = A(L)
ELSE
   B = A(M)
   A(M) = A(1)
   M = M-1
   IF ( M .EQ. 1 ) THEN
      A(1) = B
   RETURN
   ENDF
ENDIF
ENDIF

I = L
J = L+L

200 IF ( J .LE. M ) THEN

   IF ( J .LT. M ) THEN
      IF ( A(J) .LT. A(J+1) ) J = J+1
      ENDF
   IF ( B .LT. A(J) ) THEN
      A(I) = A(J)
      I = J
      J = J+J
   ELSE
      J = M+1
      ENDF
   GO TO 200
   ENDF
   A(I) = B
GO TO 100
END
SUBROUTINE STAT( N, A )
*
Declare the arrays and variables which appear
* in the common block used in this subroutine
* and which are passed through the command line.

INTEGER TOP10(10)

REAL*8 A(N), AMAX, AMIN, AVG, SUM
*
Declare the common block used in this subroutine.

COMMON/STAT/ AMAX, AMIN, AVG, TOP10
*
Initialize the maximum and minimum elements,
* the summation, and the index of the ten
* largest elements in the A array.

AMAX = A(1)
AMIN = A(1)
SUM = A(1)
DO 100 I = 1, 10
   TOPIO(I) = 1
100 CONTINUE
*
Cycle through the A array and determine the
* maximum and minimum elements, the sum of all
* the elements, and the indices of the ten
* largest elements.

DO 400 I = 2, N
   IF ( A(I) .GT. AMAX ) THEN
      AMAX = A(I)
   ELSEIF ( A(I) .LT. AMIN ) THEN
      AMIN = A(I)
   ENDIF
   SUM = SUM + A(I)
DO 300 J = 1, 10
   IF ( A(I) .GT. A(TOPIO(J)) ) THEN
DO 200 K = 10, J+1, -1
   TOP10(K) = TOP10(K-1)
   200 CONTINUE
   TOP10(J) = I
   GO TO 400
ENDIF
   300 CONTINUE
   400 CONTINUE

* Compute the average value of the A array.

AVG = SUM / DBLE( N )

RETURN

END


