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USING COMMERCIAL FINITE ELEMENT CODE CALLED ABAQUS IN MODELING HYBRID CONSTRAINED LAYERS DAMPING BEAM STRUCTURE AND QUANTIATIVE DETERMINATION OF THE STABILITY OF IMPLANT-BONE INTERFACE USING RESONANCE FREQUENCY ANALYSIS.

A Thesis

by

DANIEL DELGADO JR

Submitted to the Graduate School of the
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USING COMMERCIAL FINITE ELEMENT CODE CALLED ABAQUS IN MODELING HYBRID CONSTRAINED LAYERS DAMPING BEAM STRUCTURE AND QUANTITATIVE DETERMINATION OF THE STABILITY OF IMPLANT-BONE INTERFACE USING RESONANCE FREQUENCY ANALYSIS.

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DEDICATION

This thesis is dedicated to my wife

Guadalupe V. Delgado

who has given me invaluable educational opportunities and support.

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NOMENCLATURE

A = surface area
C = capacitance
D_{ijkl} = mechanical constitutive tensor
D = elastic modulus
D^* = dynamic elastic modulus
D_1 = elastic storage modulus
D_2 = elastic loss modulus
E_j = electric field
(F) = mechanical force vector
G^* = dynamic shear modulus
G_1 = shear storage modulus
G_2 = shear loss modulus
G_p = proportional gain constant
[I] = identity matrix
K^* = dynamic bulk modulus
K_1 = shear bulk modulus
K_2 = shear bulk modulus
[K] = stiffness bulk modulus
$[K_{uu}]$ = mechanical submatrix of the stiffness matrix
$[K_{u\phi}]$ = piezoelectric coupling submatrix of the stiffness matrix
$[K_{\phi\phi}]$ = electrical submatrix of the stiffness matrix
[M] = mass matrix

M = bending moment
(Q) = electrical charge vector
[T] = transformation matrix
W_d = energy loss per cycle
W_s = peak energy stored per cycle
a = subscript, referring to actuator
e_{ijk} = piezoelectric stress coefficients
h = thickness of layer
p = pressure
p_{ij} = dielectric constant (permittivity)
q_i = electric displacement
s = subscript, referring to sensor
u = displacement
x = Cartesian dimension
ε_{ij} = strain tensor
η = system loss factor
η_m = material loss factor
ϕ = electric potential
υ = Poisson's ratio
υ^* = dynamic Poisson's ratio
σ_{ij} = stress tensor
ω_r = resonance frequency
ω_1, ω_2 = half-power frequencies

x

PREFACE

Vibration study and control of structures is among the major research subjects in

mechanical engineering and related technical disciplines. Among the most active research

in the area, one finds the following two issues. On one hand, conventional structural

designs are often unacceptable in coping with modern problems of structural resonance

caused by the complex nature of dynamic environments and the requirements of design

objectives, including low noise, light weight, long life, and increased reliability. On the

other hand, structural dynamic characteristics can be used to infer information of the

integrity and the boundary conditions of a structure.

In chapter 1, we focus on controlling vibrations in beam structures and then focus on how

to model composite beams in Finite Elements without developing your own Finite

Element code. It has been demonstrated that the damping treatments for beam and plate

structures are effective, and the vibrational behaviors of the systems considered are

influenced by many geometrical and material parameters. Therefore, one approach to

solving the high vibration and noise levels of structural resonance problems is to

incorporate a high-energy-dissipating mechanism into the structure during fabrication

with surface damping treatments. Surface damping treatments are usually classified as

extensional or shear damping treatments. Shear damping treatments include Passive

Constrained Layer Damping (PCLD) and Active Constrained Layer Damping (ACLD).

For a given weight, the shear type of damping treatment is more efficient that the

extensional or unconstrained layer-damping treatment. However, this efficiency is balanced by greater complication in analysis and application.

In extensional damping, the structure is coated on one or both sides with damping materials. Therefore, when it is subjected to cyclic loading, the damping material will be subjected to tension-compression deformation. On the other hand, PCLD systems consist of a stiff constraining layer placed on a viscoelastic material (VEM) layer, providing energy dissipation primarily from shearing in that layer. ACLD systems generally consist of a piece of VEM layer sandwiched between an active piezoelectric layer and a host structure. The main purpose of using a piezoelectric coversheet is its active action that enhances the VEM layer damping ability by increasing the shear angle during operation. However, separate active and passive designs are considered if high active action is needed since the VEM will reduce the active authority of the piezoelectric layer.

In Chapter 2, we develop a quantitative method to establish a standard way to measure stability and osseointegration of implants based on resonance frequency analysis. Among other benefits, these measurements would provide information leading to the prediction of healing time and the implant and the monitoring of the health of the implant's interface.

ABSTRACT

Delgado, Daniel, <u>Using Commercial Finite Element Code Called ABAQUS In Modeling Hybrid Constrained Layers Damping Beam Structure and Quantitative Determination Of The Stability Of Implant-Bone Interface Using Resonance Frequency Analysis.</u> Master of Science (MS), May, 2002, 161 pp., 24 Figures, 14 tables, references, 26 titles.

In Chapter 1, it has been demonstrated that the damping treatments for beam and plate structures are effective, and the vibrational behaviors of the systems considered are influenced by many geometrical and material parameters. This has led to an interest in developing advanced "intelligent" structures. In the past, passive and active damping mechanisms have been used to reduce vibration. The uses of passive constrained layers are limited, but it has dissipative qualities for all the modes of the structure; and the uses of active constrained layers are limited to a single mode control. Recent published papers, many have suggested that a hybrid of active and passive would be the best method to use, but many have to create their own Finite Element Method code to model these hybrids structures and experimentally validate the FEM code. In this chapter we focus on active and passive constrained layers for damping structures, and we have been modeling these structures in a commercial code called ABAQUS. Therefore, the code is going to be validated with experimental and theoretical data of previous paper and determining that the code is accurate to the experimental and theoretical value give the certain material properties, and it can also be used for other structures that are more complex.

In Chapter 2, it is important to have a quantitative method to establish a standard way to measure stability and osseointegration of implants. Among other benefits, these measurements would provide information leading to the prediction of healing time and the implant and the monitoring of the health of the implant's interface.

The dental industry has been looking for non-destructive methods to measure implant integration within the bone. In previous studies, resonance frequency analysis revealed a clear relationship between resonance frequency measurements and stiffness of the implant interface and the effective length of the implant. Earlier studies have examined only one mode of vibration or have suffered from measurement difficulties. Furthermore, no study has evaluated the damping properties of the interface and surrounding tissues.

This chapter describes the development of an instrument capable of capturing and measuring information to characterize the process of dental implant osseointergration. The parameters needed to measure stability and osseointegration of implants are the stiffness of the implant components (which are a function of their geometry and material composition) and the stiffness and damping properties of the implant-bone interface and surrounding tissues. The instrument developed provides valuable information about the stiffness and damping properties of the implant-bone interface obtained through resonance frequency analysis with torsional, longitudinal and transverse vibration. Experimental, analytical, and finite element analysis results are presented.

CHAPTER 1

USING COMMERCIAL FINITE ELEMENT CODE CALLED ABAQUS IN MODELING HYBRID CONSTRAINED LAYERS DAMPING BEAM STRUCTURE

1.1 **Introduction**

There has to be an introduction to the theory and conception behind ACLD and PCLD.

According to Lumsdaine (Lumsdaine et. al.), hybrid constrained layer damping have not

been model with Finite Element Method commercial code, but using a commercial code

would let many studies in ACLD and PCLD to continue without a great deal of

investment and getting fully equip with many different testing models. Using Finite

Element code, you can also develop many changes of the model without many difficulties

than in experimental testing, it can become very expense to change the model. Also,

creating you own Finite Element code can be long time consuming task to under take

because you have to a good understanding on how Finite Element Method are used, and

this will take years of experiences to accomplish. If you do not have the expertise, you

can get into a problem that cannot be notices by the code that you create; so you will have

an uncertainly on your solution because it my take many different tries to decode and fix

all the problems with your code. In using a commercial code, ABAQUS can be a better

and easier place to start modeling advanced "intelligent" structures by incorporating

sensors, actuators into your model. Controlling mechanical systems has become an

increasing interesting by many aerospace industries in advancement studies in space

structures. In development of these structures, there has to be a faster way to develop and

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test these models. In this chapter, I will try to uses a commercial code called ABAQUS in developing models of these advanced structures.

1.2 Technical Background

In reviewing recent papers, the construction of an ACLD layer is as follows. According to Lumsdaine (Lumsdaine et. al.), a piezoelectric ceramic actuator is used as a constraining layer in the place of the simple elastic structure. This can produces additional vibration damping through two means, one active and one passive. Actively, the actuator provides a restoring moment to the base structure, attenuating its motion. This active effect is less that it would be if attached directly to the beam, as it must act through a compliant viscoelastic layer. Passively, the actuator contracts and expands at points in the vibration cycle which induces a greater shearing strain in the damping layer than would be possible in the purely passive case. (Lumsdaine et. al.) The problem is that where would it be the best placement of the actuator and sensor to give the best response. Figure 1-1 shows some examples of two alternative structures of the sensor and the actuator.

Piezoelectric Actuator

Viscoelastic Damping Layer

Base Beam

Piezoelectric Sensor

Piezoelectric Actuator

Viscoelastic Damping Layer

Piezoelectric Sensor

Base Beam
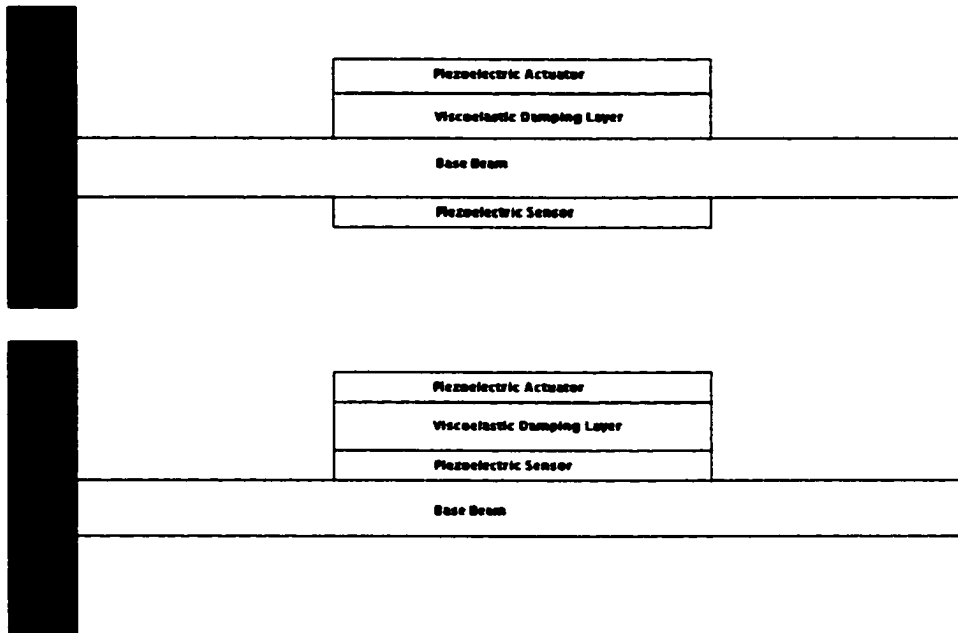
Figure 1-1 Two different Active Constrained Layer Beam Configurations.

1.3 Finite Elements Modeling

In finite elements modeling, the structures should be broken up into three parts. The first

one is the basic finite elements equations for a beam structure. The constitutive

relationship for beam material can be written as (Lumsdaine et. al.):

$$\sigma_{ij} = D_{ijkl}\varepsilon_{kl} \tag{1.1}$$

The finite elements equations can be written as:

$$[M](\ddot{u}) + [K](u) = (F) \tag{1.2}$$

Lumsdaine (Lumsdaine et al) paper derived the following steps to model the structure.

The second one is the basic finite elements equations for piezoelectricity. The

constitutive relationship for piezoelectricity material can be written as:

$$\sigma_{ij} = D_{ijkl}\varepsilon_{kl} - e_{mij}E_m \tag{1.3}$$

$$q_i = e_{ijk}\varepsilon_{jk} + p_{ij}E_j \tag{1.4}$$

The finite element equation for a piezoelectric structure can be written as:

$$[M](\ddot{u}) + [K_{uu}](u) + [K_{u\phi}](\phi) = (F) \tag{1.5}$$

$$[K_{u\phi}]^T(u) + [K_{\phi\phi}](\phi) = (Q) \tag{1.6}$$

In a static problem, these can be expressed as:

$$\begin{bmatrix} K_{uu} & K_{u\phi} \\ K_{u\phi}^T & K_{\phi\phi} \end{bmatrix}\begin{bmatrix} u \\ \phi \end{bmatrix} = \begin{bmatrix} F \\ Q \end{bmatrix} \tag{1.7}$$

If this is pre-multiplied by a transformation matrix:

$$[T] = [[I] - [K_{u\phi}][K_{\phi\phi}]] \tag{1.8}$$

the following condensed matrix is obtained, with the electric potential degrees of freedom removed:

$$[[K_{uu}] - [K_{u\phi}][K_{\phi\phi}]^{-1}[K_{u\phi}]^T](u) = (F) - [K_{u\phi}][K_{\phi\phi}]^{-1}(Q) \tag{1.9}$$

where the term $[K_{\phi\phi}]^{-1}[K_{u\phi}]^T$ (Q) represents the feedback control force. Given that the electric charge (Q) is zero, in the sensor, Equation (1.6) can be rewritten as:

$$(\phi)_s = -[K_{\phi\phi}]^{-1}[K_{u\phi}]^T(u)_s \tag{1.10}$$

Proportional control is used in the ABAQUS model examined here. In proportional feedback control, the electric potential in the actuator is related to the potential in the sensor through a gain, as in equation below:

$$(\phi)_a = G_p(\phi)_s \tag{1.11}$$

the potential applied to the actuator is given by the following equation:

$$(Q)_a = C(\phi)_a = CG_p(\phi)_s \tag{1.12}$$

where the capacitance is defined as:

$$C = \frac{p_{22}A}{h} \qquad (1.13)$$

Inserting equation (1.10) and (1.12) into equation (1.9) yields the finite elements equations of motions:

$$[M](\ddot{u}) + [K^*](u) = (F) \qquad (1.14)$$

Here is the user defines finite elements equations:

$$\begin{bmatrix} F_s \\ Q_s \\ F_a \\ Q_a \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & G_p K_{u\phi} & 0 & -K_{u\phi} \\ 0 & G_p K_{\phi\phi} & 0 & -K_{\phi\phi} \end{bmatrix} \begin{bmatrix} u_s \\ \phi_s \\ u_a \\ \phi_a \end{bmatrix} \qquad (1.14a)$$

Where $[K^*]$ is:

$$[K^*] = \begin{bmatrix} K_{uu} & K_{u\phi} & 0 & 0 \\ K^T_{u\phi} & K_{\phi\phi} & 0 & 0 \\ 0 & 0 & K_{uu} & K_{u\phi} \\ 0 & 0 & K^T_{u\phi} & K_{\phi\phi} \end{bmatrix} \text{,original form (Lumsdaine et. al.)} \qquad (1.14b)$$

$$[K^*] = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & G_p K_{u\phi} & 0 & -K_{u\phi} \\ 0 & G_p K_{\phi\phi} & 0 & -K_{\phi\phi} \end{bmatrix} \text{,new form} \qquad (1.15)$$

As mentioned above, ABAQUS has the capability of exporting the elements stiffness matrices. From each element stiffness matrix, the matrices $[K_{u\phi}]$, and $[K_{\phi\phi}]$ are needed to be extracted in order to compute the matrix $[K^*]$.

The third one is the basic finite element equations for viscoelasticity. For linear isotropic viscoelastic materials, the elastic modulus and shear modulus can be written as:

$$D^*(\omega) = D_1(\omega) + iD_2(\omega) \qquad (1.16)$$

$$G^*(\omega) = G_1(\omega) + iG_2(\omega)$$
(1.17)

Using Equation (1.4) can also be written as:

$$G^*(\omega) = G_1(\omega)[1 + i\eta_m(\omega)]$$
(1.18)

D_1, D_2, G_1, and G_2 are the storage and loss modulus for extension and shear, respectively

and η_m is the material loss factor. The frequency dependence of these and other material

properties will not be explicitly noted.

In harmonic time dependence, it can be shown that the complex bulk modulus is given

by:

$$K^* = K_1 + iK_2 = \frac{D^*}{3(1-2v^*)}$$
(1.19)

where "v^*" is the complex Poisson's ratio defined through:

$$G^* = \frac{D^*}{3(1-2v^*)}$$
(1.20)

Viscoelastic properties can be entered into ABAQUS in several ways. In the Frequency

domain, tabular values of G_1, G_2, K_1, and K_2, are normalized and can be entered as

functions of frequency. (Lumsdaine et. al.)

It is important to measure the damping energy lost in a harmonically vibrating

structure is the system loss factor, which may be defined by:

$$\eta = \frac{W_s}{2\pi W_d}$$
(1.21)

One way of calculating the system loss factor is by the half-power bandwidth method.

$$\eta = \frac{\omega_1^2 - \omega_2^2}{2\omega_r^2}$$
(1.22)

where ω_1 and ω_2 are the frequencies at the half power points and ω_r is the resonance

frequency. In this problem the damping is light, equation (1.23) can be reduced to:

$$\eta = \frac{\omega_1 - \omega_2}{\omega_r}$$ (1.23)

In using ABAQUS, Lumsdaine (Lumsdaine et. al.) created a FORTRAN program to

calculate the loss factor from ABAQUS results (see Appendix A for more information).

1.4 Active Constrained Layer Beam-No Control
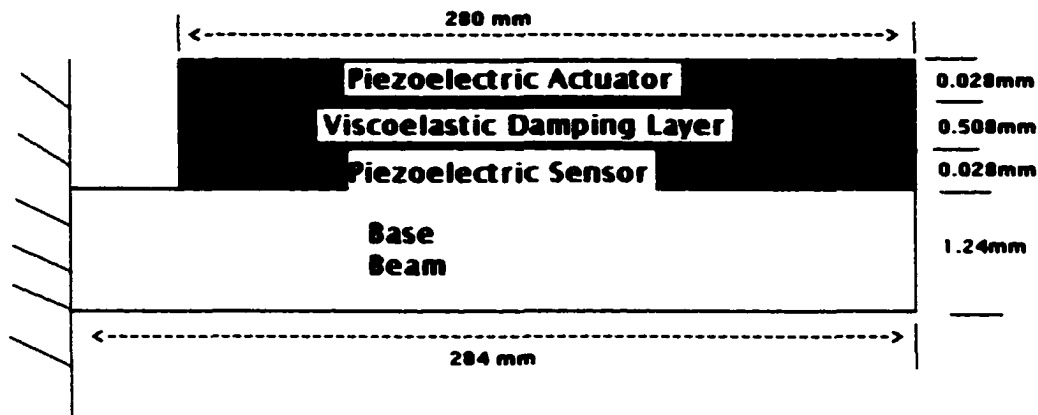
Figure1-2 Baz and Ro ACLD Beam

The results are compared with an ACLD structure examined by Baz and Ro (Baz et. al.)

and Veley and Rao (Veley et. al.). The dimensions are shown in Figure1-2. The material

properties are in Table1-1. The viscoelastic damping material has a material loss factor of

1.177 at the frequency of 4 Hz. The piezoelectric layers have a piezoelectric stress

constant e_{211} of 0.0518 C/m^2 and a permittivity p_{22} of 0.1041x 10^{-9} F/m. The results

obtained from ABAQUS are compared to with those of Baz and Ro (Baz et. al.) and

Veley & Rao (Veley et. al.) in Table 1-2.

Table 1-1 Material Properties for Baz and Ro Beam

	Base Beam (PMMA)	Damping Material (DYAD-606)	Piezo Layer (PVDF)
Density	1240 kg/m³	1104 kg/m³	1800 kg/m³
Elastic Modulus	4.25 GPa	23.7 MPa*	2.25 GPa
Poisson's Ratio	0.3	0.4	0.29

*Shear Modulus at 4 Hz

1.5 Results

Table 1-2 Results for ACLD Beam without Active Control

	Natural Frequency (Hz)	Loss Factor
Veley and Rao (2D FEM)	4.16	0.0457
Baz and Ro (Theory)	4.04	0.0413
Baz and Ro (experimental)	3.99	0.0419
ABAQUS (2D FEM)	4.18	0.0363

Table 1-3 Results for ACLD Beam with Active Control

	Natural Frequency (Hz)	Loss Factor
Veley and Rao (2D FEM)	4.43	0.131
Baz and Ro (Theory)	4.34	0.134
Baz and Ro (experimental)	4.37	0.102
ABAQUS (2D FEM)	2.63	0.092

Note: See Appendix A for ABAQUS results.

1.6 Conclusions

Using a commercial finite element code, for modeling ACLD structures would make possible to model such structures. This will allow use of finite elements features without having to develop the code from scratch. As you can see using a commercial code ABAQUS can be used to model ACLD structures. Furthermore, their need to be more

research done so to get better results from ABAQUS. Although, introducing active

control in ABAQUS could be a trivial matter and may requires some modification.

CHAPTER 2

QUANTITATIVE DETERMINATION OF THE STABILITY OF IMPLANT-BONE INTERFACE
USING RESONANCE FREQUENCY ANALYSIS

2.1 Introduction

Vibration study and control of structures are among the major research subjects in

mechanical engineering and related technical disciplines. Among the most active research

fields in this area, one finds the area of non-destructive evaluation. For a given

mechanical structure, mode shapes of oscillation and natural frequencies depend on the

structure's dimensions, materials, configuration, and boundary conditions. Thus,

resonance frequency analysis can be used to infer information of the boundary conditions

of a structure if the other parameters are known. Among many applications, this

technique offers a mean to measure stability and osseointegration of implants.

Osseointegration has been defined in literature as "a process whereby a clinically a

symptomatic rigid fixation of alloplastic materials is achieved and maintained in bone

during functional loading" (Zarb et. al.). Currently, there is an interest in enhancing the

quality and rate formation around implants by modifying their surface topography or the

use of coatings (Hallgren et. al). Thus, among other benefits stability measurements could

help define optimal healing conditions and times and allow for ongoing monitoring of the

implant-bone interface. Current radiological approaches do not provide much detail about

the nature of the interface. Investigators have used resonance frequency analysis and

developed a quantitative, non-invasive technique so that changes in implant modal

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response can be monitored from a specific point in time. This technique has been used as a research tool and has been commercialized for clinical use.

These implant-bone interface stability studies have examined only one vibration mode or have suffered from measurement difficulties. Furthermore, no study has evaluated the damping properties of the interface and surrounding tissues.

In the present study the goal was to develop an instrument capable of extracting the full range of modal information from the system so that a thorough description of the interface can be developed. The osseointegration analysis can be extended to implants in any part of the human body. Furthermore, similar analysis can be used to measure stability and integrity of other mechanical systems such as composite materials structural elements (Kessler et. al.).

2.2 Technical Background

The use of resonant frequency measurement by Meredith [13-19] to provide a quantitative method for noninvasive diagnosis of implants stability and osseointegration was a significant innovation with great clinical potential. The device is optimized to measure the stiffness of the implant/sensor stack in a particular mode of excitation. The stiffness is driven by three parameters [17]:

1. Implant's stiffness function of implant's components geometry and material composition.

2. Implant-bone interface's stiffness (bond).

3. Stiffness of the surrounding tissues, determined by the trabecular-cortical bone ratio and the bone density, by geometric factors such as the length and diameter of the implant and the nature of the tissues.

Meredith developed this instrument with the configuration shown in Figure 2-1. The cantilever beam, shown in Figure 2-1, oscillates in and out of the page.
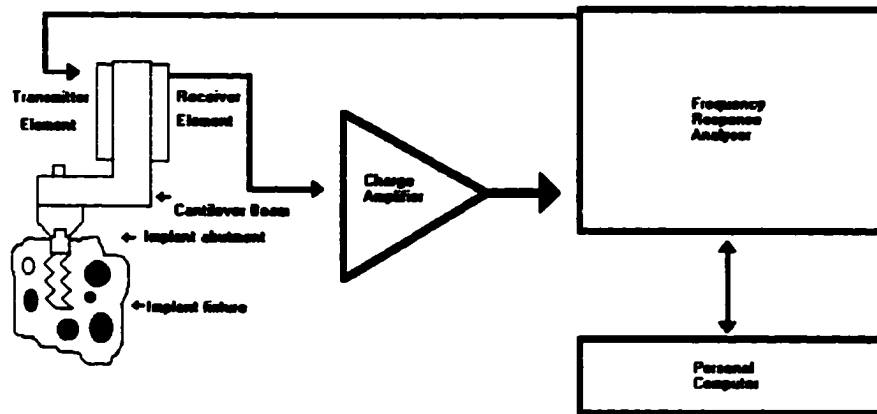
Figure 2-1 Meredith Instrumentation Design

This design is limited in its research potential by two factors. It only measures response in a single mode, which is a combination of two primary modes (oscillation of the cantilever beam and oscillation of the arm supporting the beam). It also cannot provide a complete model of the boundary conditions since it has been optimized for elastic response (stiffness) measurements only. The implant boundary conditions are more complex because bone response contains both elastic and viscoelastic components. Other investigators have approached this problem in various ways (Cawley et. al.). Accelerometers have been bonded directly to the implant or to the mass or hammer used to excite the implant. All of these approaches suffer from difficulties due to transducer limitations or problems in measurement resolution.

2.3 Problem Analysis

The stability of the implant-bone interface is determined by the dynamic modulus and damping of the interface. These properties of the implant's interface will also influence a

dynamic response of a structure attach to it. Therefore, an instrument can be design to capture as much information as possible.

The primary design consideration for this instrument was simplicity of operation since it is being designed for use in a research environment by Dental researchers. Existing accelerometers are generally not capable of measuring responses beyond 25 kHz, but dental implants have natural frequencies far beyond that value in several of their primary modes. To make the frequencies detectable, a fixture design was developed which brought the system natural frequencies into the measurable range for all three primary vibration modes (longitudinal, torsional and transverse vibrations). Theoretical and numerical modeling was done to determine the final dimensions, range of natural frequencies, and damping factors that can be measured with the resulting instrument. Experiments with different boundary conditions were conducted to replicate the process of dental implant osseointergration. The fixture design is shown in Figure 2-2. The fixture, abutment, and dental implant are shown in Figure 2-3. The abutment and the dental implant are made of titanium.
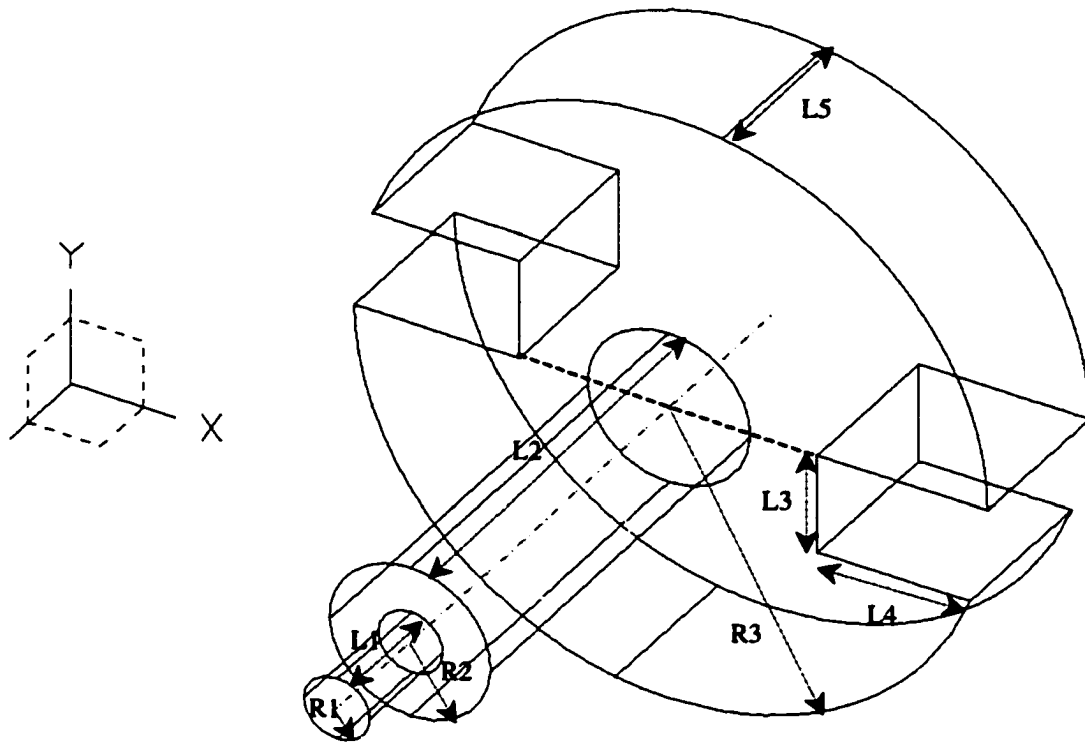
Figure 2-2 Fixture Design
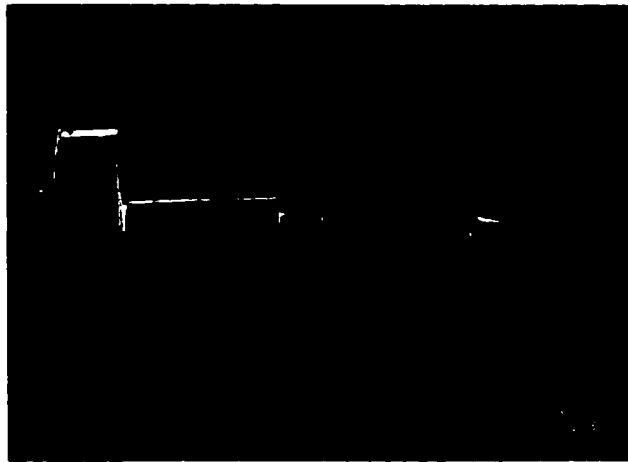
Figure 2-3 Fixture, Abutment, and Implant (Not Assembled)

The prototype fixture was made out of Aluminum for ease of fabrication. It is screwed

onto the implant abutment as shown in Figure 2-3. The accelerometer is a Kistler

8614A1000M1. The Aluminum fixture has four piezoceramic elements (PL-055.21 by

Polytec PI) that are attached as shown in Figure 2-4. The piezoceramics are the shakers of the system.

Figure 2-4 Top View of the Instrumentation

The traditional method of measuring the structure's natural frequencies and corresponding damping factors is to excite the structure in the desired mode shape with a sinusoidal wave form and to measure the amplitude of both input and output and their relative phase shift (frequency sweep method). This procedure must be repeated for each frequency that needs to be determined. In our experiments, we have used a frequency domain approach where one measures both the system input and output and then compute their respective frequency spectra. Random vibration (white noise) is sent into the system in order to estimate its transfer function. There is no need to repeat the measurement for each frequency, as was the case of the frequency sweep; this represents the main advantage of this method over the frequency sweep. Care must be taken in setting up the computerized data acquisition system so as to achieve a balance between the upper frequency limit of the spectrum, the frequency resolution, and the time required to collect the samples. The upper frequency limit determines the frequency at which samples must be taken; the Nyquist rule states that a signal must be sampled at a rate twice as high at its

highest frequency component in order to be reproduced. The frequency resolution and sampling time are closely related; the time required for collecting samples equals the number of samples taken divided by the sampling rate. Taking more samples requires longer measurement duration, which could be of concern when taking in-vivo measurements.

The configuration developed for our instrument is shown in Figure 2-5. Because of its ease of use, SignalCAL software from Dataphyics was chosen for control and data acquisition.

The instrument developed provides valuable information about the stiffness and damping properties of the implant-bone interface obtained through resonance frequency analysis with torsional, axial (longitudinal), and transverse vibration. Figures 2-6—2-9 shows the instrument's vibration modes with undistorted (grid) and distorted configurations. For the distorted configuration, dark blue regions experience minimum displacement and red regions experience maximum displacement from original configuration.
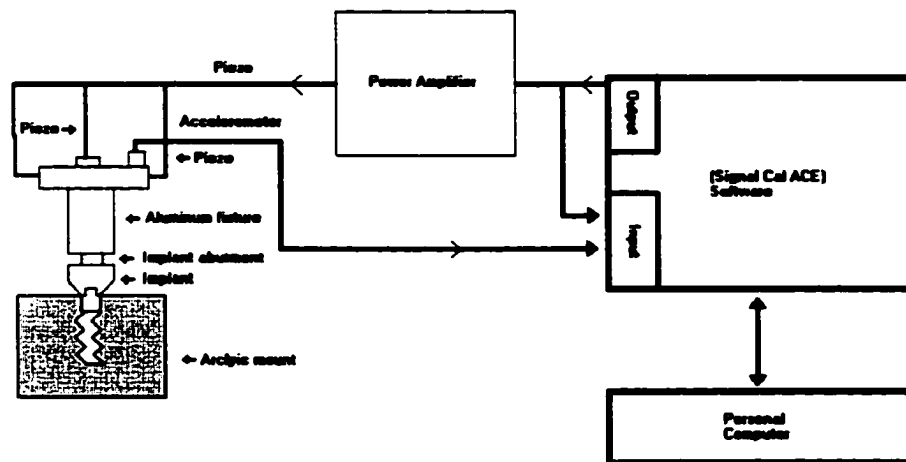
Figure 2-5 Instrumentation Configuration
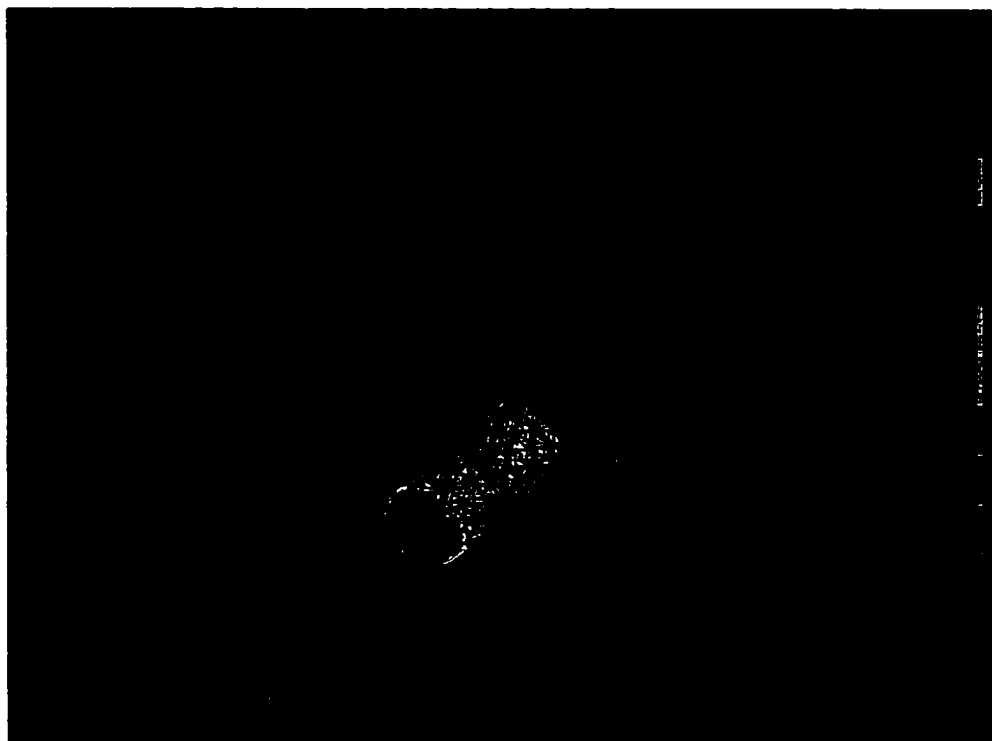
Figure 2-6 Axial Mode
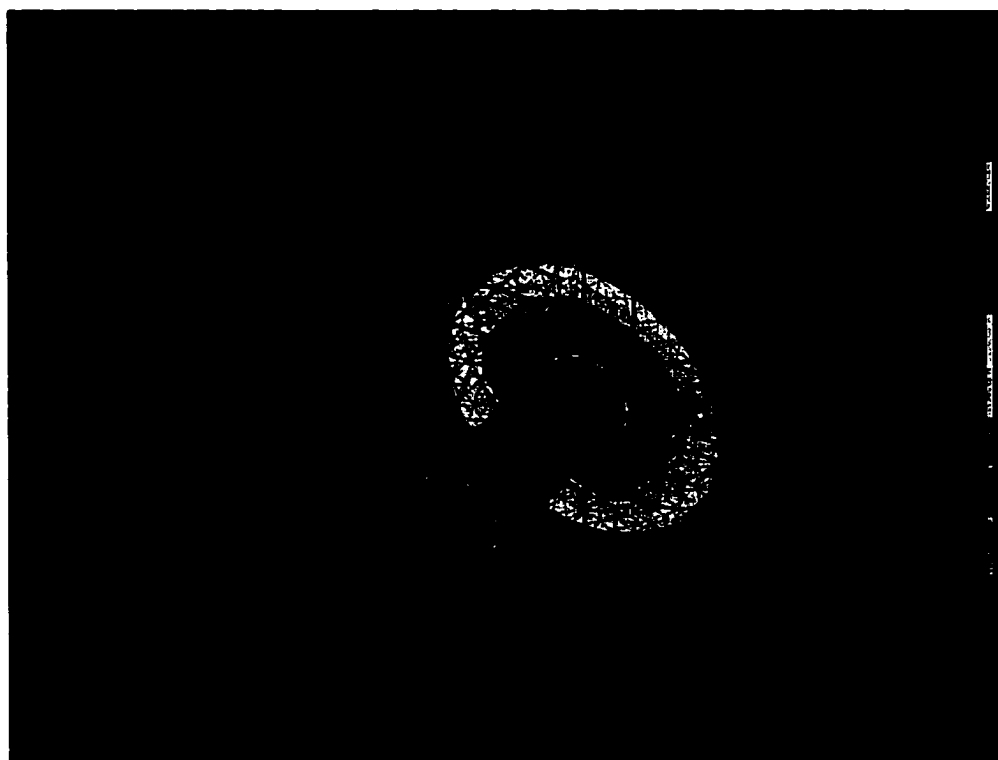
Figure 2-7 Torsional Mode
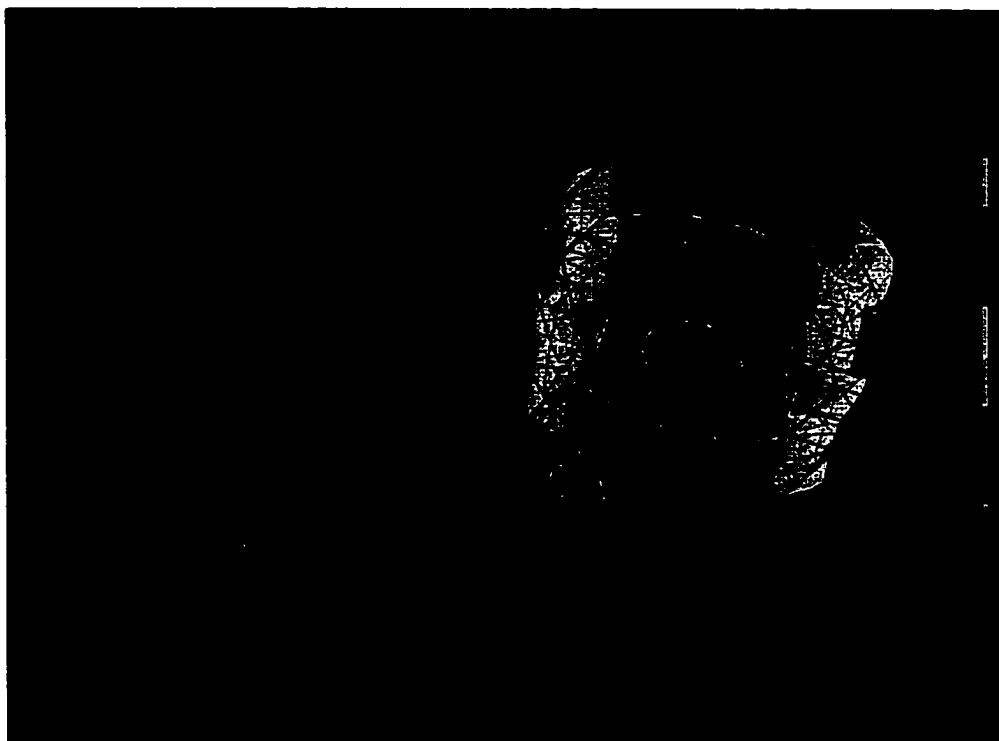
Figure 2-8 Higher Bending Mode
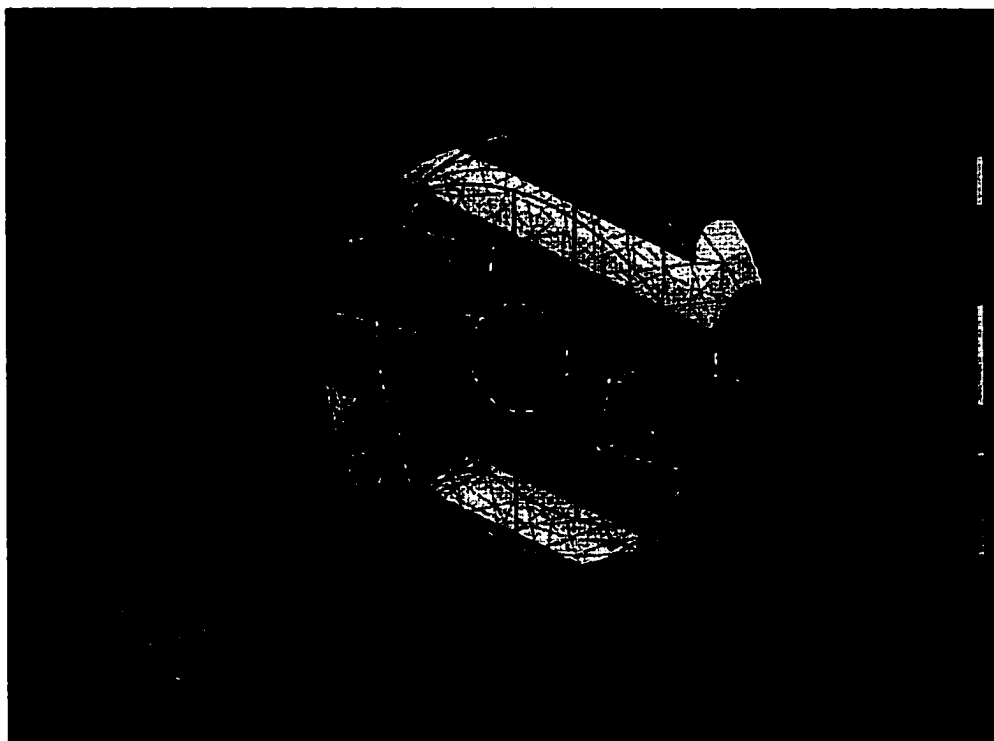
Figure 2-9 Lower Bending Mode

2.4 Results

A solution using finite element analysis (FEA) of a simplified model was compared to a simplified analytical solution to test our computer-generated designs. We used the FEA software called IDEAS to model the instrument. The instrument's simplified model used in our analysis is shown in Figure 2-10. The model consists of a simple beam with disk at the end and fixed at the interface of the implant (lower section). The simplified model for the analytical solution, shown in Figure 2-11, was solved with the following assumptions:

- Equations for torsional vibrations of a uniform shaft

- Equations for longitudinal vibrations of a uniform elastic bar

- Equations for transverse vibrations of a uniform beam

- Mass of the bar is much smaller than the mass of the disk

Table 2-1 presents the comparison between the FE simplified model results and the analytical solution for the analytical simplified model. There is good agreement between the results. However as expected, there are small differences due to the simplifications and assumptions, and the differences are smaller for torsional and transverse vibration than longitudinal vibration.

From the results generated by the FE simplified model, we selected the dimensions for the fixture in our instrumentation. Table 2-2 presents the selected fixture's dimensions (please refer to Figure 2-2 for notation).
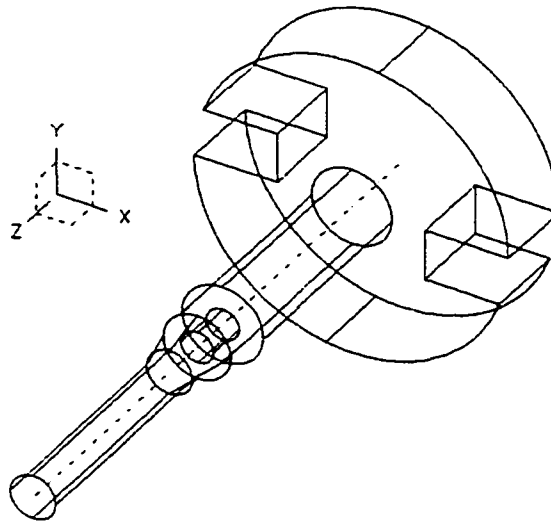
Figure 2-10 Finite Element Simplified Model
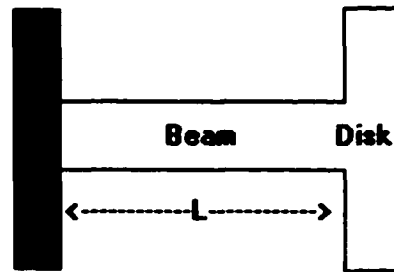
Figure 2-11 Analytical Simplified Model

Table 2-1 Comparison of the FEA and analytical Solution

	Torsional Vibration [Hz]	Transverse Vibration [Hz]	Axial (Longitudinal) Vibration [Hz]
Analytical Solution	3971	3171	26750
FEA Solution	4120	2971	23033
Difference	3.7%	6.3%	13.9%

Table 2-2 Fixture's Dimensions

Dimension	Inches
R1	0.078
R2	0.096
R3	0.375
L1	0.250
L2	0.515
L3	0.125
L4	0.200

L5	0.200

Initially, the experimental values were obtained with the implant imbedded in a brass

mount in order to simulate the rigid constraint around the implant boundary used in the

FEA model. Figure 2-12 shows one of the experimental results obtained by exciting the

different mode shapes of oscillations randomly. It is a challenge to excite only one mode

oscillation at a time (i.e. the axial mode always appeared in our experimental results).

The values of the FEA should be higher than the experimental values because the

experimental boundary conditions are not in fact perfectly rigid due to the threading of

the mount and because the threaded interface between the transducer and the implant

abutment will reduce the resonant frequency of the stack. In addition, the abutment is

screwed into the implant. The comparison of results of experimental measurements to FE

results from the instrument is presented in Table 2-3. The FE model permitted

identification of the first four modes of vibration.
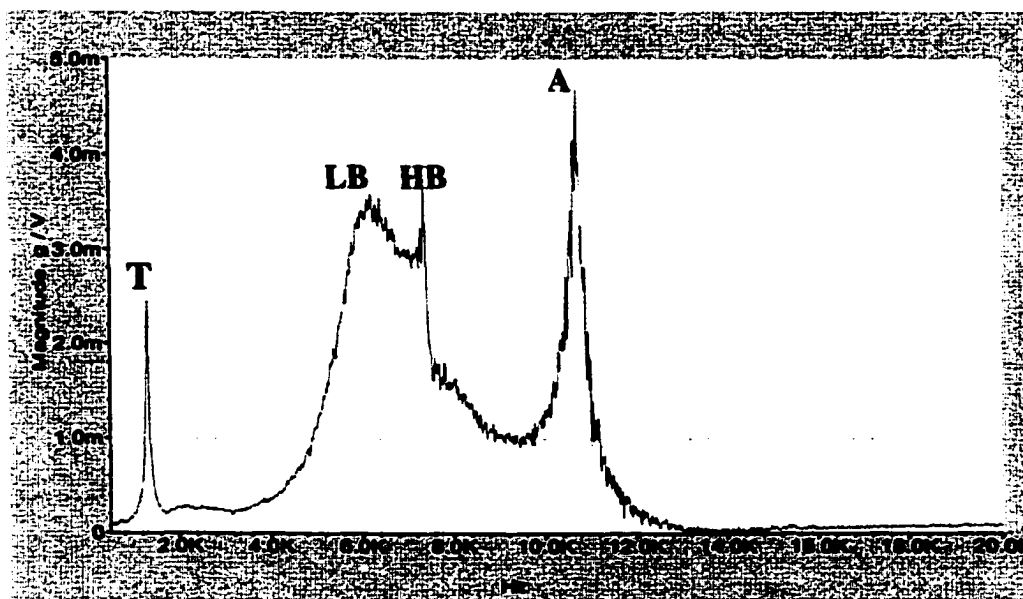
Figure 2-12 Experimental Results (Brass Mount)
[T-torsion, LB-low bending, HB-high bending, A-axial]

Table 2-3 Comparison of the FEA and Experimental Results

TYPE OF VIBRATION	FEA FREQUENCY (Hz)	EXPERIMENTAL FREQUENCY (Hz)	% DIFFERENCE
TORSIONAL MODE	1340	1313	2
LOWER BENDING MODE	9168	7125	22
HIGHER BENDING MODE	10127	8025	21
AXIAL MODE	13872	11025	21

Next, different laboratory experiments were designed and conducted to test the instrumentation's capabilities. To simulate dental operational working conditions, acrylic mounts with stiffness similar to human bones were introduced.

Brass vs. Acrylic Mounts

We obtained the natural frequencies of vibration for the selected modes of oscillation (refer to Figure 2-6—2-9) with brass and acrylic mounts. Changing from the brass mount to an acrylic mount, that is changing the dynamic modulus and damping in the interface, causes the natural frequencies of the different mode of oscillation to shift to the left. This is expected because the acrylic is a softer material than brass (please refer to Figures 2-13, and Table 2-4). The maximum changes in the natural frequencies were experienced in the torsional mode of oscillation. The axial mode of oscillation follows in the magnitude of change between the two different mounts.

We also estimated the viscous damping factors of the systems vibrating in the different modes of oscillation using the respective system's bandwidth. As expected, all viscous damping factors increased for the acrylic mount. However, in the case of torsion the damping factor only increased from 0.0268 to 0.285. The maximum changes in the damping factor were experienced in the bending modes of oscillation. The lower bending

mode shape-damping factor for a given mount was always bigger than for the higher

bending due to the dynamics of the mode shapes.
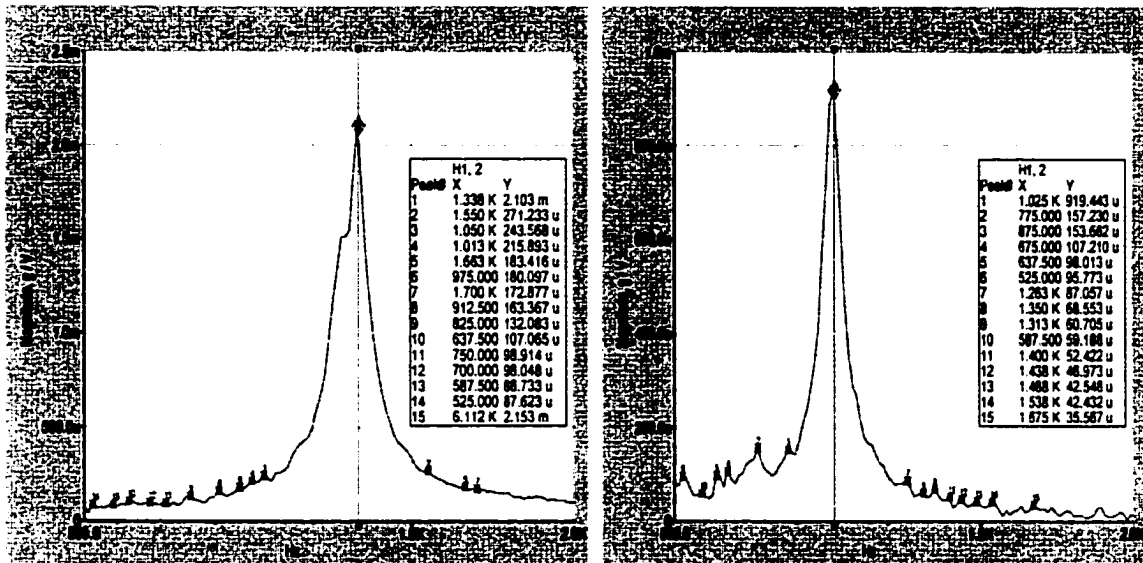
Figure 2-13 Response of Brass (Left) vs Acrylic (Right) Mount [Torsional Mode]

Table 2-4 Comparisons of the Brass and Acrylic Mounts.

Modes	Brass Mount	Acrylic Mount
Torsion	1338	1025
Lower Bending	6000	5800
Higher Bending	7425	6900
Axial	10388	9388

Different fits in Acrylic Mounts
The next experiment consisted in changing conditions in the implant fit in the acrylic

mounts. For this purpose a tight and a loose fit were considered by changing the diameter

of the hole before tapping. Figures 2-14, 2-15, 2-16, 2-17, 2-18, and 2-19, and Table 2-5

show the shift of the frequency when the hole drilled before tapping is intentionally

widened from 0.144in (3.658mm) to 0.153in (3.886mm). All the natural frequencies for

the selected modes of oscillation were reduced. The maximum changes in the natural

frequencies were experienced in the axial mode of oscillation.

Viscous damping factors are also reported in Table 2-5. The maximum changes in the

damping factor were experienced in the bending modes of oscillation. The damping

factor is an estimate by this equation $\lambda \approx \dfrac{\omega_2 - \omega_1}{2\omega_n}$

Table 2-5 Comparisons of Natural Frequencies and Damping Factors for Implants with Acrylic Mounts With Different Fits

Mode of Oscillation	Natural Frequencies		Damping Factors	
	Acrylic (0.144 in) Hz	Acrylic (0.153 in) Hz	Acrylic (0.144 in) Hz	Acrylic (0.153 in) Hz
Torsion	1213	1188	0.0221	0.0233
Lower Bending	5763	5313	0.0641	0.0738
Higher Bending	6925	6275	0.0096	0.0166
Axial	9412	7413	0.0252	0.0251
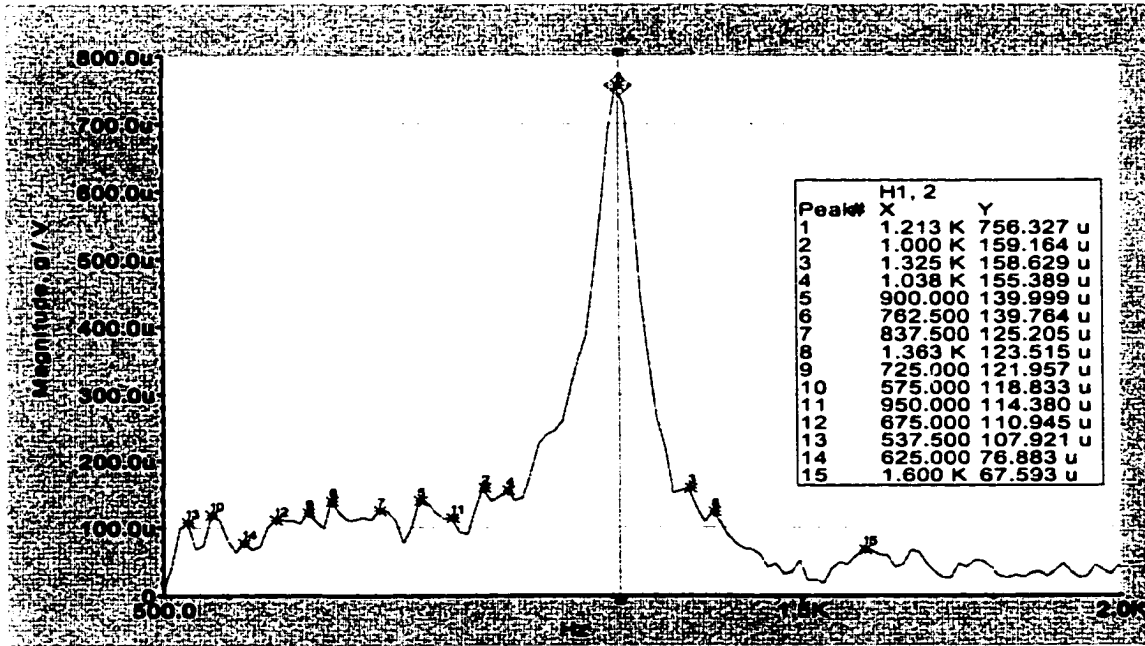
Figure 2-14 Torsion Mode for Acrylic Mounts With Oversized Predrilled Hole [0.144 in]

Peak#	H1, 2 X	Y	
1	1.188 K	819.916	u
2	1.075 K	240.342	u
3	1.025 K	176.700	u
4	975.000	169.796	u
5	725.000	150.805	u
6	937.500	145.156	u
7	1.325 K	134.418	u
8	1.388 K	118.905	u
9	675.000	118.587	u
10	875.000	115.773	u
11	562.500	115.571	u
12	812.500	88.337	u
13	1.438 K	83.884	u
14	600.000	67.960	u
15	525.000	50.264	u
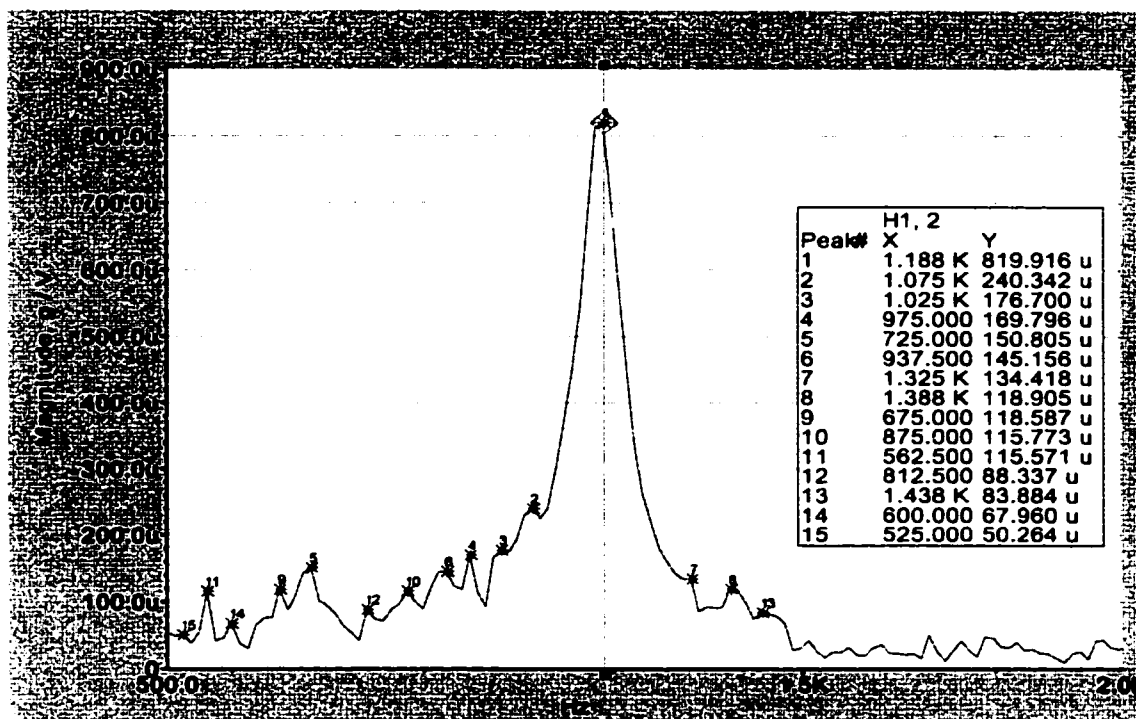
**Figure 2-15 Torsion Mode for Acrylic Mounts With Oversized Predrilled Hole
[0.153 in]**

Peak#	H1, 2 X	Y	
1	9.412 K	4.962	m
2	9.338 K	4.957	m
3	9.300 K	4.792	m
4	9.450 K	4.763	m
5	9.250 K	4.355	m
6	9.525 K	4.180	m
7	9.213 K	4.094	m
8	9.563 K	3.998	m
9	5.763 K	3.708	m
10	5.725 K	3.600	m
11	5.813 K	3.582	m
12	9.138 K	3.566	m
13	5.688 K	3.531	m
14	5.663 K	3.510	m
15	5.588 K	3.296	m
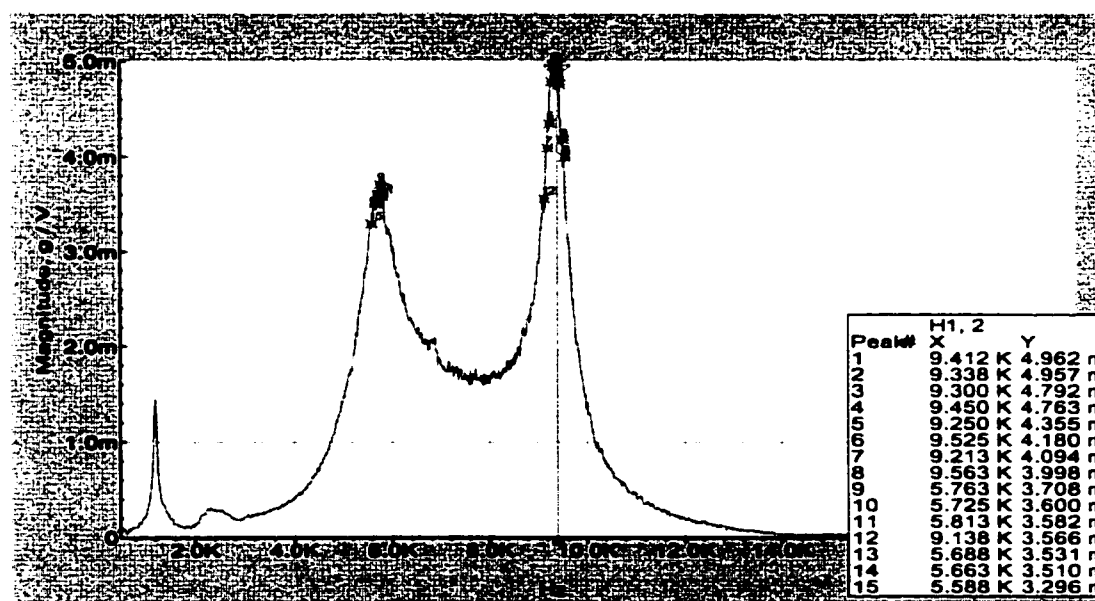
**Figure 2-16 Response of Implant with Acrylic Mount with Oversized Predrilled
Hole (0.144in.)
[Lower Bending and Axial Mode]**

Peak#	H1, 2 X		Y	
1	7.375	K	5.855	m
2	7.413	K	5.698	m
3	7.313	K	5.610	m
4	7.263	K	5.246	m
5	7.175	K	4.394	m
6	7.563	K	3.771	m
7	7.050	K	3.285	m
8	5.313	K	3.026	m
9	7.000	K	3.010	m
10	5.362	K	2.999	m
11	5.450	K	2.969	m
12	5.275	K	2.951	m
13	5.487	K	2.887	m
14	5.575	K	2.701	m
15	5.175	K	2.682	m
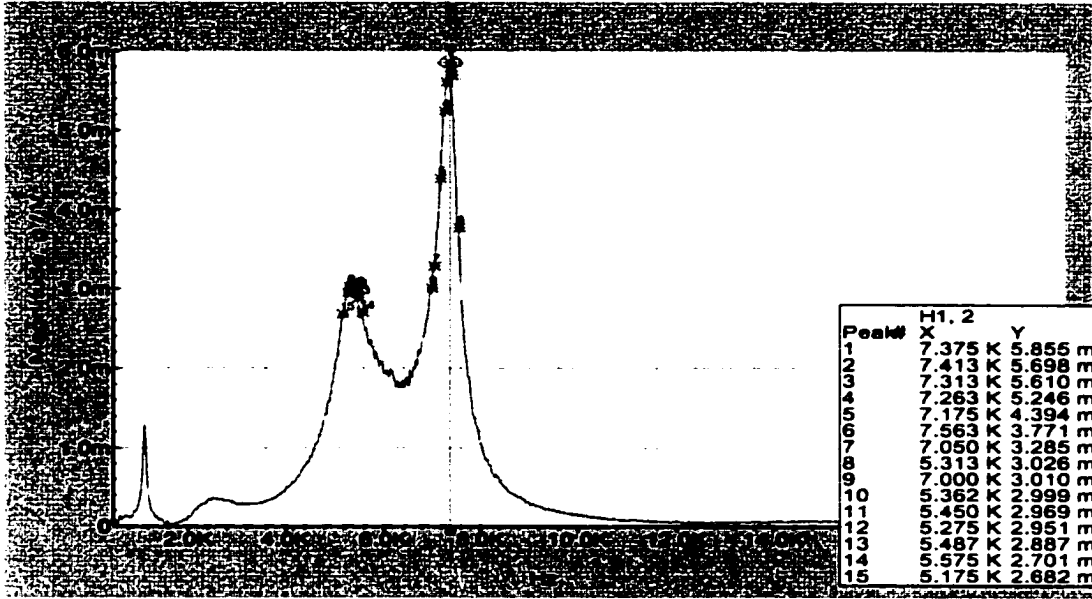
Figure 2-17 Response of Implant with Acrylic Mount with Oversized Predrilled Hole (0.153in.)
[Lower Bending and Axial Mode]

Peak#	H1, 2 X		Y	
1	9.475	K	16.081	m
2	9.412	K	15.981	m
3	9.363	K	15.344	m
4	9.325	K	14.669	m
5	9.537	K	14.335	m
6	6.925	K	13.707	m
7	9.238	K	12.303	m
8	9.662	K	11.231	m
9	9.188	K	10.587	m
10	9.725	K	9.966	m
11	9.138	K	9.537	m
12	9.800	K	8.352	m
13	9.838	K	8.217	m
14	9.938	K	6.877	m
15	9.013	K	6.790	m
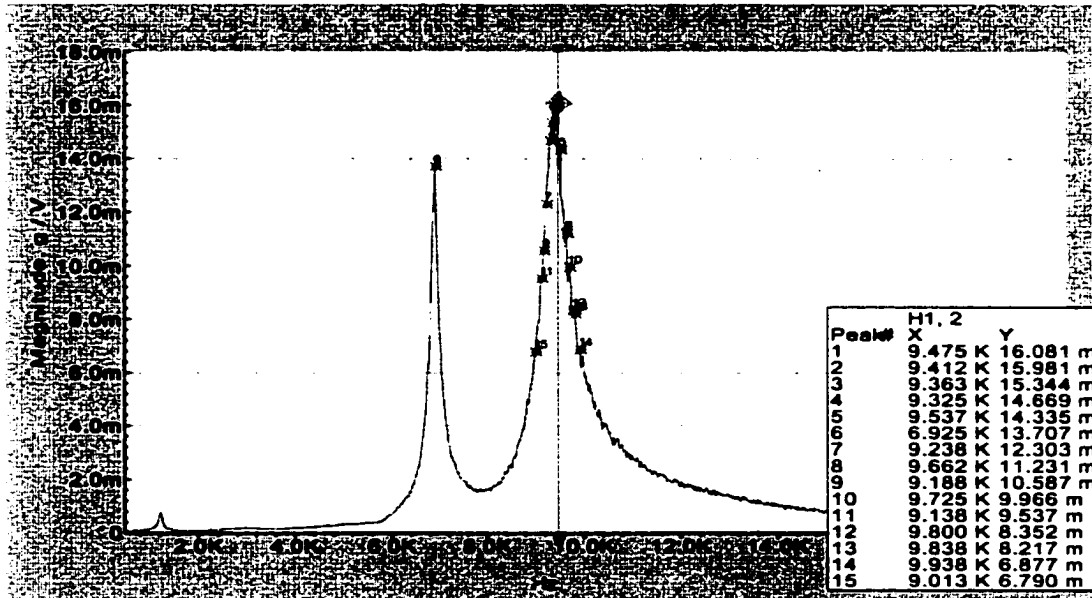
Figure 2-18 Response of Implant with Acrylic Mount and Oversized Predrilled Hole (0.144in.)
[Higher Bending and Axial Mode]
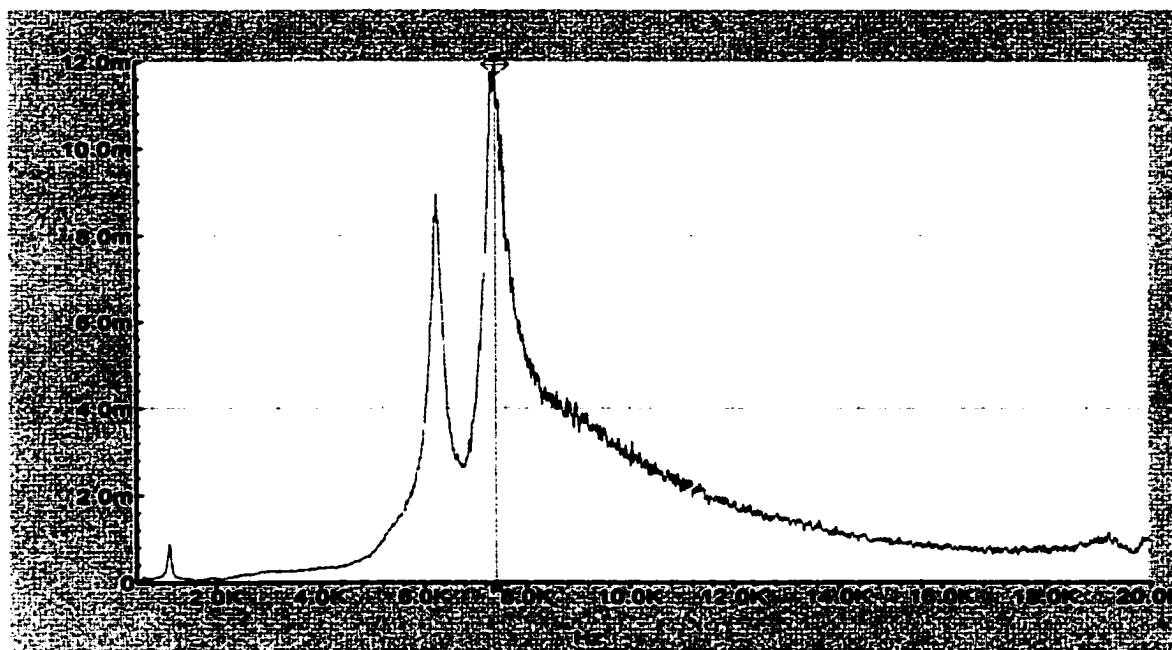
Figure 2-19 Response of Implant with Acrylic Mount with Oversized Predrilled Hole (0.153in.)
[Higher Bending and Axial Mode]

Also, we tested half threaded cases in the following table 2-6 that shows the results of the tested. The results shows that the upper and lower threaded mounts the instrument can show that there are differences in frequencies and damping factors.

Table 2-6 Acrylic Mounts Half Threaded Cases Comparisons.

	Natural Frequencies Full Threaded (Hz)	Damping Factors	Natural Frequencies Half Threaded (Hz)	Damping Factors
Mount A Lower Case	787.5	0.1238	537.5	0.0930
Mount B Upper Case	612.5	0.1551	500	0.125

Figure 2-20 Upper and Lower Mounts for Table 2-6

The instrument was also tested in time by inserting the implant in acrylic resin and

monitors the curing time and records the results every five minutes. Table 2-7 shows the

results of the frequencies response (See Appendix B for more results).

Table 2-7 Acrylic Resin Curing Time Frequencies Readings

Time (min)	Torsional (Hz)	Lower Bending (Hz)	Higher Bending (Hz)	Axial (Hz)
15	300	----	7550	----
20	1262.5	7050	7725	----
25	1525	7413	8525	~9000
30	1637.5	7737	8700	~9500
35	1712.5	7963	8863	~10000
40	1762.5	7862	8825	~10500
45	1787.5	7775	8863	~10750
50	1800	7938	8925	~10900
55	1812.5	7963	9025	~11000
60	1825	9000	9575	~11500

Figure 2-21 Curing Acrylic Mount

As you can see the frequencies response are much higher then the threaded acrylic

mounts results. This is because the interface between the implant and the acrylic is now

rigid boundary condition.

In the following Tables (2-8—2-11), we decide to create different kinds of problems with

the acrylic mounts. As you can see, the instrument demonstrated that it notice the changes

in boundary conditions, and the frequency and damping factor changed accordingly to the

boundary conditions it had.

Table 2-8 Half Threaded Acrylic Mount Comparisons to Full Threaded Acrylic Mount

	Frequency (Hz) Full Threaded	Damping Factor	Frequency (Hz) Half Threaded	Damping Factor
Torsional	875	0.03543	800	0.04688

Table 2-9 Hole on one side of the implant Comparison to Full Threaded Acrylic Mount

	Frequency (Hz) Full Threaded	Damping Factor	Frequency (Hz) hole in one side	Damping Factor
Torsional	1000	0.01875	1012.5	0.02469

Table 2-10 Hole on both sides of the implant Comparison to Full Threaded Acrylic Mount

	Frequency (Hz) Full Threaded	Damping Factor	Frequency (Hz) hole in both sides	Damping Factor
Torsional	1012.5	0.01852	950	0.03947

Table 2-11 Short Half Threaded Acrylic Mount Comparisons to Full Threaded Acrylic Mount

	Frequency (Hz) Full Threaded	Damping Factor	Frequency (Hz) Half Threaded	Damping Factor
Torsional	1000	0.01875	887.5	0.0845

In table 2-8, we decide to spit the acrylic mount in half to show a half threaded on half the implant's threading. This shows that the instrument can show the frequency changes and the damping factor changes. In table 2-9 and 2-10, there is no difference between the Frequencies but the damping factor did change and it lets know that there is something wrong. In Figure 2-21 and 2-22, it shows the experiment setup for the results.
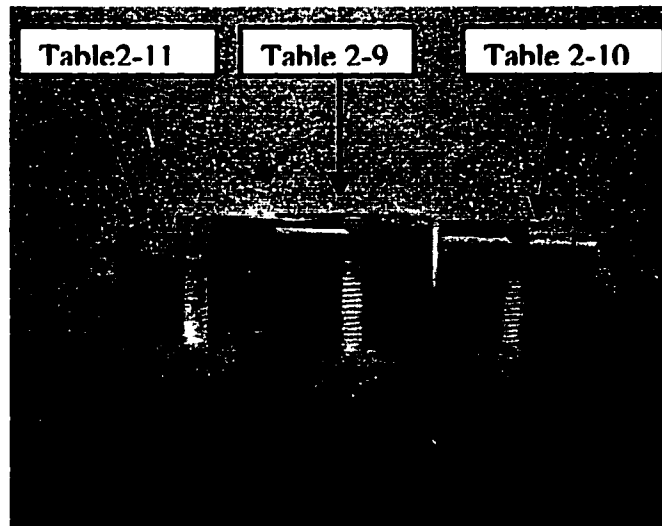
Figure 2-22 Experimental Mounts for tables 2-9—2-11 results.
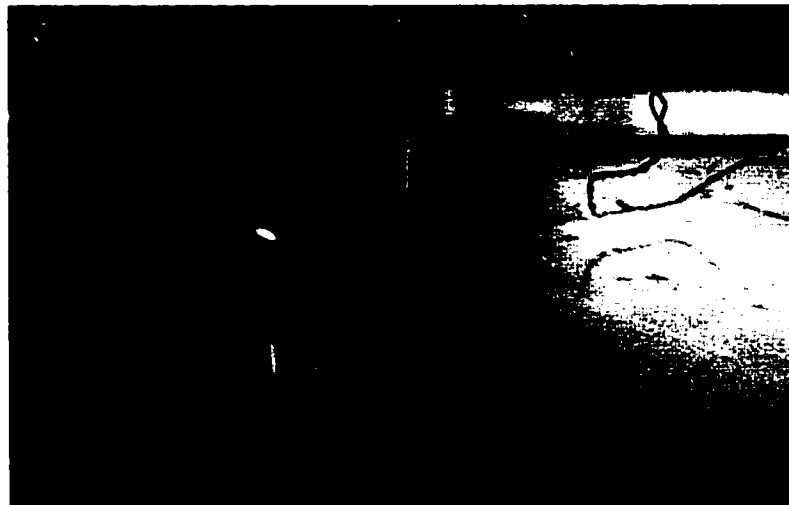
Figure 2-23 Half Threaded Mount

2.5 Conclusion

In summary, a new instrument for resonance frequency analysis of osseointegrating dental implants has been developed. The instrument is capable of capturing and measuring information to characterize the process of dental implant osseointergration. It can detect changes in the boundary conditions (i.e. modulus reduction, damping reduction, and contact area reduction). The measured natural frequencies of the transducer design correspond fairly well to predictions of both an analytical model and FEA. Changes in boundary conditions and excitation modes indicate that the identification of the first four peaks with particular modes of vibration is correct. Variations in the boundary conditions of the implant were detected by resonance frequency analysis. Thus, the instrument offers the potential to use multiple mode shapes of oscillation, natural frequencies, and damping measurements to develop a more complete picture of the implant-bone interface.

By reducing the effective length of the fixture in the instrumentation, one may increase the difference between different boundary conditions. However, reducing the size also implies that the structure's natural frequencies will increase. Thus, for simplicity of operation there is a need for accelerometers capable of measuring responses greater than 25 KHz. Meanwhile, more detailed research may be conducted in laboratories using a laser doppler vibrometer or a similar system.

The osseointegration analysis can be extended to implants in any part of the human body. Furthermore, similar analysis can be used to measure stability and integrity of other mechanical systems such as composite materials structural elements.

APPENDIX A

THE ABAQUS RESULTS FROM GETMAX AND RESULT3

asmeloss8I400 results

****

Here is the results of gain of 1.

hermes% getmax.x

4.57988021371610-03	4.0000000000000
1.2028781216563D-02	4.1833333333333
2.78632456851300-03	4.5000000000000

hermes% result3.x

max def: 0.01202878

max freq: 0.41833333E+01

low def: 0.00457988

high def: 0.00278632

half def: 0.00850563

low freq: 0.41104425E+01

high freq: 0.42624600E+01

loss factor: 0.363388E-01

****

Here is the results of gain of -1

hermes% getmax.x

4.3598241545943D-03	4.0000000000000
1.2034121673808D-02	4.2000000000000
2.8735472459135D-03	4.5000000000000

hermes% result3.x

max def: 0.01203412

max freq: 0.42000000E+01

low def: 0.00435982

high def: 0.00287355

half def: 0.00850941

low freq: 0.41212849E+01

high freq: 0.42728150E+01

loss factor: 0.360786E-01

****

Here is the results of gain of -240

hermes% getmax.x

   5.71465804756670-04   4.0000000000000

   1.1711991166967D-02   5.3000000000000

   4.2264938688296D-04   7.0000000000000

result3.x

max def: 0.01171199

max freq: 0.53000000E+01

low def: 0.00057147

high def: 0.00042265

half def: 0.00828163

low freq: 0.55459826E+01

high freq: 0.56471737E+01

loss factor: 0.190927E-01

****

Here is the results of gain of 240

hermes% getmax.x

   2.5508375309407D-03   2.0000000000000

   1.2140699623333D-02   2.6250000000000

   3.5381462132829D-03   3.0000000000000

hermes% result3.x

max def: 0.01214070

max freq: 0.26250000E+01

low def: 0.00255084

high def: 0.00353815

half def: 0.00858477

low freq: 0.25041230E+01

high freq: 0.27459077E+01

loss factor: 0.921084E-01

****

Here is the results of gain of 100

hermes% getmax.x

     1.0559382325236D-03   2.5000000000000

     1.2048138901623D-02   3.6200000000000

     1.5870771949785D-03   4.2500000000000

hermes% result3.x

max def: 0.01204814

max freq: 0.36200000E+01

low def: 0.00105594

high def: 0.00158708

half def: 0.00851932

low freq: 0.35347655E+01

high freq: 0.37085498E+01

loss factor: 0.480067E-01

****

Here is the results of gain of 250

hermes% getmax.x

     1.3489250957154D-03   1.0000000000000

     1.1994763304539D-02   2.5600000000000

     8.5393616692868D-04   4.0000000000000

hermes% result3.x

max def: 0.01199476

max freq: 0.25600000E+01

low def: 0.00134893

high def: 0.00085394

half def: 0.00848158

low freq: 0.24098196E+01

high freq: 0.26587458E+01

loss factor: 0.972368E-01

****

APPENDIX B

ABAQUS CODE FILES

37

```
*HEADING
Veley & Rao ACLD Beam
**Mannually created, passively constrained
**Fixed VE Elastic Modulus (E+04 instead of E+03)
**Non-reduced integration elements
**Constant VE properties, add bulk modulus properties
**
**For writing out the piezoelectric stiffness matrices
**
*NODE
1,        0.0, 0.0,    0.0
5,        4.0, 0.0,    0.0
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406,      0.0, 0.62,   0.0
410,      4.0, 0.62,   0.0
810,    284.0, 0.62,   0.0
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410,810,2
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815,1215,1
*NGEN,NSET=SENSMID
1216,1616,2
*NGEN,NSET=SENSTOP
1617,2017,1
*NGEN,NSET=ACTUBOT
2419,2819,1
*NGEN,NSET=ACTUMID
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3221,3621,1
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*ELGEN,ELSET=BEAM
401,202,2
*ELEMENT,TYPE=CPS8E
1,815,817,1619,1617,816,1218,1618,1216
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811,1
ACTUBOT,9
SENSBOT,9
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EPOT
*NODE PRINT
U
EPOT
CECHG
*EL FILE
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EPG,EFLX,PHEPG,PHEFL
*EL PRINT
EPG1,EPG2,EFLX2
PHEPG,PHEFL
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DEFINED,
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APPENDIX C

IDEAS FEA RESULTS FOR IMPLANT MODEL

41

LIST OF FILE NAMES

Page	IDEAS Model File Names	Comments	Figure
43	Newloading10test15.mf1	Changing Boundary Conditions (Final Fixture Design Includes the implant)	2-10
44	Newloading10test1.mf1	Testing theory results	2-2
45	Newloading10test10.mf1	Testing geometry of Fixture model	2-2
46	Newloading10test15.mf1	Varying Boundary Conditions	2-10
47	Newloading10test15AA.mf1	Changing Material Properties Al to Ti	2-10

MODEL FILE : /home/ddelgado/newloading10test15.mf1
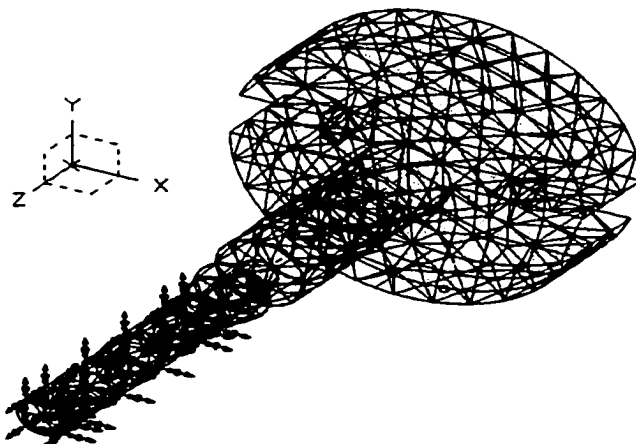
NUMBER OF NODES   :   2815
NUMBER OF ELEMENTS   :   1417

MODE	FREQUENCY	MODAL MASS	RESIDUAL
1	586.8267	2.66813E-02	-4.54E-09
2	598.0080	2.63100E-02	-8.79E-09
3	1384.5524	1.53376E-02	-1.06E-09
4	9495.9675	1.16959E-02	-5.45E-12
5	10488.7851	9.33128E-03	1.22E-11
6	14342.6758	3.00655E-02	3.29E-11
7	36261.5184	2.62645E-03	1.82E-12
8	36501.4180	2.76403E-03	1.14E-11
9	42774.2096	6.52030E-03	-3.55E-11
10	56904.5190	6.86889E-03	-1.47E-10

MODEL FILE : /home/ddelgado/newloading10test1.mf1
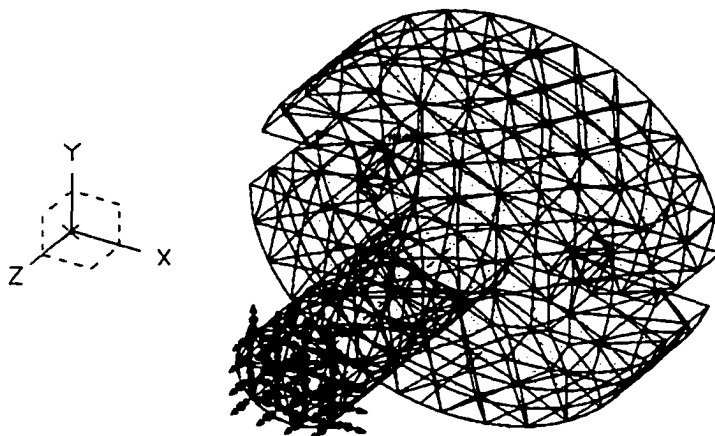
NUMBER OF NODES   :   2072
NUMBER OF ELEMENTS :   1050

MODE	FREQUENCY	MODAL MASS	RESIDUAL
1	3351.5753	2.67074E-02	-2.06E-10
2	3429.7605	2.55344E-02	-1.03E-10
3	4665.9611	1.51915E-02	-2.02E-11
4	15604.7144	1.21046E-02	1.03E-11
5	16961.4060	9.12605E-03	2.05E-12
6	24974.2903	2.13314E-02	3.14E-12
7	43108.4226	6.50120E-03	2.79E-12
8	58642.0477	5.40799E-03	-1.94E-12
9	59617.3409	4.62228E-03	1.96E-13
10	72315.4874	2.80207E-03	-2.38E-11

MODEL FILE : /home/ddelgado/newloading10test10.mf1
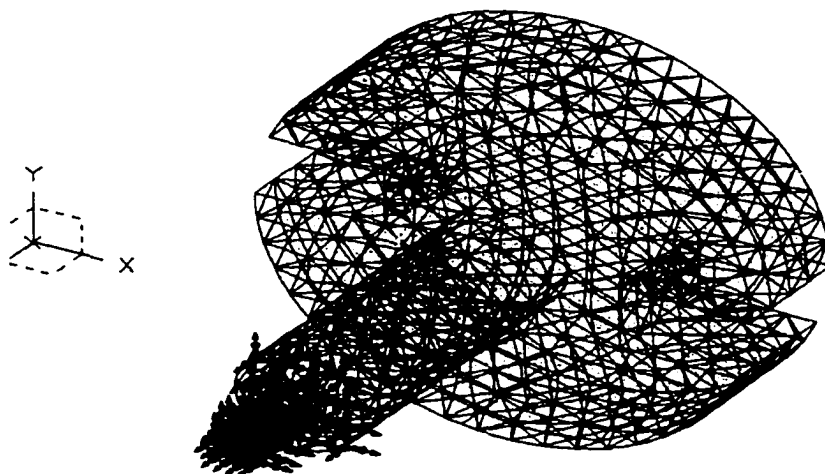

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NUMBER OF NODES      :    6699
NUMBER OF ELEMENTS   :    3802
```

MODE	FREQUENCY	MODAL MASS	RESIDUAL
1	2989.5365	2.65809E-02	-3.03E-10
2	3058.8493	2.54647E-02	-2.39E-10
3	4240.3763	1.51293E-02	8.15E-11
4	14121.1510	1.19219E-02	-2.47E-11
5	15431.1458	8.99552E-03	2.90E-11
6	23683.9946	2.18706E-02	1.21E-13
7	42467.4439	6.39247E-03	6.24E-12
8	58462.2336	5.45390E-03	6.23E-12
9	59023.4491	4.72629E-03	1.70E-11
10	72173.0539	2.76617E-03	-1.62E-10

MODEL FILE : /home/ddelgado/newloading10test15.mf1


```
NUMBER OF NODES      :    2815
NUMBER OF ELEMENTS   :    1417
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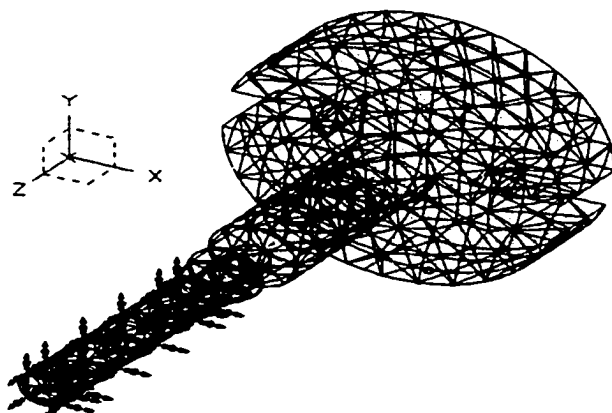
MODE	FREQUENCY	MODAL MASS	RESIDUAL
1	622.2883	2.65700E-02	-1.14E-09
2	635.5787	2.61934E-02	-4.10E-09
3	1447.3904	1.53299E-02	9.20E-10
4	10145.6983	1.13761E-02	-1.66E-11
5	11228.6423	9.00694E-03	-3.33E-12
6	15165.9528	2.93387E-02	-1.43E-11
7	42285.4285	5.19896E-03	1.00E-10
8	42551.6756	5.55008E-03	8.98E-11
9	42785.1466	7.02963E-03	4.41E-11
10	57019.3019	6.90697E-03	1.98E-10

MODEL FILE : /home/ddelgado/newloading10test15AA.mf1
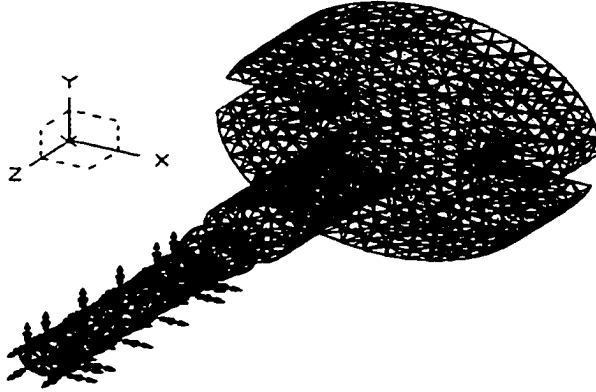

```
NUMBER OF NODES      :    7322
NUMBER OF ELEMENTS   :    4075

ACTIVE UNITS SYSTEM : Inch (pound f)
TEMPERATURE MODE    : Relative Temperatures
```

MODE	FREQUENCY	MODAL MASS	RESIDUAL
1	564.6779	3.19995E-02	-7.13E-09
2	574.9463	3.13295E-02	1.54E-08
3	1340.0367	1.52960E-02	1.11E-09
4	9168.8393	1.15805E-02	-3.12E-11
5	10127.4471	9.20404E-03	-4.05E-11
6	13872.2753	2.99357E-02	-5.47E-12
7	34765.6681	4.67591E-03	6.59E-11
8	34912.3474	5.00870E-03	4.77E-11
9	41255.6014	6.39187E-03	1.30E-10
10	55409.4789	6.76534E-03	1.62E-10

APPENDIX D

SIGNAL CAL ACE SOFTWARE GRAPH RESULTS

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Sensor Placements Results pages 50-64

Piezo
(1&2)

sensor

Piezo
(3&4) or
sensor

sensor

Piezo (1&2)

Piezo (3&4)
or sensor
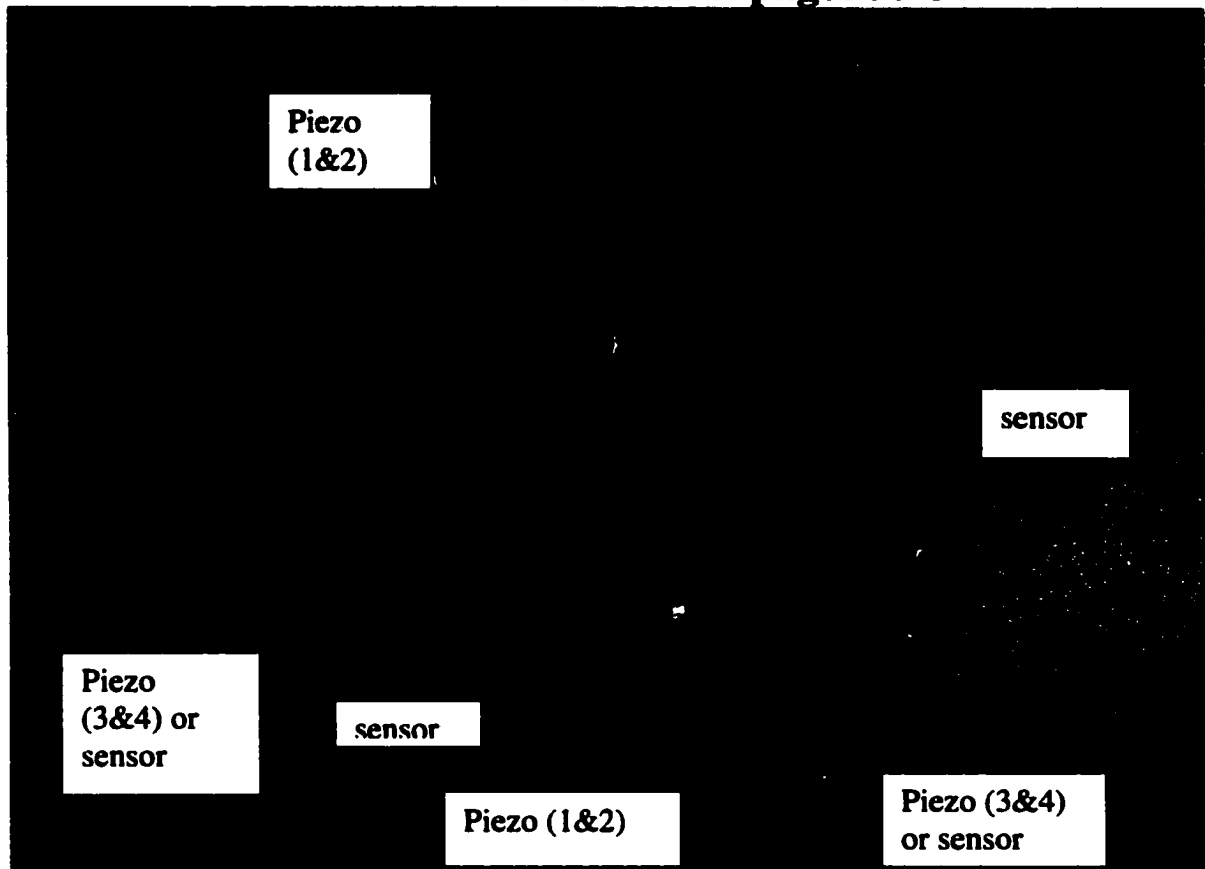
RED arrows indicate all the location the sensor and piezos were placed.

Brass mount   In the middle of the implant place the sensors.

H1, 2		
Peak#	X	Y
1	1.375 K	3.397 m
2	2.738 K	527.256 u
3	2.663 K	479.511 u
4	2.600 K	464.009 u
5	2.550 K	454.791 u
6	2.513 K	423.937 u
7	2.475 K	414.977 u
8	2.425 K	413.228 u
9	2.238 K	391.187 u
10	2.300 K	390.285 u
11	1.225 K	389.559 u
12	2.363 K	387.291 u
13	1.625 K	342.255 u
14	1.675 K	341.492 u
15	2.125 K	290.149 u

H1, 2		
Peak#	X	Y
1	5.888 K	8.756 m
2	5.713 K	8.681 m
3	5.788 K	8.338 m
4	5.950 K	8.307 m
5	5.838 K	8.046 m
6	6.038 K	7.537 m
7	5.650 K	7.446 m
8	5.550 K	7.397 m
9	6.150 K	7.358 m
10	5.487 K	7.305 m
11	6.075 K	7.272 m
12	6.000 K	7.268 m
13	5.612 K	6.805 m
14	5.400 K	6.605 m
15	5.275 K	6.562 m

Peak#	H1, 2	
	X	Y
1	3.712 K	4.354 m
2	3.638 K	4.353 m
3	3.775 K	4.343 m
4	4.013 K	4.137 m
5	3.825 K	4.046 m
6	3.938 K	4.036 m
7	3.538 K	3.972 m
8	3.600 K	3.887 m
9	3.488 K	3.817 m
10	3.400 K	3.785 m
11	3.425 K	3.781 m
12	4.050 K	3.644 m
13	4.150 K	3.633 m
14	4.350 K	3.580 m
15	3.113 K	3.536 m

Unthreaded Case

Peak#	H1, 2 X	Y
1	2.837 K	3.271
2	2.712 K	1.539
3	16.038 K	1.521
4	15.913 K	1.455
5	15.850 K	1.391
6	2.975 K	1.339
7	15.975 K	1.321
8	19.450 K	1.300
9	19.512 K	1.278
10	16.087 K	1.266
11	15.788 K	1.242
12	15.750 K	1.230
13	19.575 K	1.229
14	16.125 K	1.133
15	15.713 K	1.118

Threaded Case   moving sensor closer to the one side of the piezos.

Peak#	H1, 2 X	Y
1	10.313 K	16.668
2	10.275 K	14.553
3	7.175 K	11.470
4	10.388 K	11.046
5	7.125 K	9.865
6	7.900 K	9.400
7	10.488 K	7.265
8	10.138 K	6.794
9	10.525 K	6.256
10	10.625 K	6.032
11	7.838 K	5.477
12	10.663 K	5.385
13	10.588 K	5.151
14	10.075 K	5.031
15	7.275 K	4.821
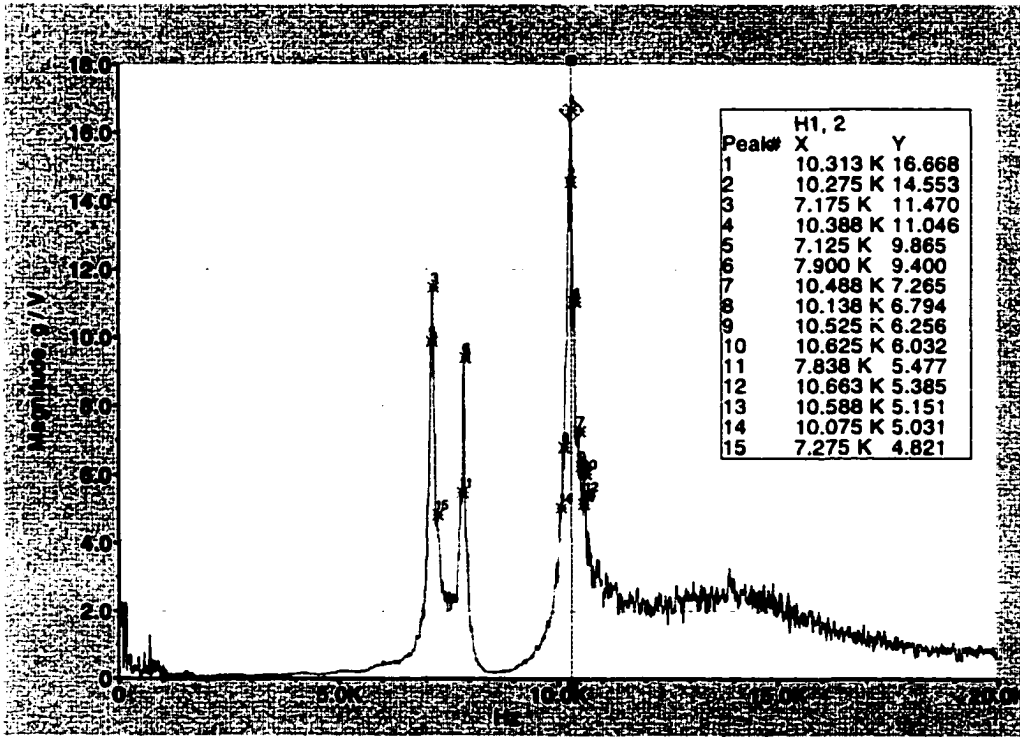
Threaded Case   moving sensor to the orginal position.

Peak#	H1, 2 X	Y
1	10.375 K	15.362
2	10.275 K	14.983
3	7.638 K	13.950
4	10.313 K	13.588
5	7.688 K	9.706
6	10.225 K	9.016
7	10.475 K	8.971
8	12.500	6.862
9	10.175 K	6.744
10	7.750 K	6.414
11	10.113 K	5.805
12	10.575 K	5.602
13	10.538 K	5.512
14	10.625 K	4.688
15	10.038 K	4.093
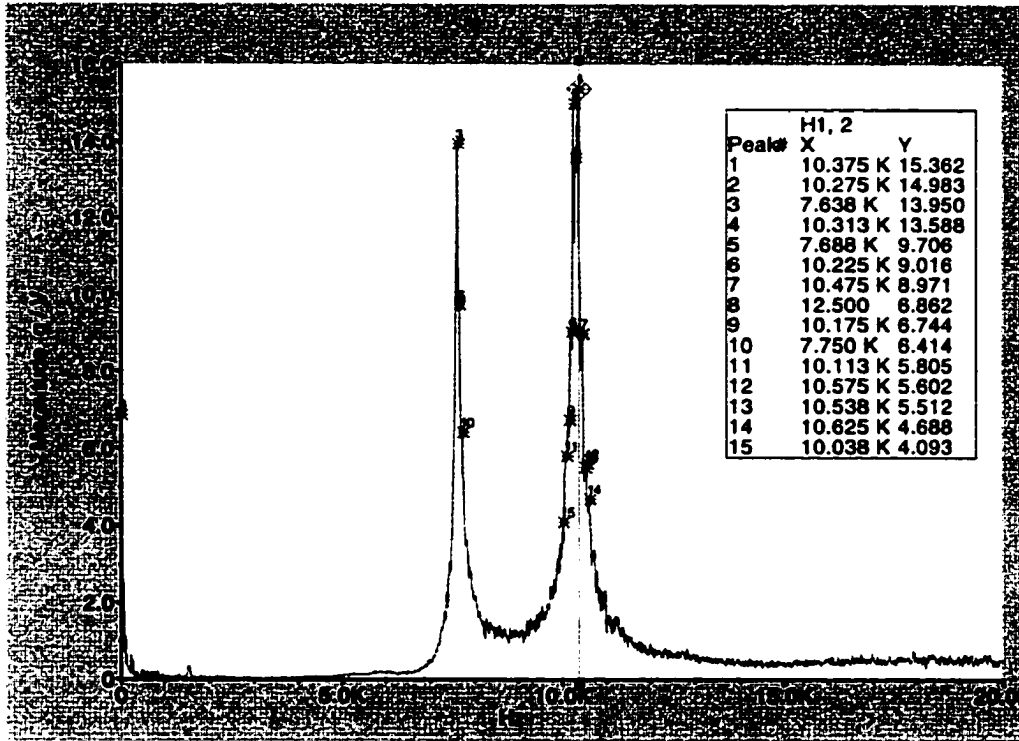
Threaded Case   With only one piezo on the left sided tape.

Peak#	H1, 2 X	Y
1	9.850 K	35.915
2	9.800 K	32.716
3	9.925 K	29.897
4	9.738 K	25.484
5	9.688 K	19.086
6	10.025 K	18.706
7	7.250 K	15.186
8	7.288 K	14.717
9	10.100 K	13.452
10	7.100 K	13.341
11	7.200 K	12.779
12	7.163 K	12.307
13	7.050 K	12.139
14	10.188 K	10.962
15	7.400 K	10.343
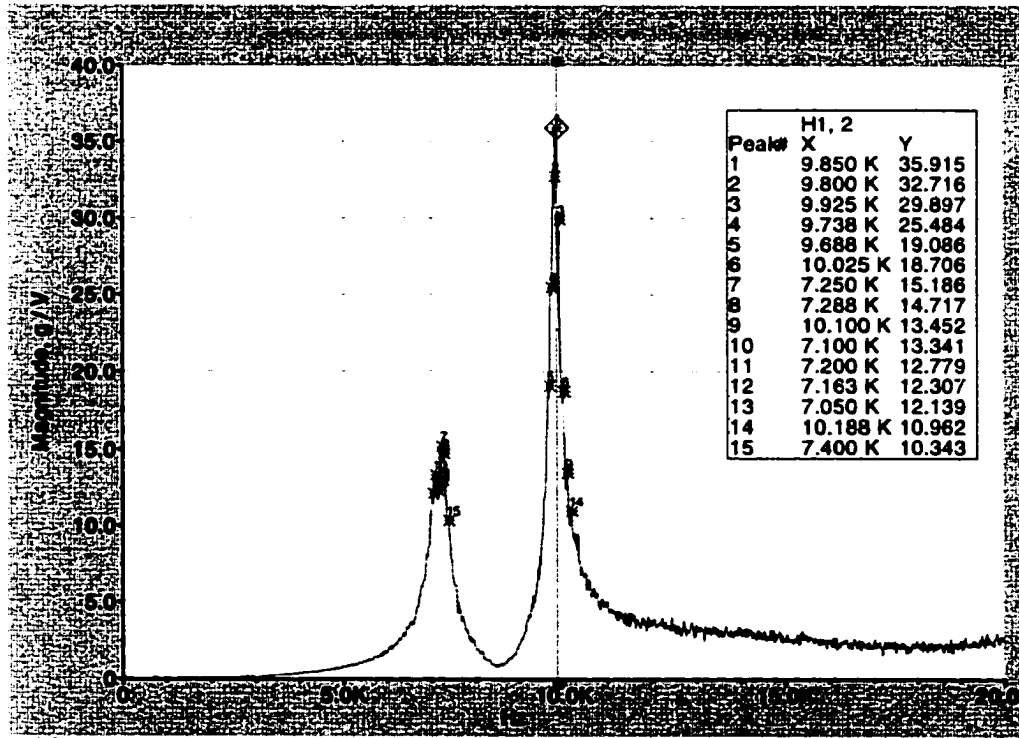
threaded Case   With the one sided piezo on only.

Peak#	H1, 2 X	Y
1	12.500	55.558
2	7.150 K	36.645
3	7.088 K	29.059
4	7.263 K	23.765
5	7.362 K	17.734
6	6.938 K	14.330
7	7.450 K	13.890
8	6.900 K	12.401
9	7.525 K	11.362
10	6.862 K	10.172
11	9.850 K	9.841
12	7.575 K	9.674
13	9.800 K	9.433
14	50.000	8.864
15	7.638 K	8.538
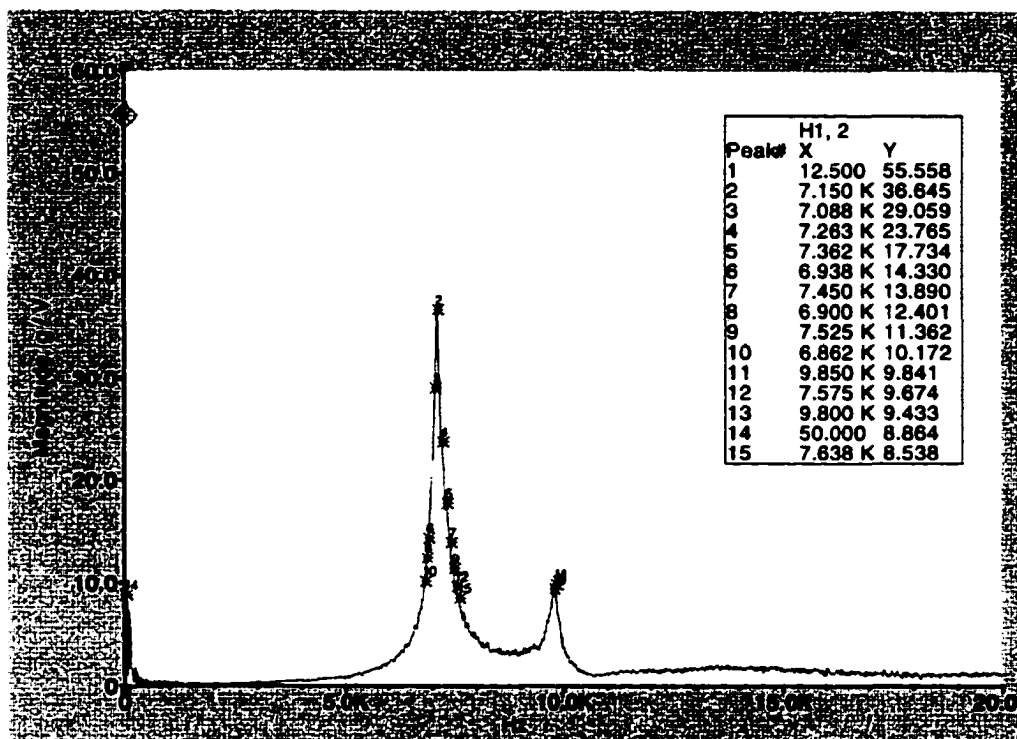
Threaded Case   Closer look at the small peak at 0-5KHz.

H1, 2
X: 1475
Y: 0.502272
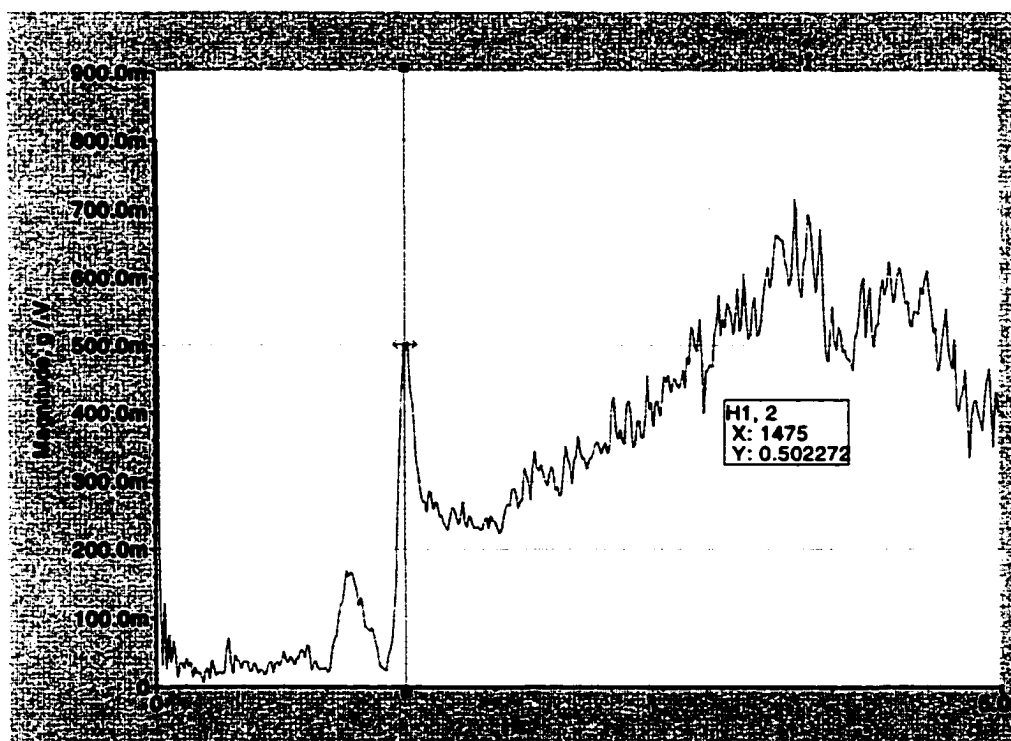
Threaded Case   **With the sensor changes direction of measures.**

Peak#	H1, 2 X	Y
1	7.050 K	23.270
2	7.125 K	19.249
3	9.888 K	16.557
4	9.838 K	16.111
5	7.175 K	12.776
6	9.950 K	12.698
7	7.237 K	11.280
8	9.775 K	10.559
9	9.988 K	9.765
10	7.338 K	8.905
11	7.288 K	8.842
12	6.925 K	8.467
13	7.388 K	8.428
14	7.425 K	7.427
15	10.088 K	7.210

Threaded Case   **with the sensor change direction.**

Peak#	H1, 2 X	Y
1	1.463 K	532.452 m
2	4.763 K	355.510 m
3	4.737 K	353.503 m
4	4.663 K	340.044 m
5	4.225 K	336.372 m
6	4.188 K	327.919 m
7	50.000	325.176 m
8	4.150 K	324.900 m
9	4.625 K	320.354 m
10	4.112 K	313.389 m
11	187.500	311.901 m
12	4.037 K	303.024 m
13	4.300 K	303.020 m
14	4.525 K	299.963 m
15	3.850 K	298.677 m

Threaded Case   **With the sensor change direction.**

Peak#	H1, 2 X	Y
1	9.813 K	19.543
2	9.863 K	18.217
3	7.263 K	16.631
4	9.912 K	15.663
5	9.738 K	15.580
6	7.362 K	13.166
7	9.688 K	11.306
8	9.988 K	11.213
9	9.625 K	9.002
10	7.400 K	8.104
11	9.513 K	6.756
12	7.500 K	5.962
13	10.088 K	5.745
14	10.138 K	5.446
15	9.412 K	4.977

Threaded Case   **Unbalanced mass**   **Same as above**

Peak#	H1, 2 X	Y
1	7.700 K	20.536
2	10.250 K	15.363
3	10.138 K	14.704
4	10.188 K	14.492
5	7.763 K	13.346
6	10.350 K	9.457
7	7.825 K	7.422
8	10.388 K	7.339
9	10.038 K	7.299
10	9.988 K	6.961
11	9.950 K	5.849
12	9.875 K	5.173
13	10.450 K	5.075
14	9.838 K	4.954
15	10.475 K	4.878

Threaded Case

Peak#	H1, 2 X	Y
1	5.888 K	4.217 m
2	5.763 K	4.104 m
3	5.850 K	4.101 m
4	9.150 K	3.795 m
5	9.250 K	3.780 m
6	5.938 K	3.769 m
7	5.675 K	3.547 m
8	5.975 K	3.502 m
9	5.638 K	3.466 m
10	9.287 K	3.343 m
11	9.338 K	3.304 m
12	6.025 K	3.289 m
13	9.188 K	3.247 m
14	5.513 K	2.938 m
15	5.438 K	2.896 m

Threaded Case

Peak#	H1, 2 X	Y
1	5.850 K	4.323 m
2	5.663 K	4.051 m
3	5.750 K	3.822 m
4	5.813 K	3.724 m
5	5.900 K	3.719 m
6	9.138 K	3.636 m
7	5.938 K	3.592 m
8	9.175 K	3.585 m
9	5.600 K	3.534 m
10	6.013 K	3.477 m
11	9.063 K	3.444 m
12	9.213 K	3.435 m
13	8.888 K	3.366 m
14	5.550 K	3.309 m
15	5.438 K	3.307 m

Threaded Case

H1, 2		
Peak#	X	Y
1	4.675 K	2.869 m
2	4.775 K	2.825 m
3	4.713 K	2.726 m
4	4.850 K	2.664 m
5	4.612 K	2.554 m
6	4.888 K	2.532 m
7	4.813 K	2.529 m
8	4.938 K	2.516 m
9	4.538 K	2.249 m
10	5.013 K	2.101 m
11	5.125 K	1.848 m
12	4.413 K	1.844 m
13	4.463 K	1.766 m
14	4.350 K	1.715 m
15	5.213 K	1.573 m

Threaded Case

H1, 2		
Peak#	X	Y
1	4.612 K	2.270 m
2	4.800 K	2.152 m
3	4.950 K	2.115 m
4	4.713 K	2.112 m
5	4.862 K	2.071 m
6	4.987 K	2.030 m
7	4.675 K	2.018 m
8	5.050 K	1.945 m
9	4.450 K	1.872 m
10	4.550 K	1.788 m
11	4.400 K	1.784 m
12	5.100 K	1.716 m
13	4.500 K	1.699 m
14	5.138 K	1.682 m
15	5.175 K	1.658 m

Threaded Case
Unbalanced masses of sensors

H1, 2		
Peak#	X	Y
1	9.963 K	8.257 m
2	9.888 K	7.706 m
3	9.925 K	7.617 m
4	10.000 K	6.870 m
5	9.850 K	6.545 m
6	9.800 K	6.181 m
7	10.075 K	6.104 m
8	10.038 K	6.031 m
9	10.113 K	5.519 m
10	9.763 K	5.237 m
11	10.188 K	4.786 m
12	10.313 K	4.303 m
13	9.675 K	4.204 m
14	10.250 K	3.703 m
15	9.625 K	3.628 m

Threaded Case
Unbalanced

H1, 2		
Peak#	X	Y
1	9.838 K	5.405 m
2	9.975 K	5.033 m
3	9.900 K	4.978 m
4	9.938 K	4.783 m
5	9.763 K	4.727 m
6	10.050 K	4.701 m
7	10.188 K	4.389 m
8	10.113 K	4.349 m
9	10.150 K	4.333 m
10	10.400 K	4.256 m
11	9.725 K	3.457 m
12	10.313 K	3.414 m
13	9.662 K	3.173 m
14	11.513 K	3.110 m
15	10.450 K	3.061 m

Threaded Case

H1, 2		
Peak#	X	Y
1	5.313 K	1.852 m
2	5.263 K	1.846 m
3	5.413 K	1.804 m
4	5.188 K	1.745 m
5	5.375 K	1.739 m
6	5.513 K	1.726 m
7	5.150 K	1.626 m
8	5.638 K	1.609 m
9	5.725 K	1.583 m
10	4.913 K	1.567 m
11	5.450 K	1.566 m
12	5.575 K	1.560 m
13	5.025 K	1.560 m
14	4.950 K	1.527 m
15	5.063 K	1.516 m

Threaded Case
unbalanced masses of sensors

H1, 2		
Peak#	X	Y
1	7.362 K	1.936 m
2	7.325 K	1.779 m
3	7.175 K	1.763 m
4	7.288 K	1.747 m
5	7.438 K	1.703 m
6	7.813 K	1.482 m
7	8.425 K	1.478 m
8	7.050 K	1.477 m
9	8.475 K	1.437 m
10	9.863 K	1.432 m
11	8.338 K	1.429 m
12	6.975 K	1.421 m
13	8.275 K	1.414 m
14	7.550 K	1.411 m
15	7.112 K	1.398 m

Unthreaded Case

	H1, 2	
Peak#	X	Y
1	16.325 K	3.702 m
2	16.125 K	3.664 m
3	16.225 K	3.630 m
4	16.087 K	3.557 m
5	16.150 K	3.432 m
6	16.038 K	3.231 m
7	16.375 K	2.985 m
8	16.413 K	2.835 m
9	15.963 K	2.658 m
10	15.900 K	2.440 m
11	15.825 K	2.062 m
12	15.725 K	1.664 m
13	15.763 K	1.650 m
14	16.475 K	1.490 m
15	15.650 K	1.465 m

Unthreaded Case

	H1, 2	
Peak#	X	Y
1	15.588 K	15.004 m
2	15.488 K	10.589 m
3	15.738 K	10.559 m
4	15.450 K	9.896 m
5	15.525 K	9.613 m
6	15.838 K	9.089 m
7	15.925 K	8.870 m
8	15.675 K	8.659 m
9	15.350 K	7.747 m
10	15.888 K	7.331 m
11	15.250 K	6.601 m
12	15.313 K	6.450 m
13	16.050 K	5.997 m
14	16.150 K	5.355 m
15	15.175 K	4.995 m

Unthreaded Case

Peak#	H1, 2 X		Y	
1	7.425 K	2.301 m
2	7.163 K	2.266 m
3	7.025 K	2.168 m
4	7.588 K	2.151 m
5	7.638 K	2.126 m
6	7.237 K	2.121 m
7	6.825 K	2.083 m
8	6.862 K	2.076 m
9	7.737 K	2.073 m
10	7.325 K	2.073 m
11	7.513 K	2.045 m
12	7.100 K	2.033 m
13	7.375 K	2.033 m
14	7.475 K	1.990 m
15	6.713 K	1.967 m

Unthreaded Case

Peak#	H1, 2 X		Y	
1	6.275 K	1.183 m
2	6.950 K	1.176 m
3	6.038 K	1.150 m
4	6.575 K	1.128 m
5	6.900 K	1.122 m
6	6.750 K	1.108 m
7	6.112 K	1.093 m
8	6.487 K	1.089 m
9	6.987 K	1.080 m
10	7.413 K	1.071 m
11	7.275 K	1.064 m
12	6.825 K	1.064 m
13	5.500 K	1.063 m
14	6.388 K	1.058 m
15	6.325 K	1.045 m

Unthreaded Case
Balanced masses of sensors

Peak#	X	Y
1	15.100 K	1.836 m
2	15.138 K	1.654 m
3	14.813 K	1.637 m
4	15.063 K	1.487 m
5	14.913 K	1.457 m
6	15.000 K	1.447 m
7	15.363 K	1.429 m
8	15.313 K	1.408 m
9	15.213 K	1.391 m
10	15.275 K	1.389 m
11	8.488 K	1.385 m
12	15.413 K	1.384 m
13	8.338 K	1.378 m
14	8.825 K	1.346 m
15	14.875 K	1.337 m

Brass mount   **piezo 1&2 on**   **Torsional Vibration**

	H1, 2	
Peak#	X	Y
1	7.388 K	21.976 m
2	7.425 K	21.293 m
3	7.350 K	21.214 m
4	7.300 K	20.899 m
5	7.475 K	20.846 m
6	7.237 K	20.797 m
7	7.513 K	20.117 m
8	7.563 K	19.407 m
9	7.200 K	19.140 m
10	7.625 K	18.632 m
11	7.125 K	17.519 m
12	7.688 K	16.462 m
13	7.725 K	15.850 m
14	7.788 K	15.098 m
15	10.325 K	14.847 m

Brass mount   **piezo 3&4 on**   **Axial Vibration**

	H1, 2	
Peak#	X	Y
1	10.388 K	9.136 m
2	10.425 K	9.092 m
3	10.338 K	9.058 m
4	10.288 K	8.744 m
5	10.250 K	7.986 m
6	10.500 K	7.780 m
7	10.213 K	7.193 m
8	10.563 K	6.787 m
9	10.075 K	5.451 m
10	10.650 K	5.277 m
11	9.925 K	4.126 m
12	9.875 K	3.822 m
13	1.313 K	3.778 m
14	10.800 K	3.620 m
15	6.200 K	3.241 m

FINAL PLACEMENT OF SENSOR AND PIEZOS PAGES 66-76

Sensor

Torsional
Piezo (1&2)

Axial Piezo (3&4)
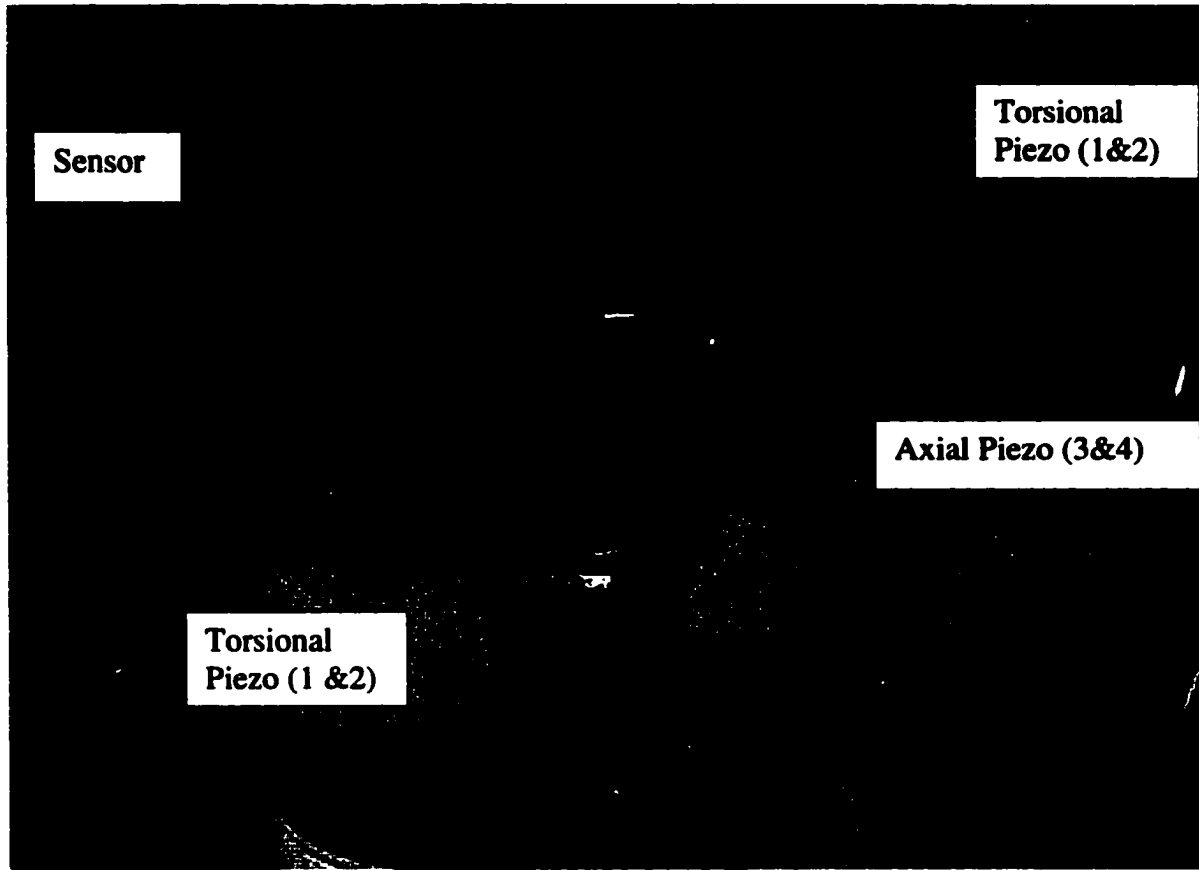
Torsional
Piezo (1 &2)

PAGES 77-88 shows the testing results for Table 2-7.
PAGES 89-104 shows the testing results for Table 2-6.
PAGES 105-153 shows the testing results for Table 2-8,2-9,2-10,2-11

Brass mount   **vibration with axial piezo 3&4**

	H1, 2	
Peak#	X	Y
1	10.388 K	3.752 m
2	10.450 K	3.464 m
3	7.425 K	3.187 m
4	7.475 K	3.148 m
5	7.525 K	3.129 m
6	7.575 K	2.966 m
7	10.288 K	2.922 m
8	7.350 K	2.810 m
9	10.575 K	2.580 m
10	10.213 K	2.515 m
11	7.700 K	2.383 m
12	7.737 K	2.335 m
13	7.788 K	2.187 m
14	6.000 K	2.159 m
15	6.112 K	2.153 m

Close up of Torsion vibration

	H1, 2	
Peak#	X	Y
1	1.338 K	2.103 m
2	1.550 K	271.233 u
3	1.050 K	243.568 u
4	1.013 K	215.893 u
5	1.663 K	183.416 u
6	975.000	180.097 u
7	1.700 K	172.877 u
8	912.500	163.367 u
9	825.000	132.083 u
10	637.500	107.065 u
11	750.000	98.914 u
12	700.000	98.048 u
13	587.500	88.733 u
14	525.000	87.623 u
15	6.112 K	2.153 m

Brass Mount   **Torsion vibration Piezo 1& 2**

Peak#	X	Y
H1, 2		
1	7.463 K	24.202 m
2	7.425 K	24.139 m
3	7.388 K	23.087 m
4	7.350 K	22.560 m
5	7.550 K	22.466 m
6	7.675 K	17.854 m
7	7.775 K	14.755 m
8	7.813 K	14.488 m
9	10.363 K	14.270 m
10	10.438 K	12.977 m
11	7.862 K	12.961 m
12	7.050 K	12.795 m
13	7.000 K	11.918 m
14	7.925 K	11.610 m
15	7.963 K	11.070 m

Torsion close up

Peak#	X	Y
H1, 2		
1	1.338 K	836.723 u
2	1.275 K	772.369 u
3	1.138 K	181.385 u
4	1.088 K	170.893 u
5	1.513 K	150.423 u
6	525.000	139.107 u
7	1.550 K	127.875 u
8	837.500	124.202 u
9	950.000	116.571 u
10	562.500	114.851 u
11	1.638 K	106.613 u
12	875.000	106.491 u
13	912.500	104.705 u
14	1.600 K	104.169 u
15	700.000	89.159 u

Acrylic mount

Threaded Axial vibration
P3&P4

H1, 2		
Peak#	X	Y
1	1.025 K	919.443 u
2	775.000	157.230 u
3	875.000	153.662 u
4	675.000	107.210 u
5	637.500	98.013 u
6	525.000	95.773 u
7	1.263 K	87.057 u
8	1.350 K	68.553 u
9	1.313 K	60.705 u
10	587.500	59.188 u
11	1.400 K	52.422 u
12	1.438 K	46.973 u
13	1.488 K	42.548 u
14	1.538 K	42.432 u
15	1.675 K	35.567 u

Axial max value

H1, 2		
Peak#	X	Y
1	8.750 K	8.167 m
2	8.713 K	8.119 m
3	8.387 K	4.425 m
4	8.275 K	3.573 m
5	8.225 K	3.418 m
6	8.175 K	3.132 m
7	8.137 K	3.087 m
8	8.100 K	2.897 m
9	8.025 K	2.774 m
10	7.963 K	2.606 m
11	7.875 K	2.443 m
12	7.825 K	2.327 m
13	7.775 K	2.260 m
14	7.725 K	2.166 m
15	9.125 K	2.033 m

Torsion Vibration

Peak#	H1, 2 X	Y
1	7.138 K	15.358 m
2	7.100 K	14.994 m
3	7.063 K	14.694 m
4	7.200 K	14.261 m
5	8.725 K	14.152 m
6	7.000 K	13.948 m
7	7.250 K	13.604 m
8	8.688 K	13.427 m
9	8.825 K	12.560 m
10	8.650 K	12.308 m
11	7.300 K	12.089 m
12	6.925 K	11.927 m
13	7.413 K	10.539 m
14	7.525 K	8.679 m
15	7.625 K	7.585 m

Better response

Peak#	H1, 2 X	Y
1	9.100 K	2.127 m
2	9.162 K	1.992 m
3	7.350 K	1.083 m
4	7.000 K	1.009 m
5	9.388 K	778.541 u
6	9.475 K	616.868 u
7	7.588 K	537.079 u
8	9.600 K	475.319 u
9	8.638 K	455.332 u
10	9.650 K	443.437 u
11	9.700 K	417.512 u
12	9.750 K	397.747 u
13	7.750 K	389.138 u
14	8.550 K	380.926 u
15	8.425 K	364.037 u

Torsion   Balance mass for Accelerometer

Peak#	H1, 2 X	Y
1	7.063 K	14.156 m
2	7.175 K	13.998 m
3	7.125 K	13.822 m
4	6.950 K	13.776 m
5	6.987 K	13.573 m
6	7.237 K	13.191 m
7	7.288 K	12.964 m
8	6.900 K	12.888 m
9	7.350 K	12.651 m
10	6.825 K	12.240 m
11	7.413 K	12.194 m
12	7.450 K	11.461 m
13	6.763 K	11.029 m
14	7.500 K	10.785 m
15	7.575 K	9.873 m

Axial   Balance mass

Peak#	H1, 2 X	Y
1	6.388 K	2.251 m
2	6.475 K	2.243 m
3	6.250 K	2.214 m
4	6.350 K	2.211 m
5	6.513 K	2.201 m
6	6.188 K	2.180 m
7	6.638 K	2.178 m
8	6.313 K	2.176 m
9	6.112 K	2.168 m
10	6.150 K	2.165 m
11	6.013 K	2.161 m
12	6.588 K	2.156 m
13	6.088 K	2.145 m
14	6.700 K	2.113 m
15	5.950 K	2.109 m

Close up of torsion

Peak#	H1, 2 X	Y
1	887.500	663.067 u
2	750.000	179.210 u
3	700.000	143.608 u
4	512.500	105.902 u
5	612.500	87.080 u
6	562.500	84.381 u
7	1.163 K	74.806 u
8	1.213 K	63.699 u
9	1.400 K	53.343 u
10	1.688 K	49.162 u
11	1.263 K	47.442 u
12	1.350 K	46.619 u
13	1.600 K	44.636 u
14	1.638 K	42.287 u
15	1.475 K	41.497 u

Unthreaded acrylic mount   Torsion vibration   Balance masses

Peak#	H1, 2 X	Y
1	14.663 K	17.085 m
2	14.713 K	16.651 m
3	14.625 K	16.511 m
4	14.575 K	15.279 m
5	14.513 K	13.336 m
6	14.475 K	12.892 m
7	14.900 K	11.061 m
8	14.338 K	9.837 m
9	14.975 K	9.230 m
10	14.250 K	8.839 m
11	14.200 K	8.239 m
12	14.150 K	8.020 m
13	15.075 K	7.564 m
14	14.038 K	7.359 m
15	15.113 K	6.808 m

Unthreaded   **Axial vibration**   **Balance mass**

H1, 2		
Peak#	X	Y
1	14.575 K	6.131 m
2	14.700 K	6.037 m
3	14.500 K	6.027 m
4	14.613 K	5.997 m
5	14.900 K	5.979 m
6	14.788 K	5.931 m
7	14.863 K	5.820 m
8	14.738 K	5.793 m
9	14.363 K	5.742 m
10	14.438 K	5.701 m
11	14.663 K	5.627 m
12	14.950 K	5.627 m
13	14.325 K	5.425 m
14	15.013 K	5.401 m
15	14.238 K	5.325 m

Unbalance masses
axial vibration

H1, 2		
Peak#	X	Y
1	14.688 K	10.017 m
2	14.763 K	9.949 m
3	14.650 K	9.597 m
4	14.575 K	9.193 m
5	14.875 K	9.175 m
6	14.838 K	9.097 m
7	14.613 K	9.090 m
8	14.950 K	8.691 m
9	14.500 K	8.102 m
10	15.000 K	8.049 m
11	14.463 K	7.944 m
12	15.075 K	7.900 m
13	15.038 K	7.716 m
14	15.138 K	7.562 m
15	14.388 K	7.173 m

Unbalance masses
Torsion vibration

Peak#	X	Y
	H1, 2	
1	14.138 K	23.183 m
2	14.175 K	22.973 m
3	14.038 K	17.771 m
4	13.913 K	13.141 m
5	13.850 K	11.643 m
6	13.738 K	9.952 m
7	13.700 K	8.924 m
8	13.663 K	8.255 m
9	13.600 K	7.771 m
10	14.938 K	7.488 m
11	14.825 K	7.480 m
12	14.888 K	7.458 m
13	13.550 K	7.368 m
14	14.750 K	7.272 m
15	13.475 K	7.118 m

H1, 2
Peak #1
X: 1312.5
Y: 0.00253593

new mount little oversizes by .144in   mount#3   Axial vibration

H1, 2		
Peak#	X	Y
1	1.213 K	1.748 m
2	1.463 K	400.303 u
3	1.650 K	220.432 u
4	1.738 K	204.251 u
5	1.700 K	200.877 u
6	912.500	178.871 u
7	875.000	163.118 u
8	825.000	131.837 u
9	550.000	123.872 u
10	775.000	105.899 u
11	600.000	96.799 u
12	712.500	96.351 u
13	637.500	84.117 u
14	6.388 K	2.503 m
15	6.737 K	2.474 m

mount #3   torsion vibration

H1, 2		
Peak#	X	Y
1	1.213 K	756.327 u
2	1.000 K	159.164 u
3	1.325 K	158.629 u
4	1.038 K	155.389 u
5	900.000	139.999 u
6	762.500	139.764 u
7	837.500	125.205 u
8	1.363 K	123.515 u
9	725.000	121.957 u
10	575.000	118.833 u
11	950.000	114.380 u
12	675.000	110.945 u
13	537.500	107.921 u
14	625.000	76.883 u
15	1.600 K	67.593 u

mount #4   torsion vibration   unbalance masses   size .153
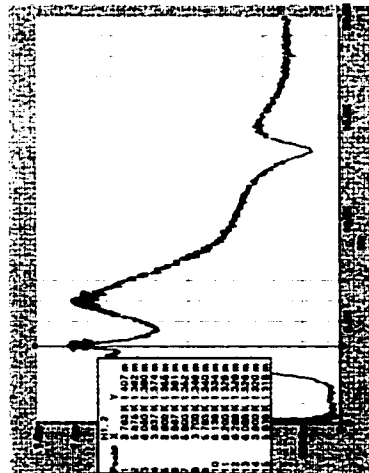
	H1, 2	
Peak#	**X**	**Y**
1	1.188 K	819.916 u
2	1.075 K	240.342 u
3	1.025 K	176.700 u
4	975.000	169.796 u
5	725.000	150.805 u
6	937.500	145.156 u
7	1.325 K	134.418 u
8	1.388 K	118.905 u
9	675.000	118.587 u
10	875.000	115.773 u
11	562.500	115.571 u
12	812.500	88.337 u
13	1.438 K	83.884 u
14	600.000	67.960 u
15	525.000	50.264 u

	H1, 2	
Peak#	**X**	**Y**
1	1.188 K	1.873 m
2	1.463 K	240.083 u
3	1.500 K	216.277 u
4	925.000	178.151 u
5	887.500	163.139 u
6	1.613 K	162.845 u
7	1.663 K	160.161 u
8	1.700 K	156.657 u
9	812.500	136.850 u
10	712.500	125.955 u
11	575.000	120.252 u
12	637.500	81.797 u
13	512.500	64.000 u
14	6.538 K	2.225 m
15	6.250 K	2.211 m

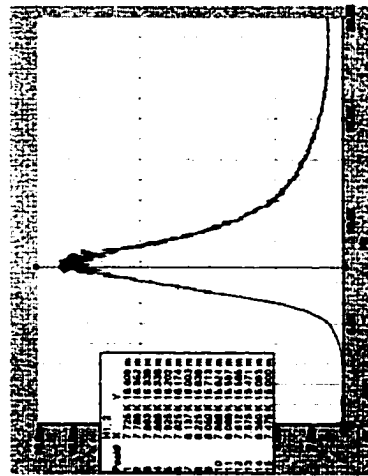CLOSE UP ON TORSION

AXIAL VIBRATION
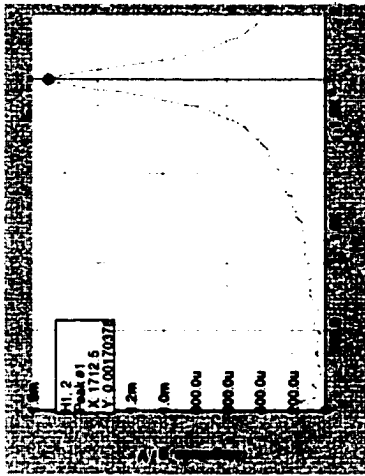
TORSION VIBRATION

5 min

CLOSE UP ON TORSION

AXIAL VIBRATION

TORSION VIBRATION

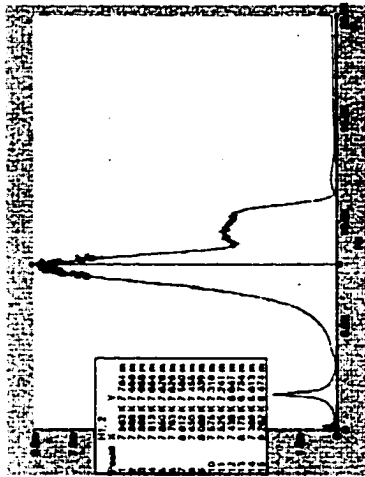10 min

CLOSE UP ON TORSION

AXIAL VIBRATION

TORSION VIBRATION

15 min
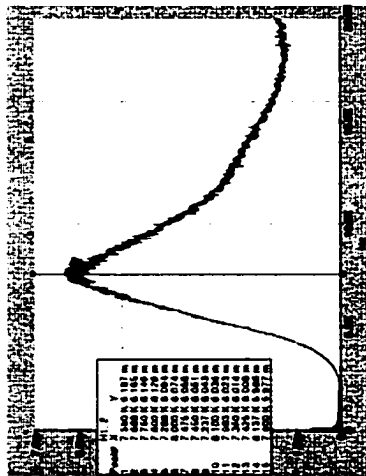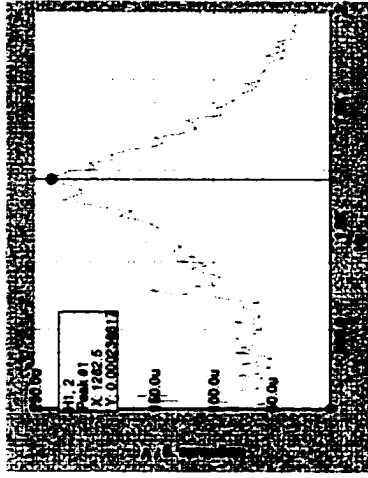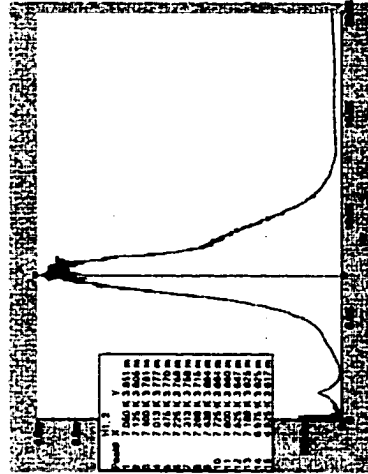
CLOSE UP ON TORSION

AXIAL VIBRATION

TORSION VIBRATION

25 min

CLOSE UP ON TORSION
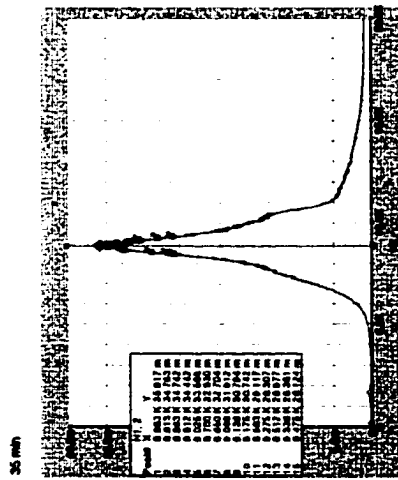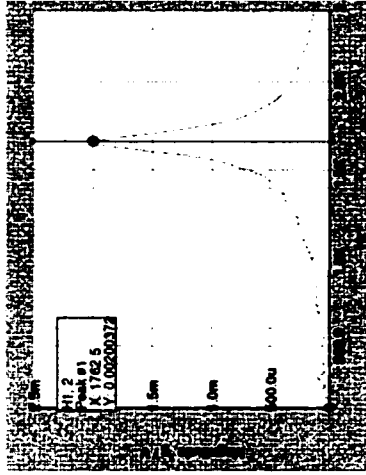
AXIAL VIBRATION

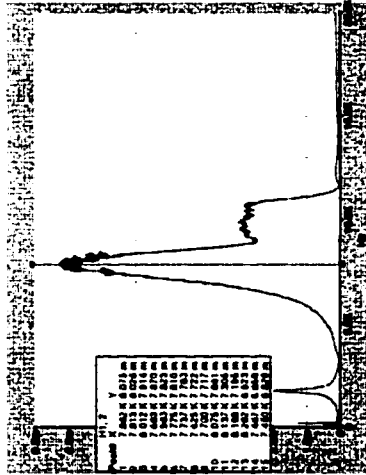TORSION VIBRATION

30 min

CLOSE UP ON TORSION

AXIAL VIBRATION

TORSION VIBRATION

CLOSE UP ON TORSION

AXIAL VIBRATION

TORSION VIBRATION

CLOSE UP ON TORSION

AXIAL VIBRATION

TORSION VIBRATION

CLOSE UP ON TORSION

AXIAL VIBRATION

TORSION VIBRATION

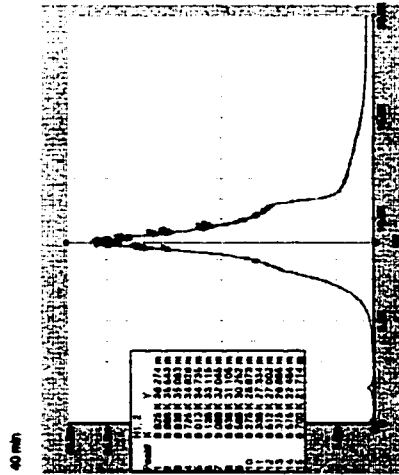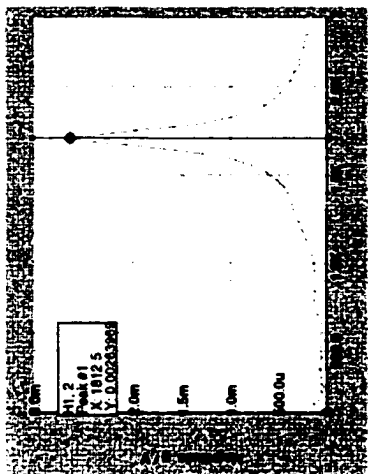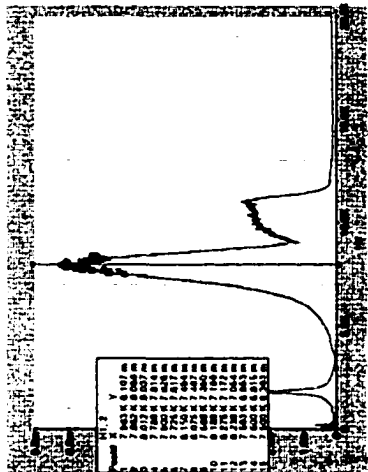CLOSE UP ON TORSION
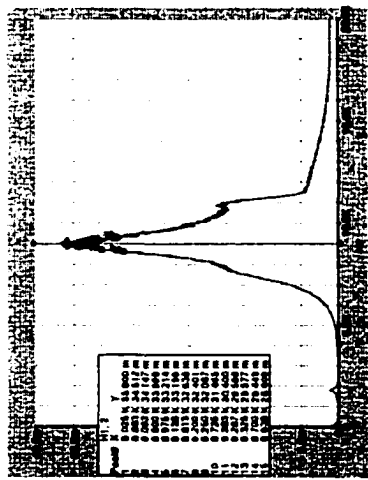
AXIAL VIBRATION

TORSION VIBRATION

CLOSE UP ON TORSION

AXIAL VIBRATION

TORSION VIBRATION

Torsion Vibration of Mount A Full Threaded

Peak#	H1, 2 X	Y
1	9.050 K	3.357 m
2	9.275 K	3.343 m
3	9.225 K	3.336 m
4	9.300 K	3.306 m
5	9.350 K	3.305 m
6	9.613 K	3.287 m
7	9.400 K	3.283 m
8	9.588 K	3.282 m
9	8.963 K	3.282 m
10	8.988 K	3.281 m
11	9.125 K	3.278 m
12	9.563 K	3.268 m
13	9.650 K	3.257 m
14	8.912 K	3.248 m
15	9.500 K	3.243 m

H1, 2
Peak #1
X: 787.5
Y: 0.00051 9246

Axial vibration

Peak#	X	Y
H1, 2		
1	9.912 K	7.578 m
2	9.988 K	7.539 m
3	9.838 K	7.533 m
4	9.800 K	7.533 m
5	9.500 K	7.533 m
6	9.875 K	7.528 m
7	10.038 K	7.509 m
8	9.638 K	7.508 m
9	9.738 K	7.498 m
10	10.100 K	7.484 m
11	10.163 K	7.461 m
12	9.700 K	7.440 m
13	9.463 K	7.433 m
14	9.575 K	7.420 m
15	9.537 K	7.407 m

5.0K   10.0K   Hz

80m 70m 60m 50m 40m 0

close up axial

H1, 2
Peak #1
X: 9912.5
Y: 0.00757819

Torsional Vibration of Mount B.

Peak#	H1,2 X	Y
1	5.338 K	5.251 m
2	5.388 K	5.164 m
3	5.175 K	4.739 m
4	5.237 K	4.670 m
5	9.050 K	4.167 m
6	9.000 K	4.149 m
7	9.150 K	4.095 m
8	9.113 K	4.092 m
9	5.525 K	4.091 m
10	8.938 K	4.083 m
11	8.912 K	4.057 m
12	8.888 K	4.053 m
13	9.313 K	4.048 m
14	9.225 K	4.047 m
15	8.738 K	3.992 m

Close up on Torsion

H1, 2
Peak #1
X: 612.5
Y: 0.000396569

Axial Vibration

Peak#	H1,2 X	Y
1	7.200 K	9.126 m
2	6.913 K	8.979 m
3	7.125 K	8.969 m
4	6.862 K	8.946 m
5	6.825 K	8.864 m
6	6.675 K	8.806 m
7	6.987 K	8.750 m
8	6.788 K	8.743 m
9	6.638 K	8.660 m
10	6.750 K	8.648 m
11	7.275 K	8.589 m
12	6.425 K	8.487 m
13	6.325 K	8.411 m
14	7.038 K	8.394 m
15	7.612 K	8.281 m

Hz

close up of Axial

H1, 2
Peak #1
X: 9950
Y: 0.00789895

Mount A Lower half Threaded

Peak#	H1, 2 X	Y
1	8.412 K	5.166 m
2	8.463 K	5.154 m
3	8.338 K	5.151 m
4	8.300 K	5.117 m
5	8.625 K	5.106 m
6	8.200 K	5.105 m
7	8.863 K	5.102 m
8	8.150 K	5.091 m
9	8.238 K	5.086 m
10	8.675 K	5.084 m
11	8.825 K	5.065 m
12	8.563 K	5.055 m
13	8.375 K	5.054 m
14	8.113 K	5.053 m
15	8.763 K	5.052 m

97

Torsional Vibration

H1, 2
Peak #1
X: 537.5
Y: 0.000332071

Axial Vibration

Peak#	H1,2 X	Y
1	5.925 K	2.655 m
2	7.638 K	2.368 m
3	5.300 K	2.363 m
4	7.725 K	2.362 m
5	4.875 K	2.354 m
6	4.975 K	2.297 m
7	7.775 K	2.280 m
8	5.138 K	2.278 m
9	8.100 K	2.239 m
10	8.075 K	2.228 m
11	7.588 K	2.194 m
12	8.025 K	2.190 m
13	8.162 K	2.190 m
14	8.213 K	2.189 m
15	5.175 K	2.176 m

Close up on Axial

H1, 2
Peak #1
X: 7637.5
Y: 0.0023679
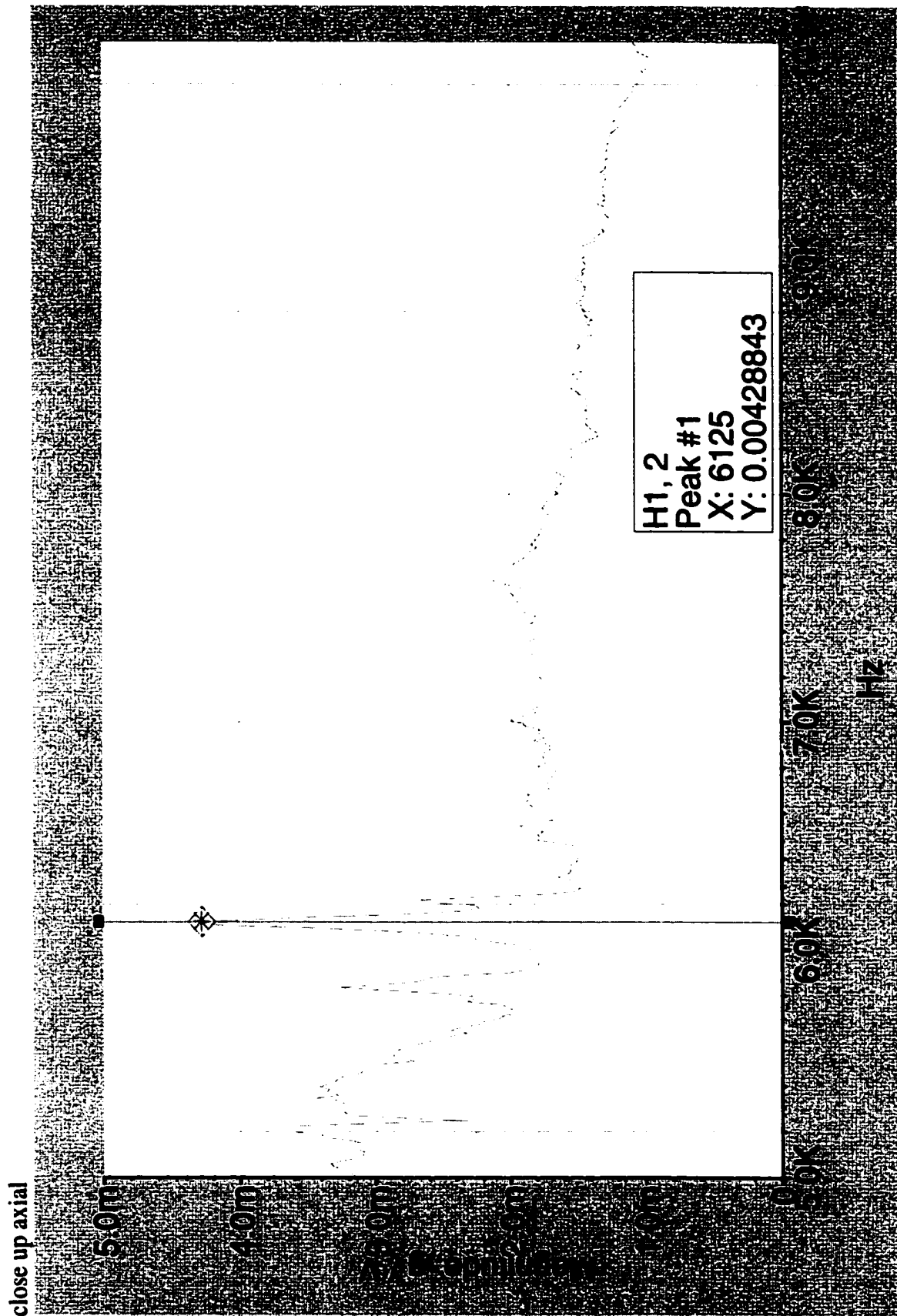
Mount B Upper half Threaded Case Torsional Vibration

Peak#	H1, 2 X	Y
1	8.100 K	4.081 m
2	8.175 K	4.072 m
3	7.975 K	4.068 m
4	8.338 K	4.063 m
5	8.262 K	4.059 m
6	8.000 K	4.051 m
7	7.938 K	4.041 m
8	8.063 K	4.034 m
9	7.913 K	4.024 m
10	8.375 K	4.021 m
11	8.412 K	4.002 m
12	8.463 K	3.989 m
13	7.825 K	3.972 m
14	8.512 K	3.970 m
15	8.638 K	3.953 m

102

H1, 2
Peak #1
X: 500
Y: 0.00035469

1.0K

Hz

400.0u

350.0u

300.0u

250.0u

200.0u

150.0u

100.0u

50.0u

0.0

Axial Vibration

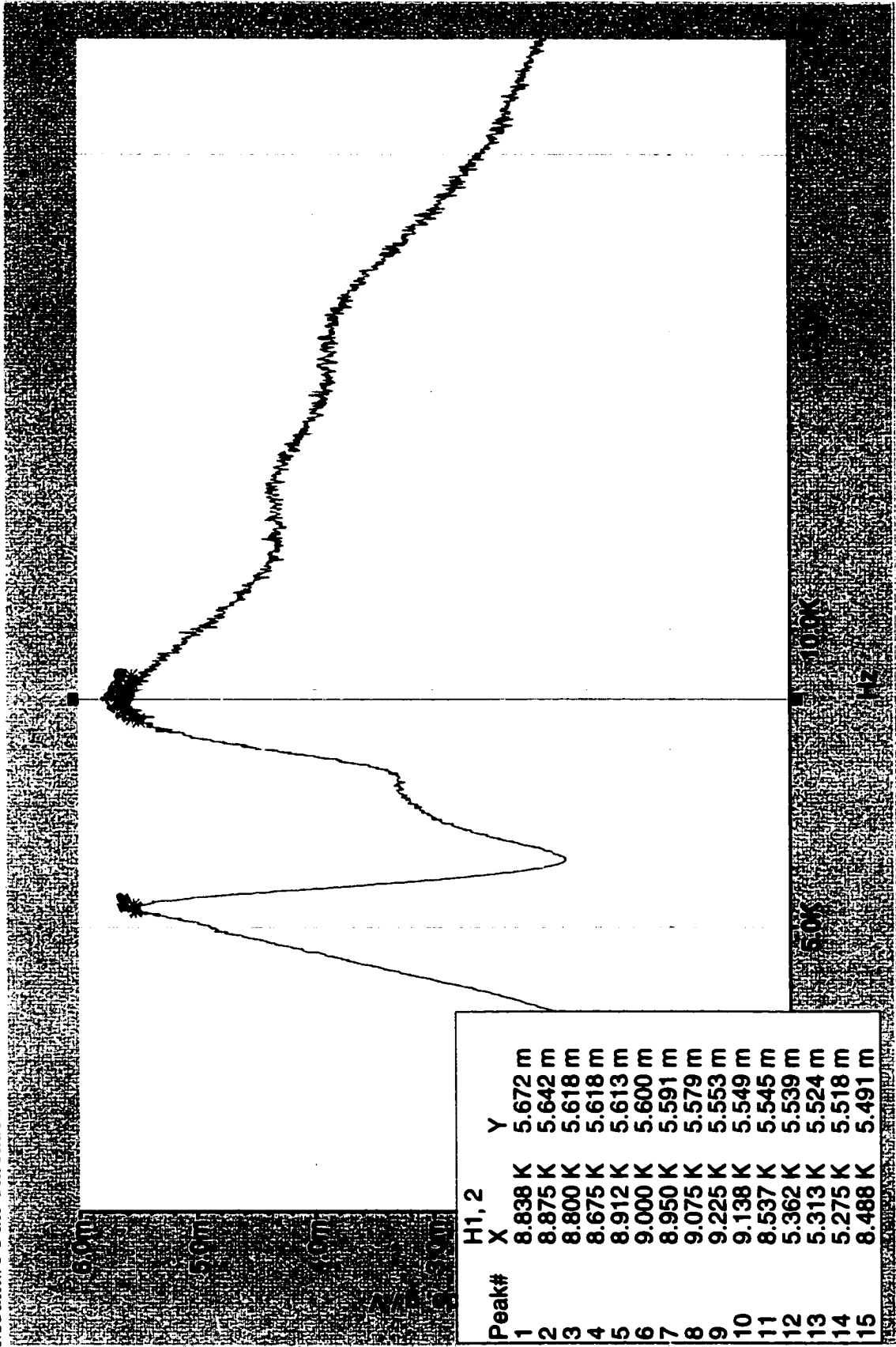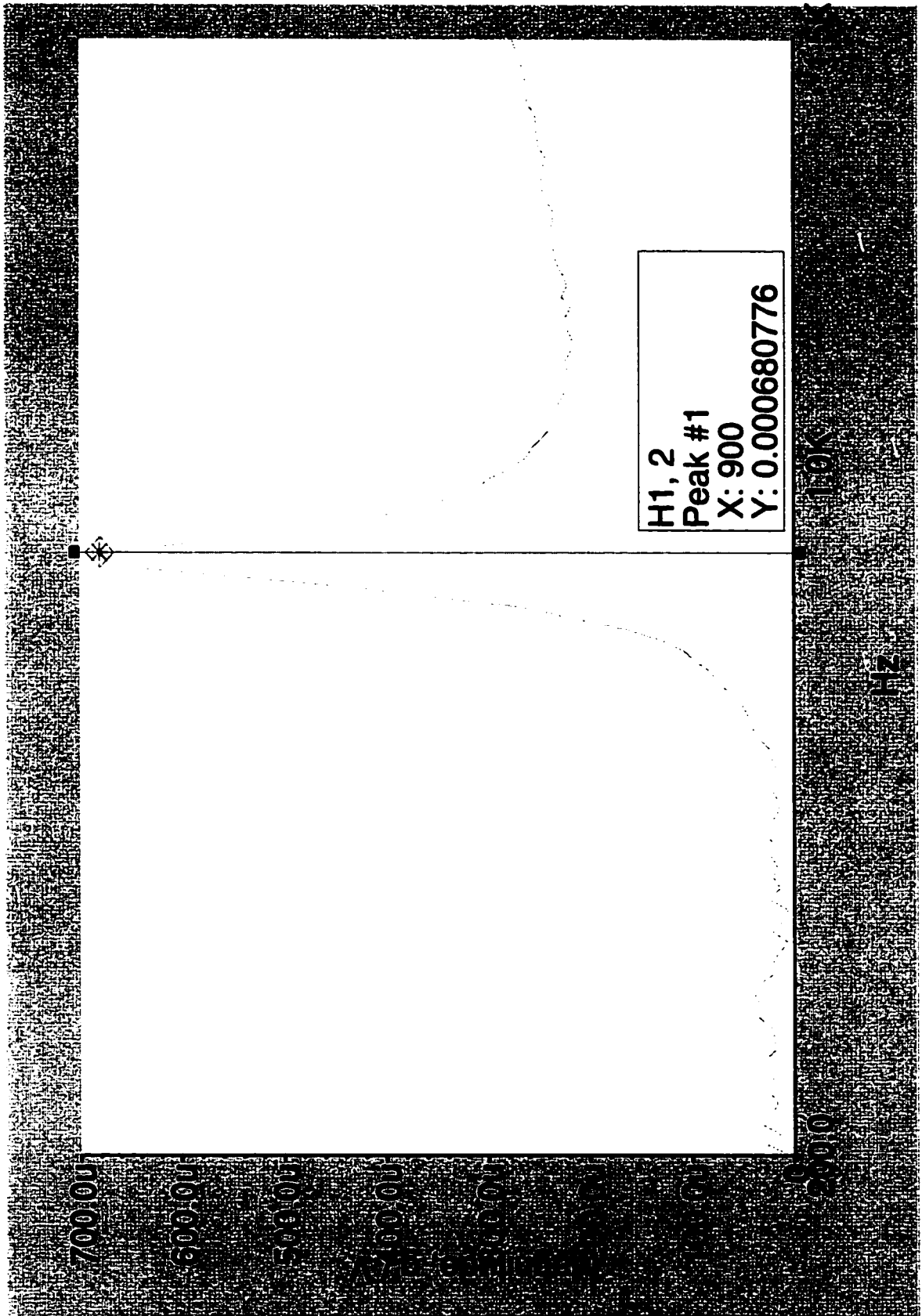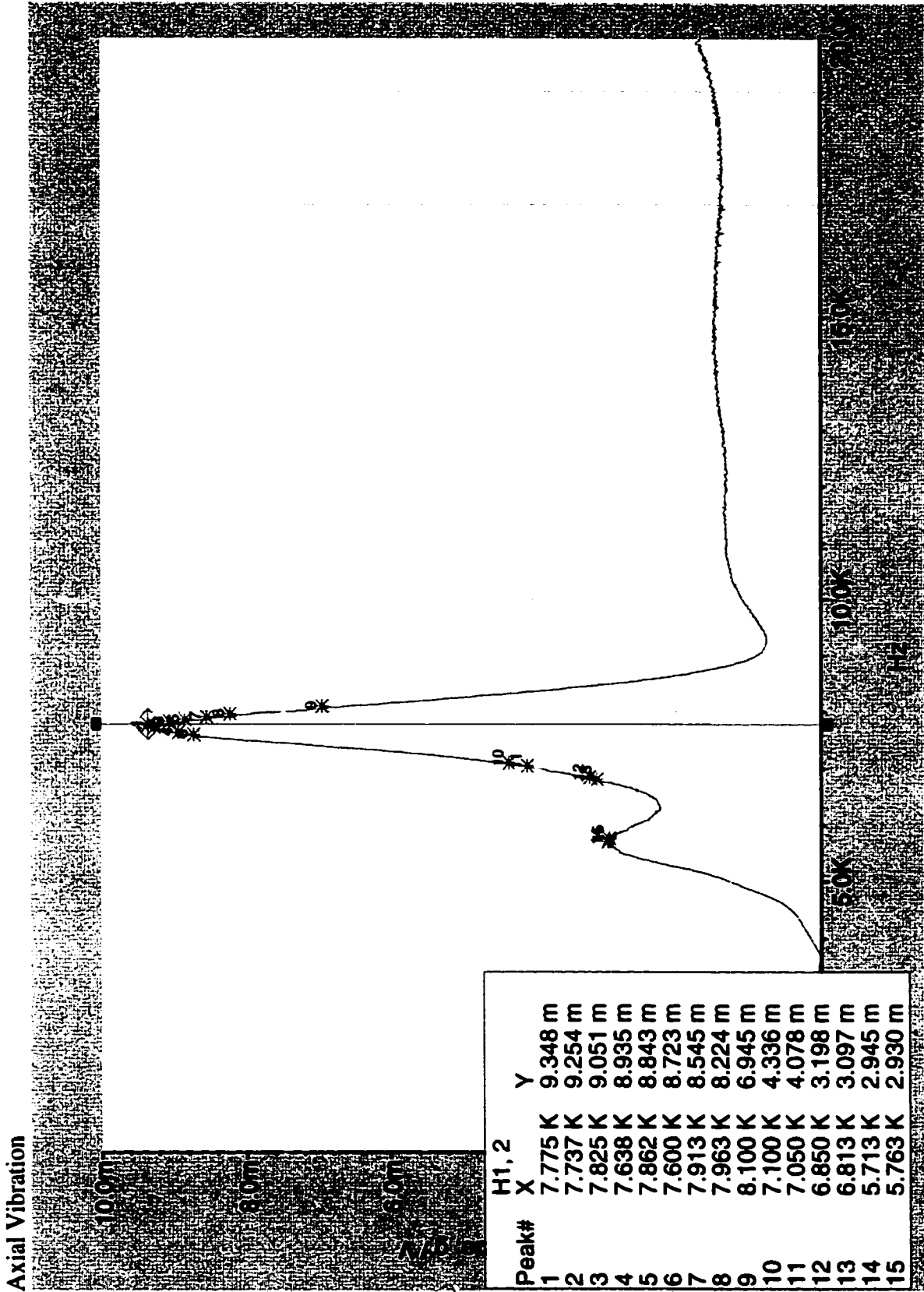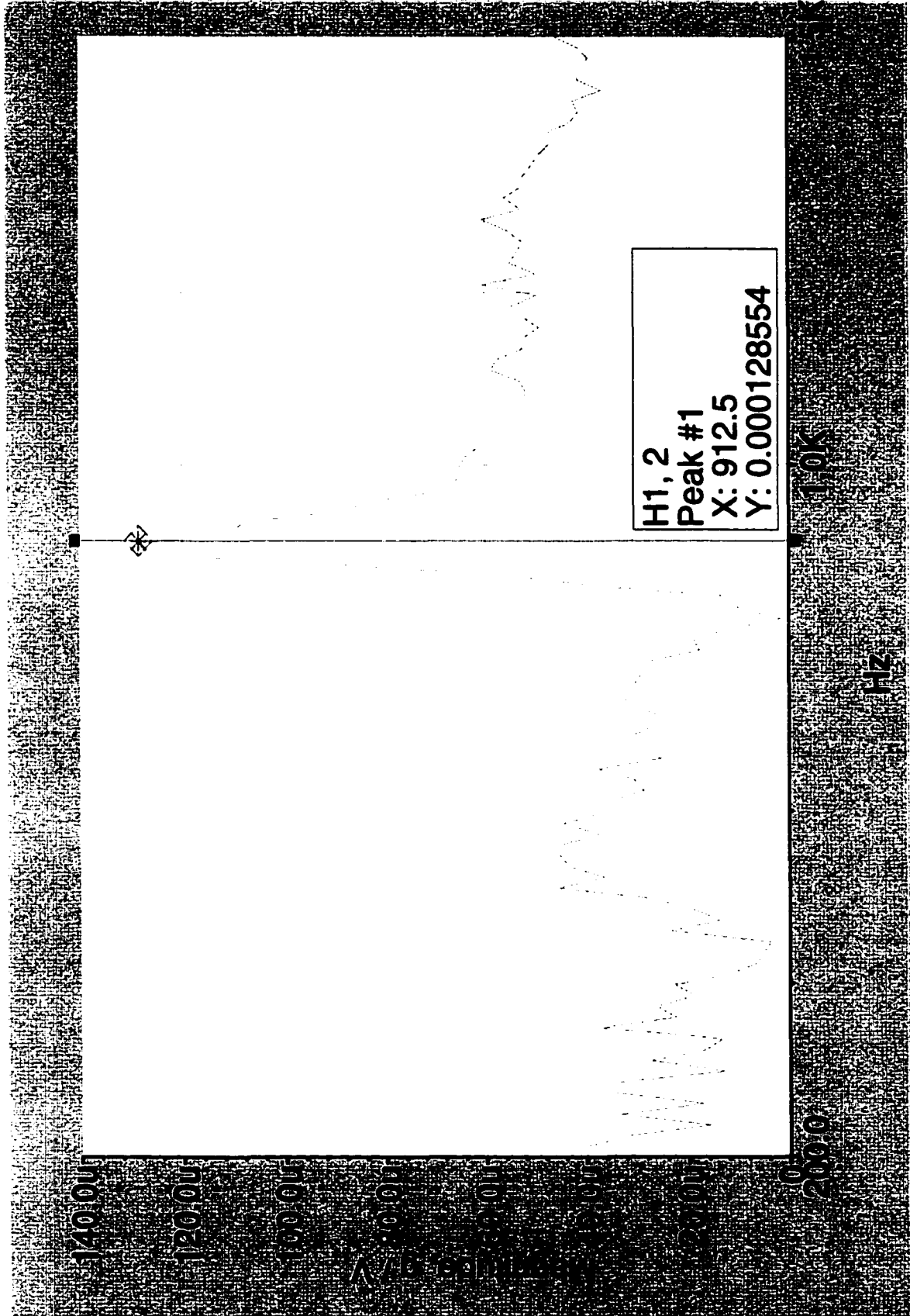| Peak#	H1,2 X	Y
1	6.125 K	4.288 m
2	5.225 K	3.621 m
3	5.350 K	3.444 m
4	5.400 K	3.413 m
5	5.063 K	3.334 m
6	5.838 K	3.281 m
7	5.288 K	3.231 m
8	5.000 K	3.163 m
9	5.125 K	3.147 m
10	5.538 K	2.871 m
11	6.225 K	2.673 m
12	5.650 K	2.449 m
13	5.775 K	2.323 m
14	4.713 K	2.203 m
15	7.650 K	2.141 m

103

close up axial

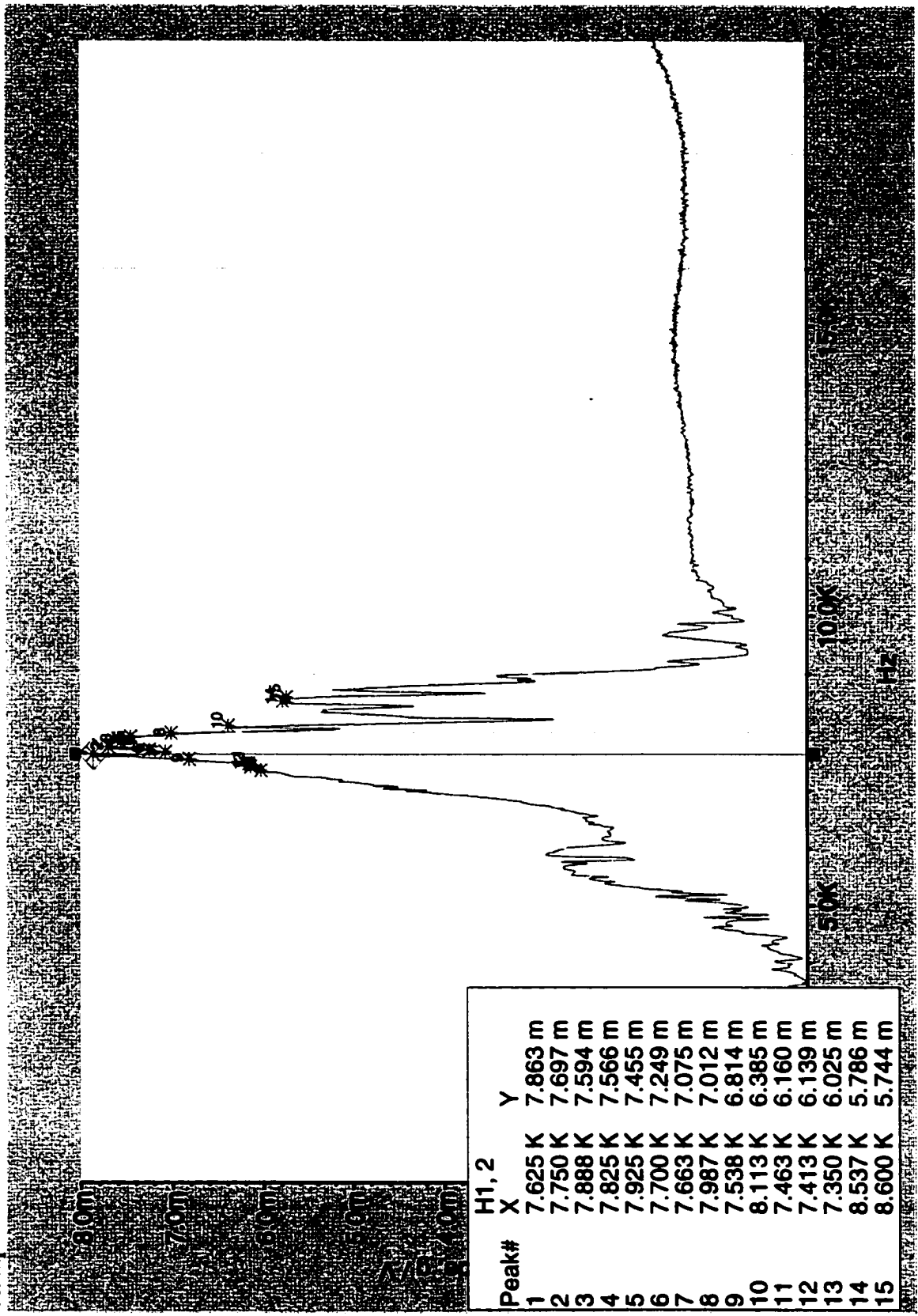H1, 2
Peak #1
X: 6125
Y: 0.00428843

104

Mount#1 Full Threaded Case Torsional Vibration

Peak#	H1, 2 X	Y
1	8.838 K	5.672 m
2	8.875 K	5.642 m
3	8.800 K	5.618 m
4	8.675 K	5.618 m
5	8.912 K	5.613 m
6	9.000 K	5.600 m
7	8.950 K	5.591 m
8	9.075 K	5.579 m
9	9.225 K	5.553 m
10	9.138 K	5.549 m
11	8.537 K	5.545 m
12	5.362 K	5.539 m
13	5.313 K	5.524 m
14	5.275 K	5.518 m
15	8.488 K	5.491 m

H1, 2
Peak #1
X: 900
Y: 0.0006680776

Axial Vibration

H1, 2		
Peak#	X	Y
1	7.775 K	9.348 m
2	7.737 K	9.254 m
3	7.825 K	9.051 m
4	7.638 K	8.935 m
5	7.862 K	8.843 m
6	7.600 K	8.723 m
7	7.913 K	8.545 m
8	7.963 K	8.224 m
9	8.100 K	6.945 m
10	7.100 K	4.336 m
11	7.050 K	4.078 m
12	6.850 K	3.198 m
13	6.813 K	3.097 m
14	5.713 K	2.945 m
15	5.763 K	2.930 m

100m 8.0m 6.0m

5.0K 10.0K 15.0K 20.0K Hz

H1, 2
Peak #1
X: 912.5
Y: 0.000128554

108

Clamped Results Axial

Peak#	H1, 2 X	Y
1	7.625 K	7.863 m
2	7.750 K	7.697 m
3	7.888 K	7.594 m
4	7.825 K	7.566 m
5	7.925 K	7.455 m
6	7.700 K	7.249 m
7	7.663 K	7.075 m
8	7.987 K	7.012 m
9	7.538 K	6.814 m
10	8.113 K	6.385 m
11	7.463 K	6.160 m
12	7.413 K	6.139 m
13	7.350 K	6.025 m
14	8.537 K	5.786 m
15	8.600 K	5.744 m

Hz

50K   100K

H1, 2
Peak #1
X: 887.5
Y: 0.00131727

Half Threaded Case

Peak#	H1, 2 X	Y
1	18.950 K	6.853 m
2	18.887 K	6.811 m
3	19.063 K	6.755 m
4	18.813 K	6.725 m
5	19.150 K	6.546 m
6	18.738 K	6.506 m
7	18.700 K	6.415 m
8	19.213 K	6.228 m
9	18.663 K	6.098 m
10	19.288 K	6.004 m
11	8.012 K	5.859 m
12	7.725 K	5.858 m
13	7.750 K	5.847 m
14	7.638 K	5.844 m
15	7.938 K	5.811 m

113

H1, 2
Peak #1
X: 762.5
Y: 0.000349897

114

Axial

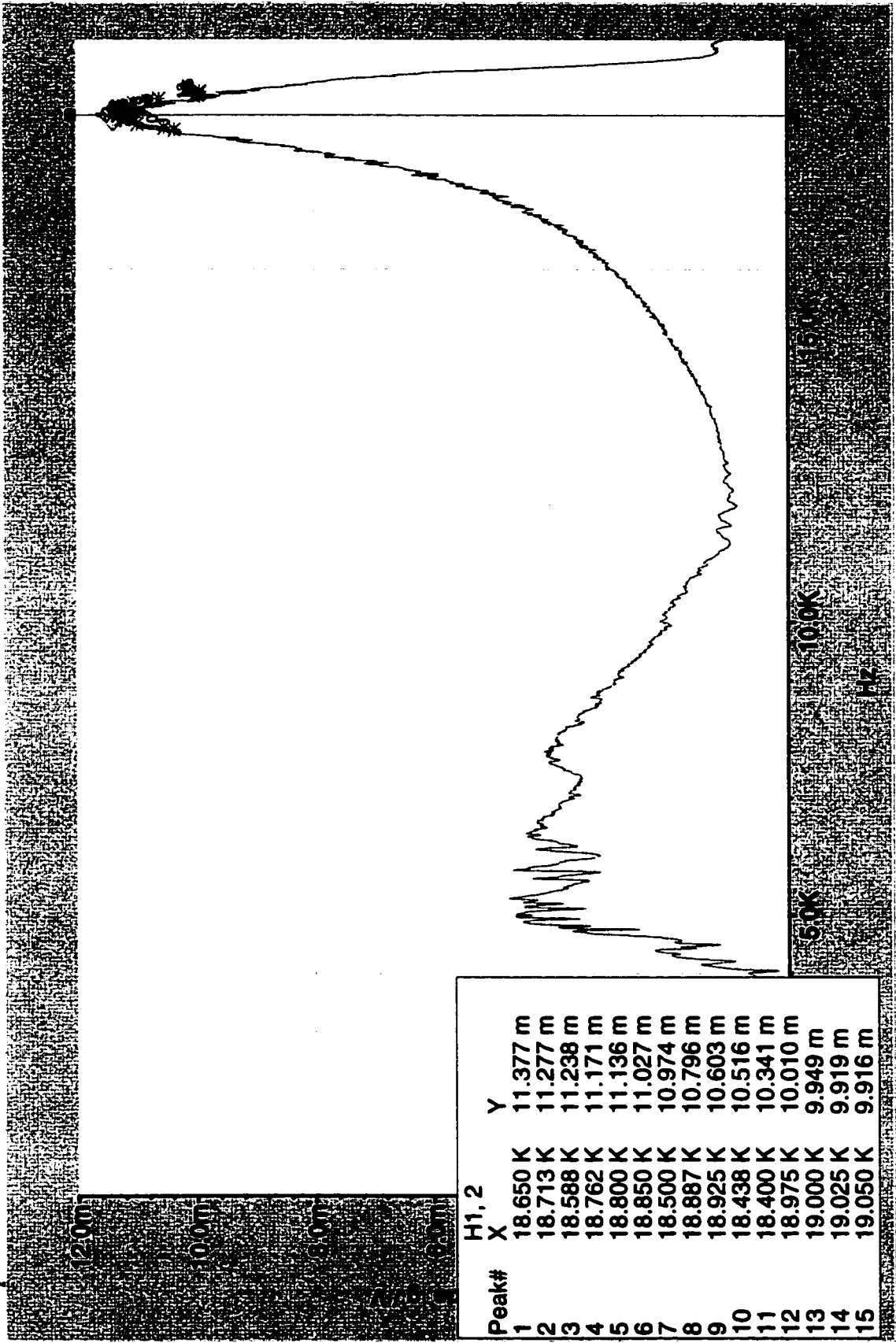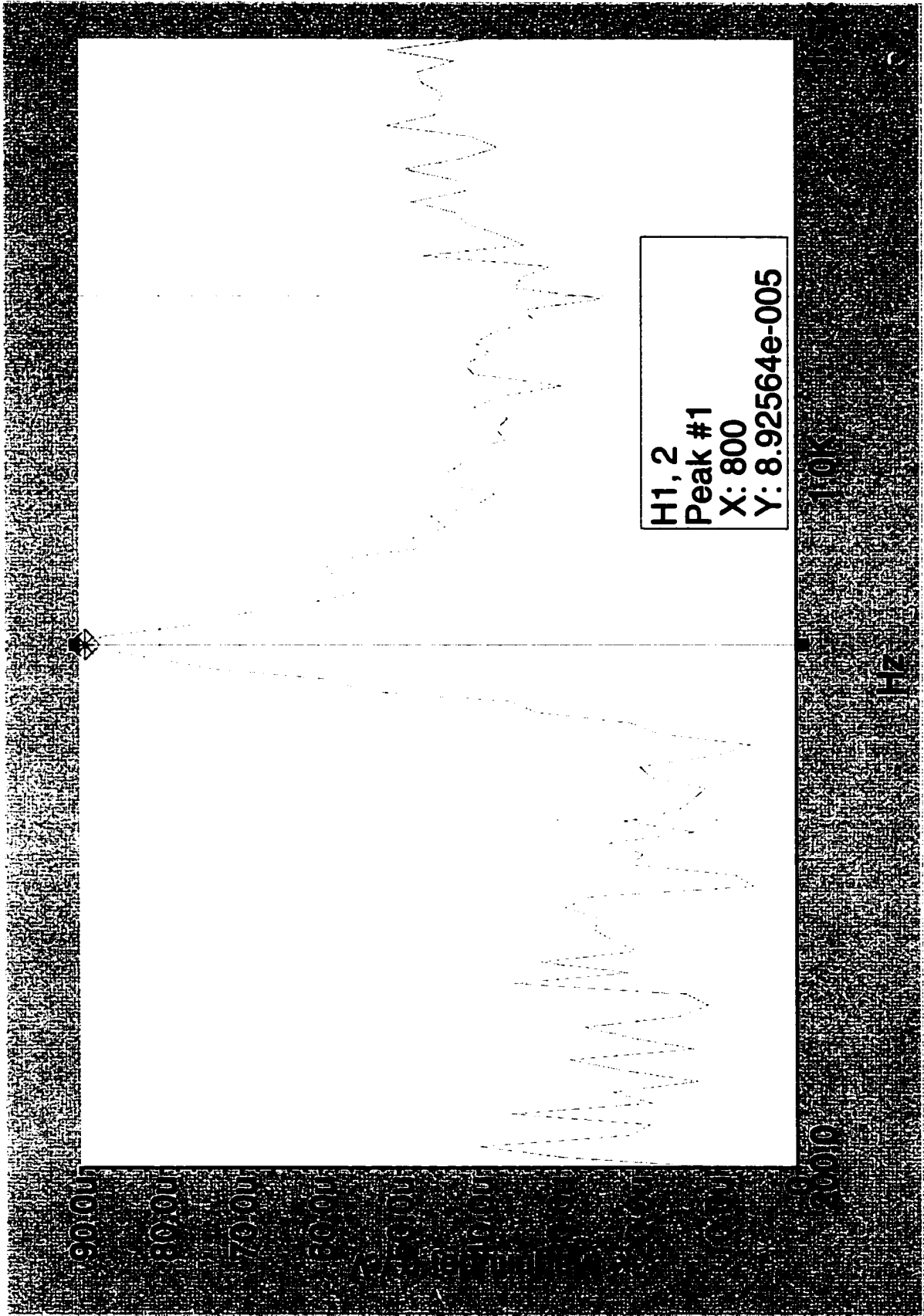| Peak#	H1, 2 X	Y
1	18.700 K	11.357 m
2	18.575 K	11.279 m
3	18.637 K	11.246 m
4	18.762 K	11.217 m
5	18.538 K	11.091 m
6	18.800 K	10.916 m
7	18.475 K	10.824 m
8	18.887 K	10.654 m
9	18.850 K	10.595 m
10	18.387 K	10.511 m
11	18.913 K	10.178 m
12	18.338 K	10.068 m
13	19.025 K	9.495 m
14	18.225 K	9.292 m
15	19.063 K	9.231 m

H1, 2
Peak #1
X: 775
Y: 7.79563e-005

Clamped Results Axial

Peak#	H1, 2 X	Y
1	18.650 K	11.377 m
2	18.713 K	11.277 m
3	18.588 K	11.238 m
4	18.762 K	11.171 m
5	18.800 K	11.136 m
6	18.850 K	11.027 m
7	18.500 K	10.974 m
8	18.887 K	10.796 m
9	18.925 K	10.603 m
10	18.438 K	10.516 m
11	18.400 K	10.341 m
12	18.975 K	10.010 m
13	19.000 K	9.949 m
14	19.025 K	9.919 m
15	19.050 K	9.916 m

Torsional

Peak#	H1,2 X	Y
1	19.025 K	7.327 m
2	18.887 K	7.212 m
3	18.988 K	7.169 m
4	18.950 K	7.143 m
5	19.100 K	7.055 m
6	19.137 K	7.054 m
7	18.825 K	6.960 m
8	19.200 K	6.788 m
9	18.725 K	6.705 m
10	18.775 K	6.705 m
11	19.262 K	6.575 m
12	19.338 K	6.297 m
13	19.375 K	5.989 m
14	8.012 K	5.982 m
15	7.938 K	5.911 m

119

H1, 2
Peak #1
X: 800
Y: 0.0004449755
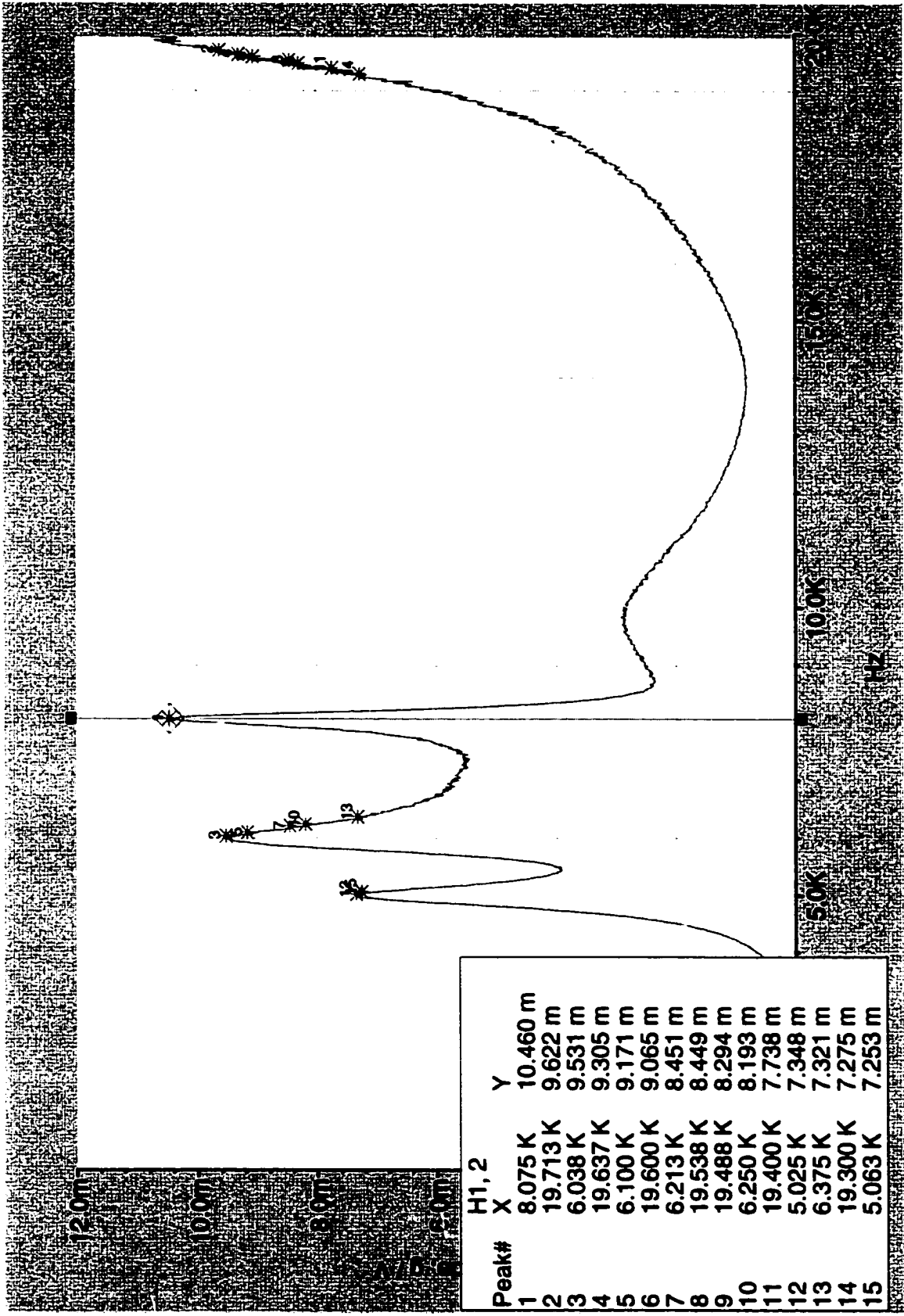
Full Threaded Results Mount #2 Torsional

Peak#	H1, 2 X	Y
1	4.963 K	9.315 m
2	8.512 K	7.565 m
3	8.650 K	7.511 m
4	8.475 K	7.510 m
5	8.787 K	7.505 m
6	8.425 K	7.483 m
7	8.313 K	7.472 m
8	8.863 K	7.461 m
9	8.763 K	7.460 m
10	8.713 K	7.452 m
11	8.588 K	7.449 m
12	8.275 K	7.431 m
13	8.825 K	7.423 m
14	8.963 K	7.398 m
15	8.925 K	7.358 m

121

H1, 2
Peak #1
X: 1037.5
Y: 0.00145701

Axial

H1, 2

Peak#	X	Y
1	8.075 K	10.460 m
2	19.713 K	9.622 m
3	6.038 K	9.531 m
4	19.637 K	9.305 m
5	6.100 K	9.171 m
6	19.600 K	9.065 m
7	6.213 K	8.451 m
8	19.538 K	8.449 m
9	19.488 K	8.294 m
10	6.250 K	8.193 m
11	19.400 K	7.738 m
12	5.025 K	7.348 m
13	6.375 K	7.321 m
14	19.300 K	7.275 m
15	5.063 K	7.253 m

Hz

H1, 2
Peak #1
X: 1037.5
Y: 7.36878e-005

124

125

Clamped Result for Damping Factor

H1, 2
Peak #1
X: 1000
Y: 0.00131382

Hz

Axial Damping Factor

H1, 2
Peak #1
X: 8337.5
Y: 0.0105955

126

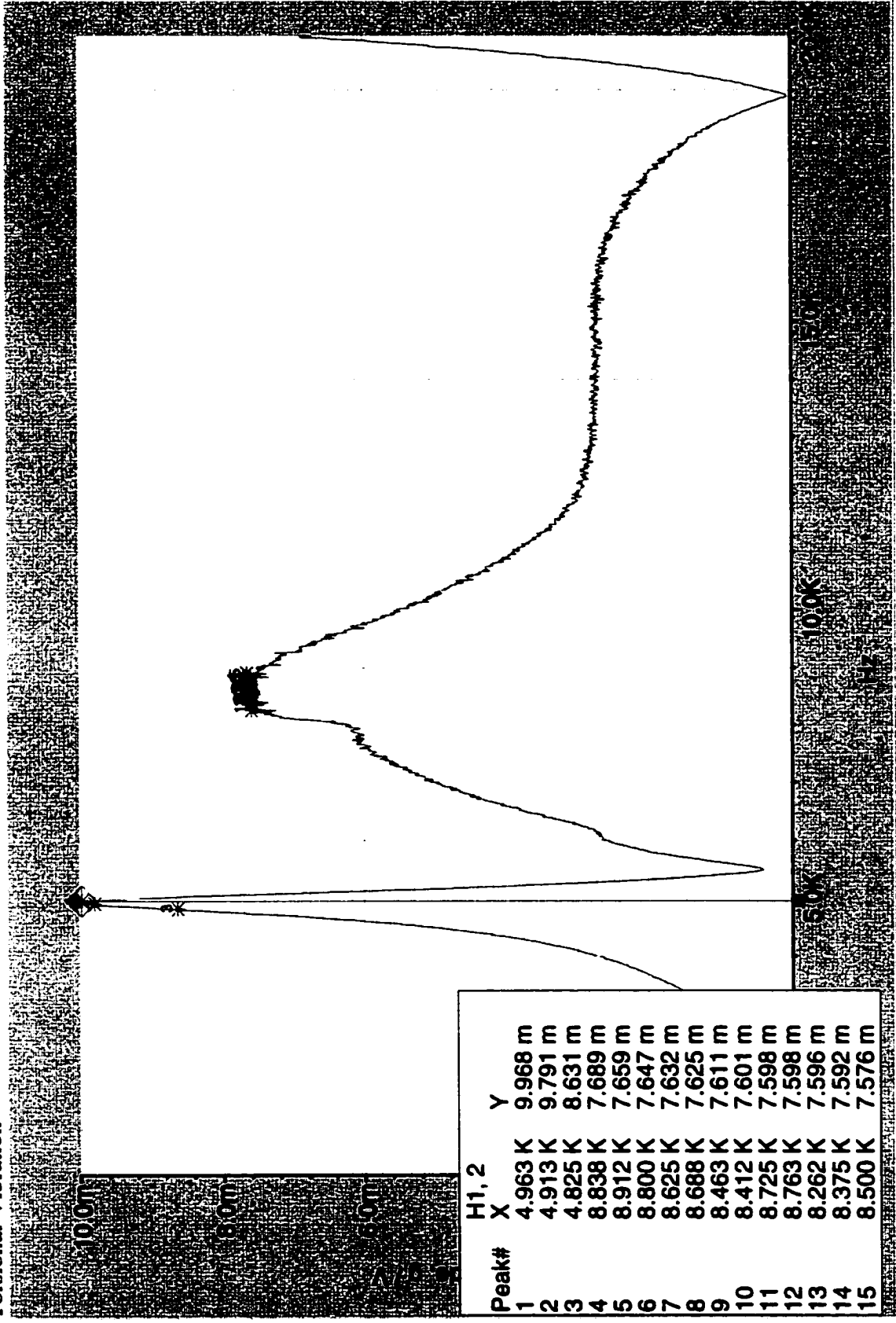**Axial for Mount #2 with a hole on one side see picture**

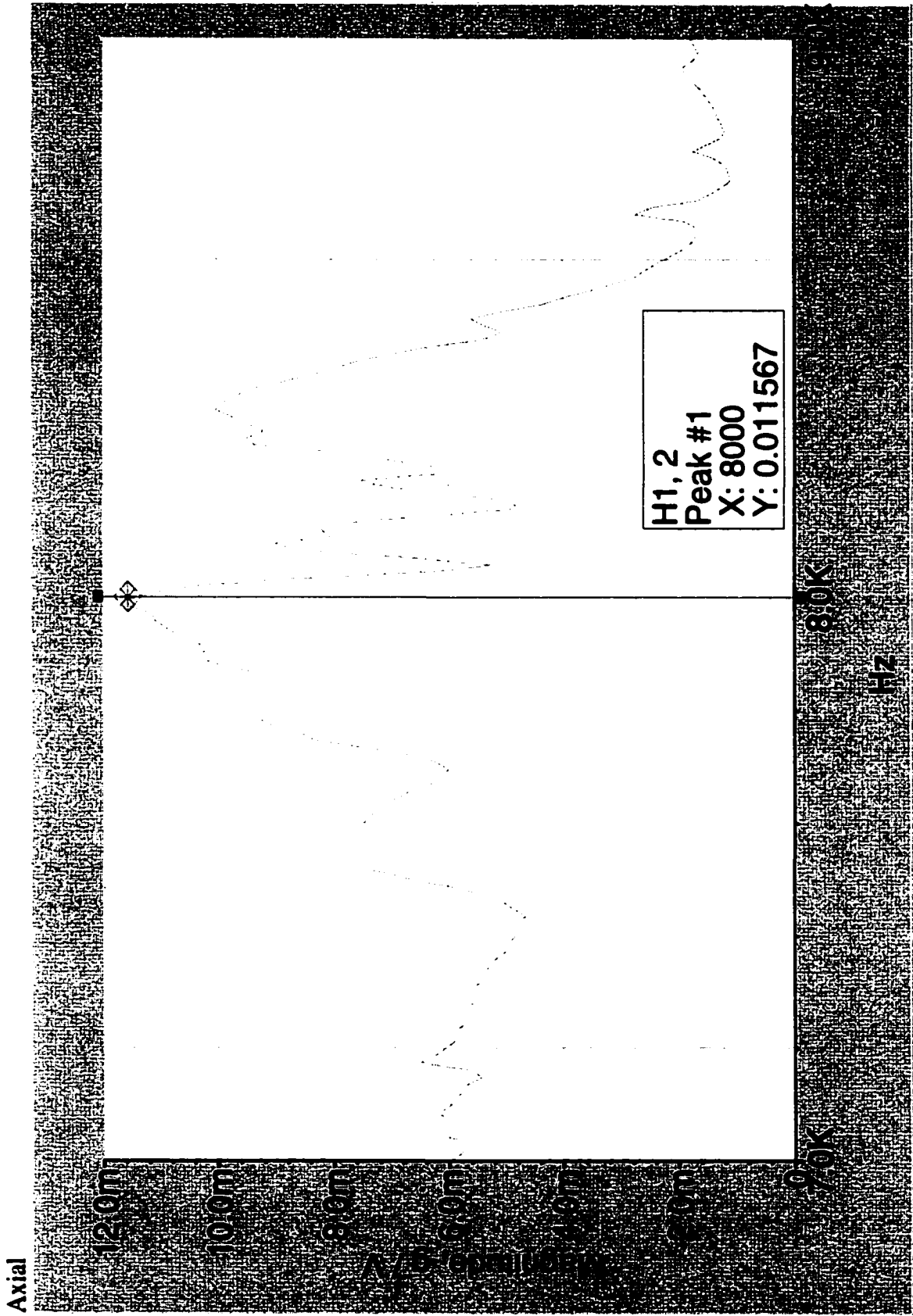| Peak#	H1, 2 X	Y
1	8.050 K	13.657 m
2	8.025 K	13.504 m
3	19.762 K	12.813 m
4	19.637 K	11.792 m
5	19.563 K	10.408 m
6	19.500 K	9.892 m
7	19.450 K	9.566 m
8	6.150 K	9.175 m
9	6.200 K	9.119 m
10	6.100 K	8.964 m
11	19.413 K	8.924 m
12	19.375 K	8.767 m
13	6.313 K	8.553 m
14	19.288 K	8.376 m
15	19.325 K	8.303 m

Torsional Vibration

Peak#	H1, 2 X	Y
1	4.963 K	9.968 m
2	4.913 K	9.791 m
3	4.825 K	8.631 m
4	8.838 K	7.689 m
5	8.912 K	7.659 m
6	8.800 K	7.647 m
7	8.625 K	7.632 m
8	8.688 K	7.625 m
9	8.463 K	7.611 m
10	8.412 K	7.601 m
11	8.725 K	7.598 m
12	8.763 K	7.598 m
13	8.262 K	7.596 m
14	8.375 K	7.592 m
15	8.500 K	7.576 m

128

H1, 2
Peak #1
X: 1062.5
Y: 0.0008841725

Clamped Torsional

H1, 2
Peak #1
X: 1012.5
Y: 0.00132332

130

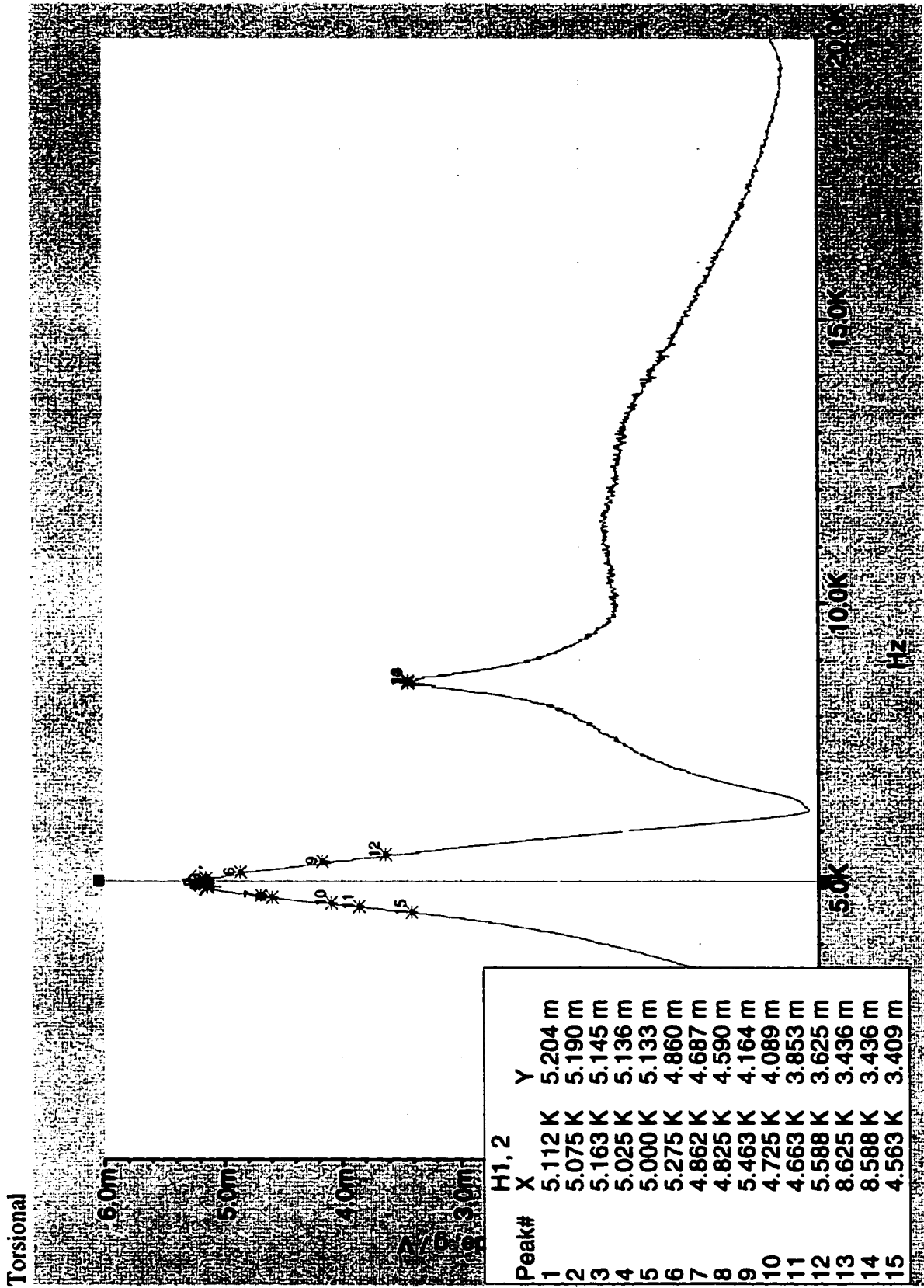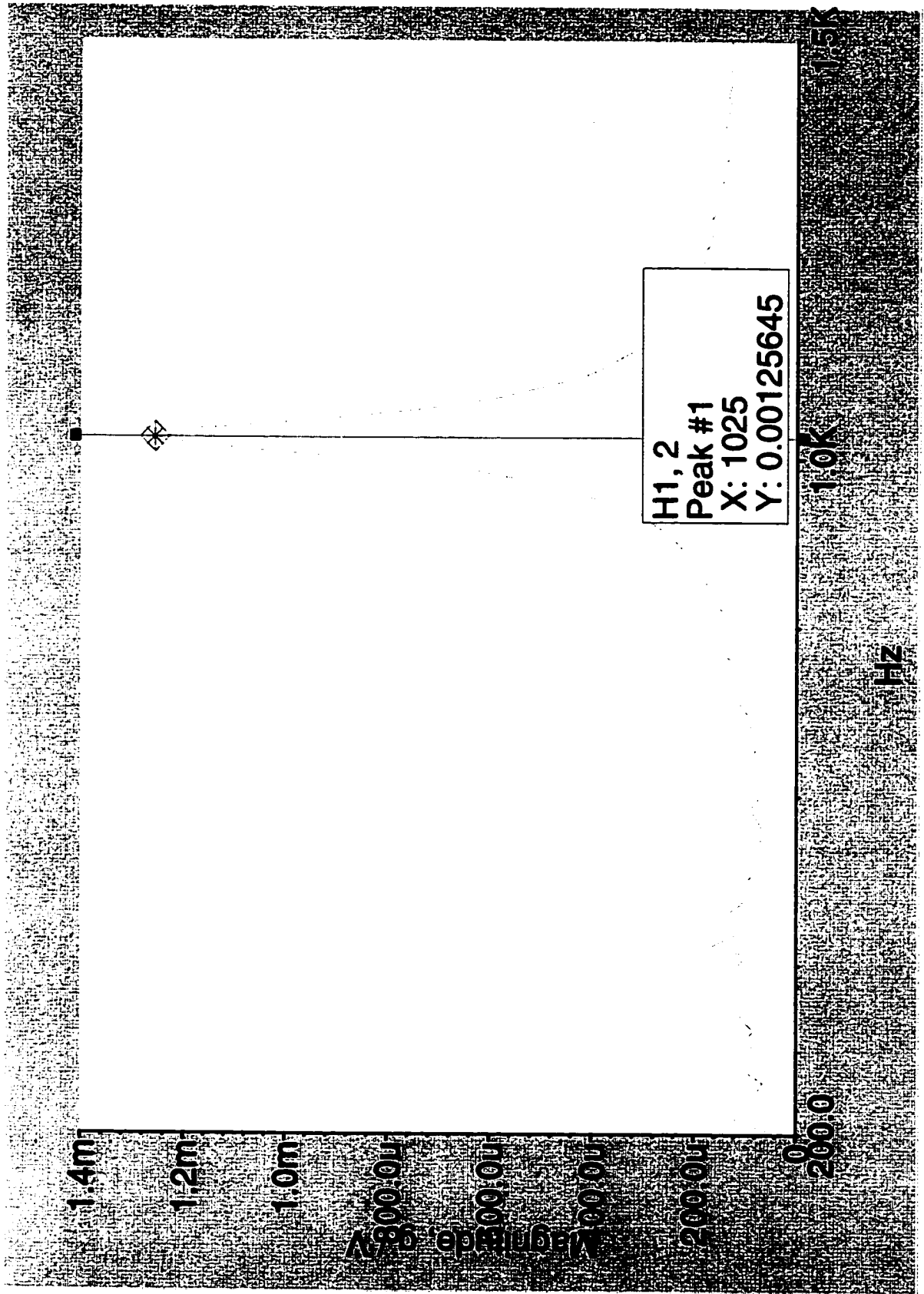**Full Threaded Mount #3 Axial**

	H1, 2	
Peak#	X	Y
1	6.563 K	12.091 m
2	6.538 K	12.047 m
3	6.600 K	11.887 m
4	6.475 K	11.830 m
5	6.663 K	11.464 m
6	6.700 K	11.226 m
7	6.750 K	11.004 m
8	8.512 K	10.826 m
9	6.788 K	10.656 m
10	8.563 K	10.593 m
11	6.838 K	10.241 m
12	6.900 K	9.854 m
13	8.425 K	9.847 m
14	6.950 K	9.617 m
15	7.013 K	9.176 m

132

H1, 2
Peak #1
X: 1037.5
Y: 0.000244274

Magnitude g/V

250.0u

200.0u

150.0u

100.0u

50.0u

200.0

1.0K

1.5K

Hz

Torsional

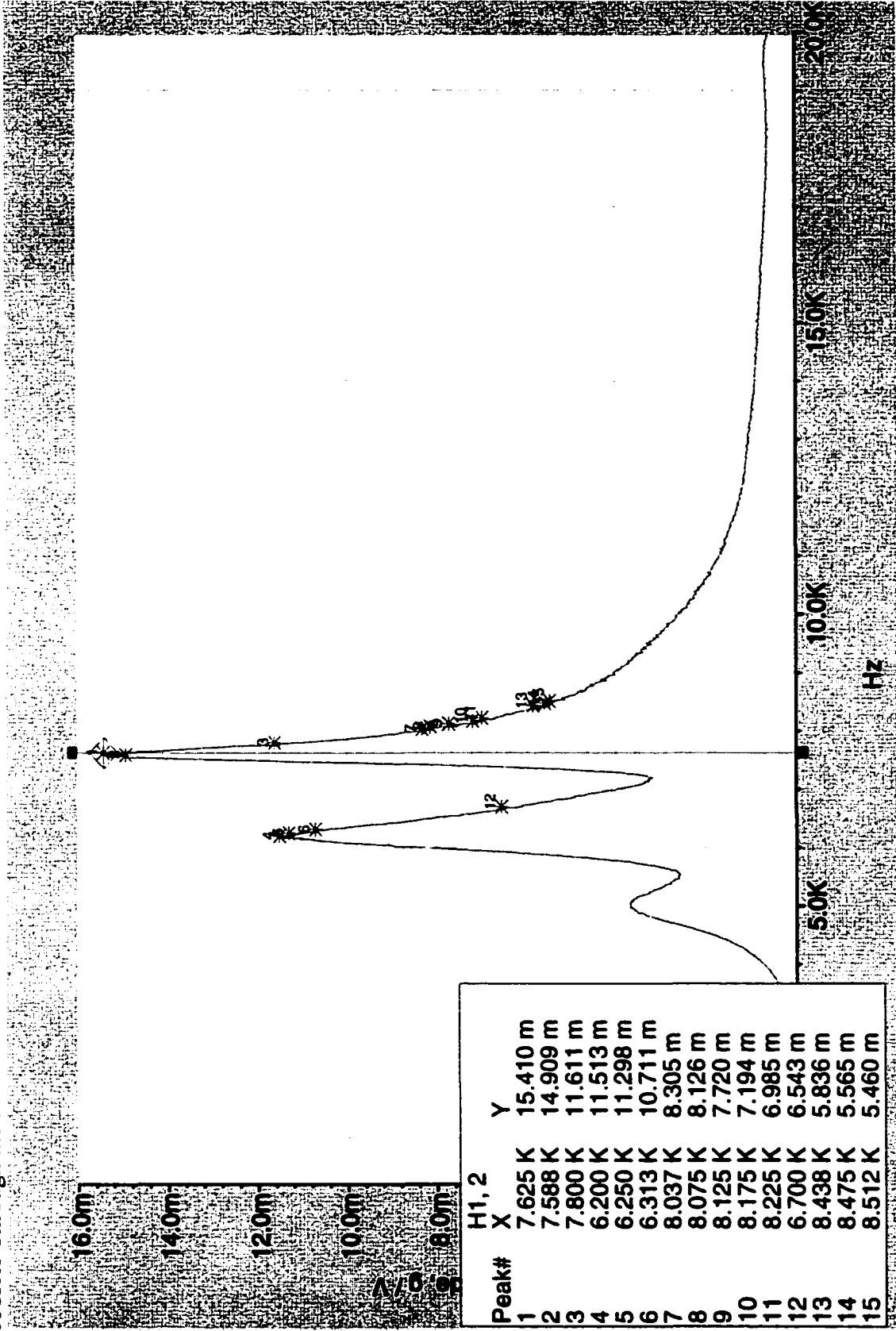| Peak#	H1, 2 X	Y
1	5.112 K	5.204 m
2	5.075 K	5.190 m
3	5.163 K	5.145 m
4	5.025 K	5.136 m
5	5.000 K	5.133 m
6	5.275 K	4.860 m
7	4.862 K	4.687 m
8	4.825 K	4.590 m
9	5.463 K	4.164 m
10	4.725 K	4.089 m
11	4.663 K	3.853 m
12	5.588 K	3.625 m
13	8.625 K	3.436 m
14	8.588 K	3.436 m
15	4.563 K	3.409 m

6.0m 5.0m 4.0m 3.0m

5.0K 10.0K 15.0K 20.0K Hz

134

H1, 2
Peak #1
X: 1025
Y: 0.00125645

135

Clamped Torsional Results

H1, 2
Peak #1
X: 1012.5
Y: 0.0018285

Axial Clamped

H1, 2
Peak #1
X: 6512.5
Y: 0.0108083
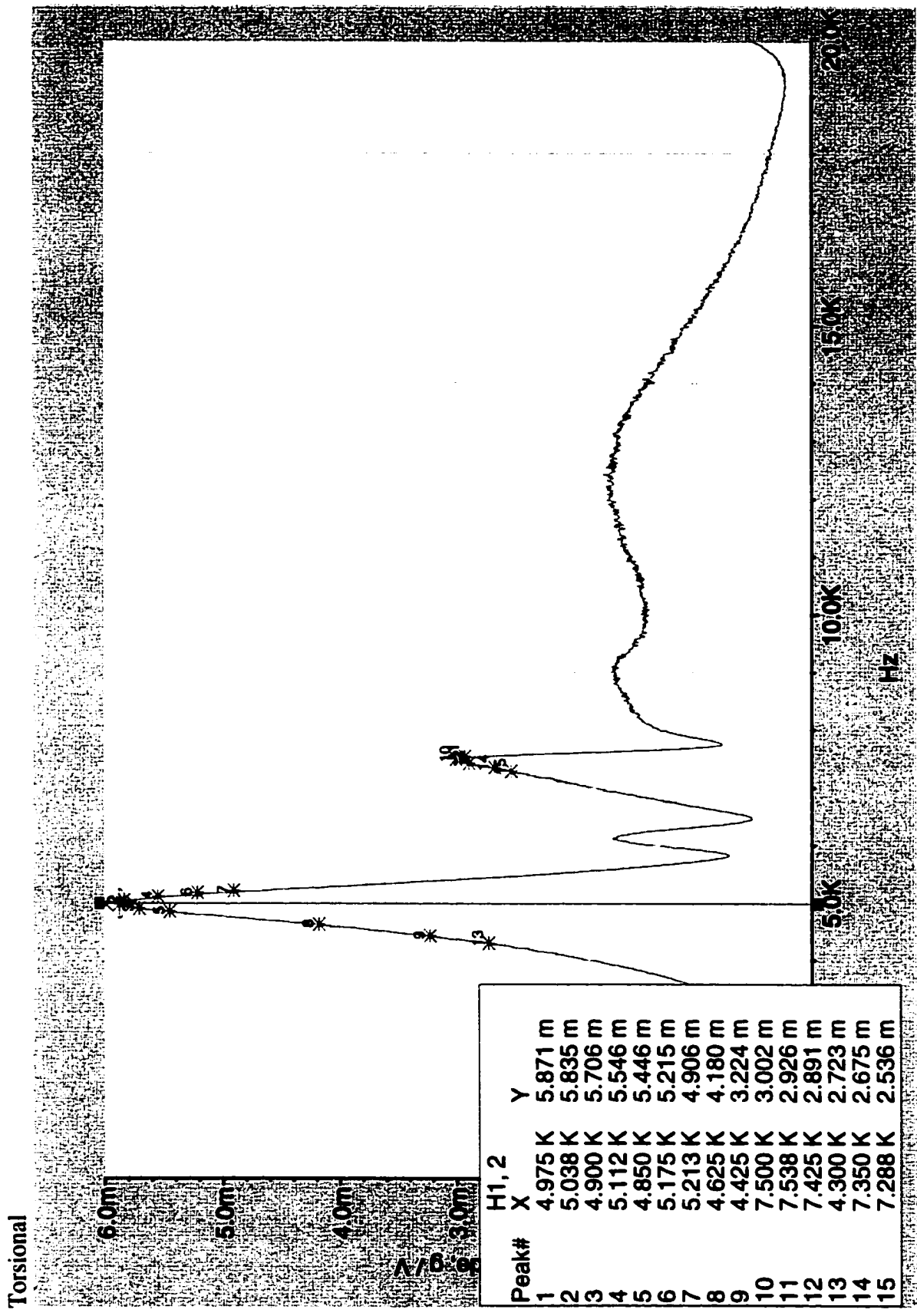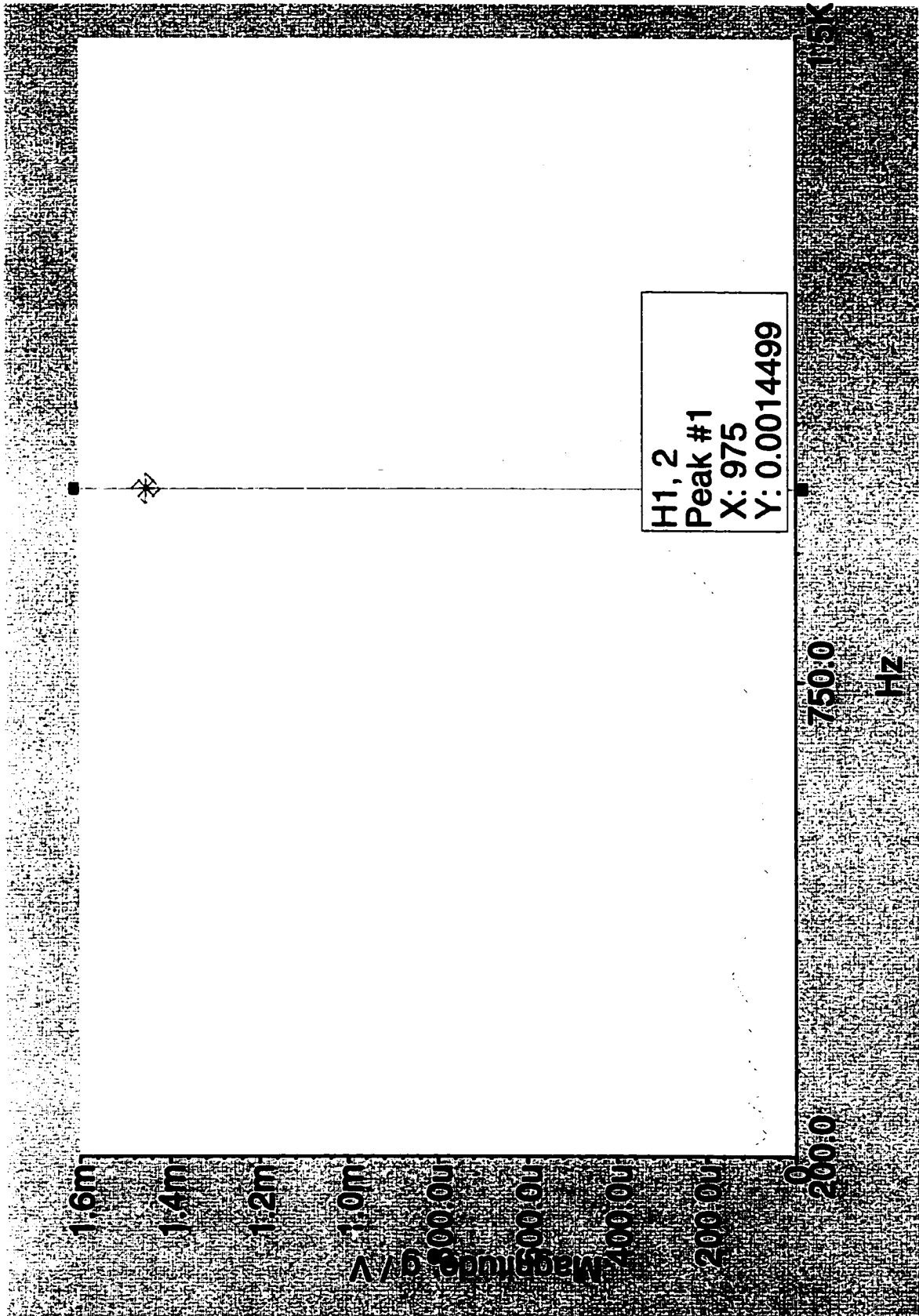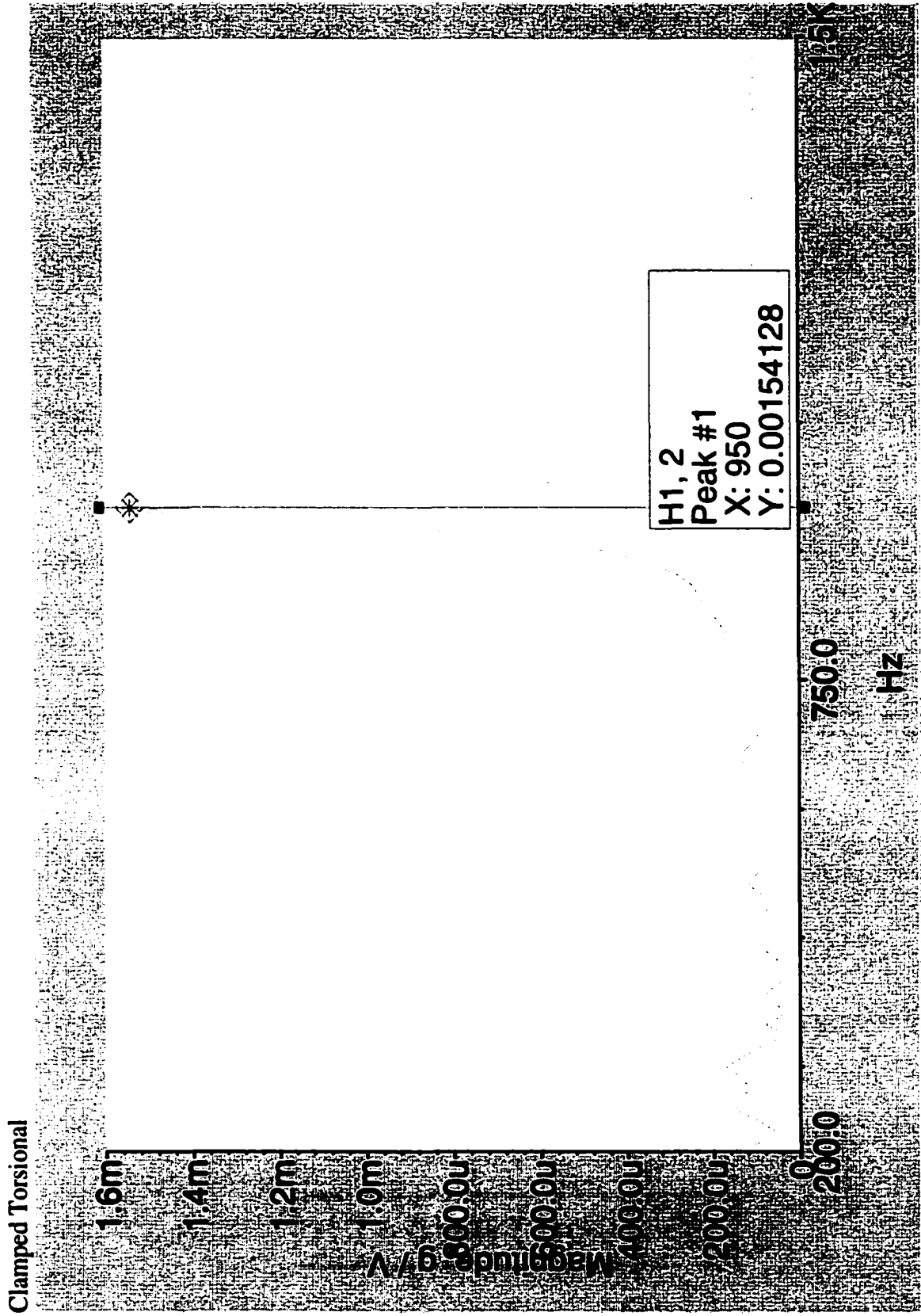
A Hole Through the Mount on both sides. Axial

Peak#	H1, 2 X	Y
1	7.625 K	15.410 m
2	7.588 K	14.909 m
3	7.800 K	11.611 m
4	6.200 K	11.513 m
5	6.250 K	11.298 m
6	6.313 K	10.711 m
7	8.037 K	8.305 m
8	8.075 K	8.126 m
9	8.125 K	7.720 m
10	8.175 K	7.194 m
11	8.225 K	6.985 m
12	6.700 K	6.543 m
13	8.438 K	5.836 m
14	8.475 K	5.565 m
15	8.512 K	5.460 m

16.0m
14.0m
12.0m
10.0m
8.0m
µV/0.00

5.0K   10.0K   15.0K   20.0K

Hz

H1, 2
Peak #1
X: 975
Y: 0.000188828

Torsional

Peak#	H1,2 X	Y
1	4.975 K	5.871 m
2	5.038 K	5.835 m
3	4.900 K	5.706 m
4	5.112 K	5.546 m
5	4.850 K	5.446 m
6	5.175 K	5.215 m
7	5.213 K	4.906 m
8	4.625 K	4.180 m
9	4.425 K	3.224 m
10	7.500 K	3.002 m
11	7.538 K	2.926 m
12	7.425 K	2.891 m
13	4.300 K	2.723 m
14	7.350 K	2.675 m
15	7.288 K	2.536 m

deg/V

6.0m 5.0m 4.0m 3.0m

5.0K 10.0K 15.0K 20.0K
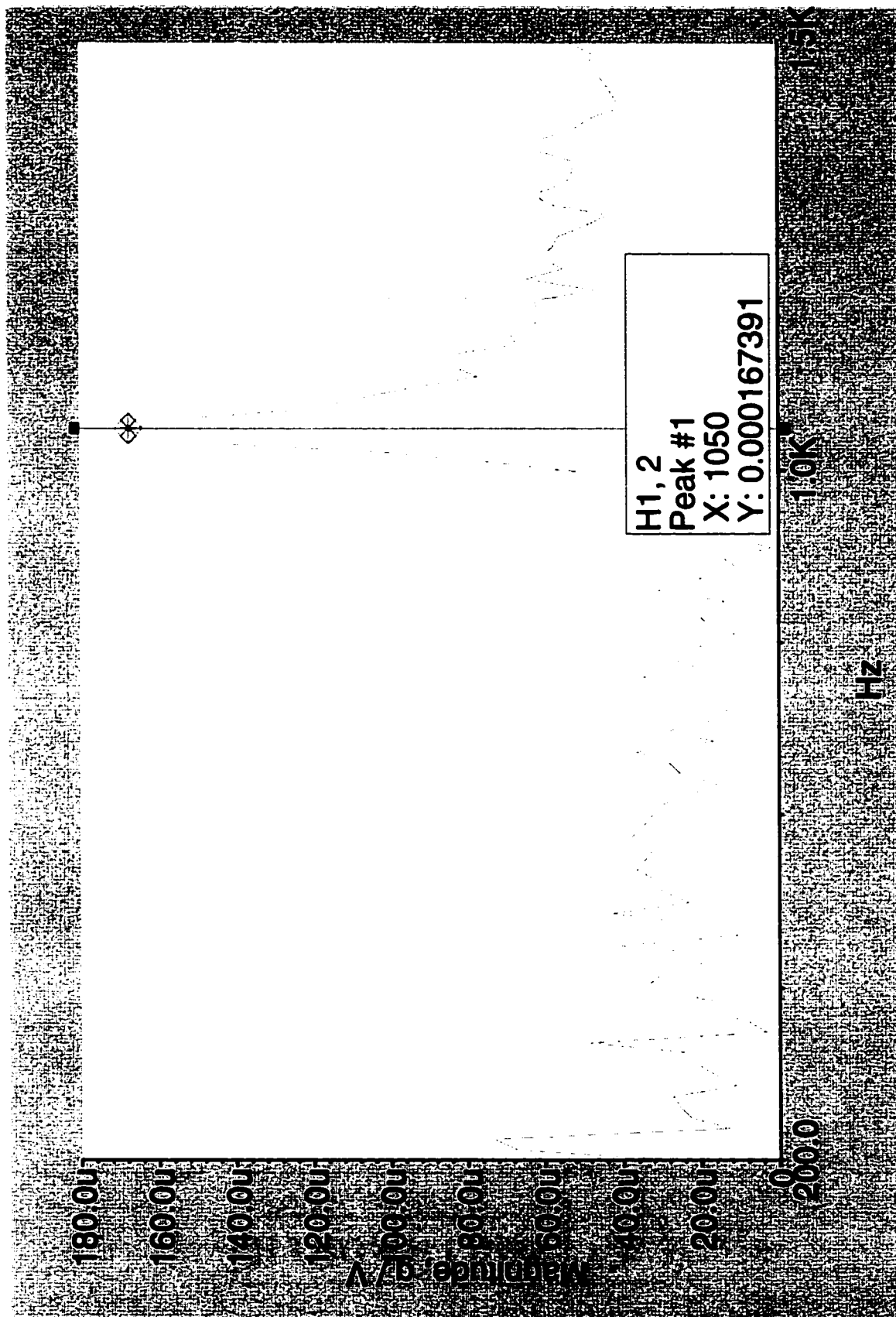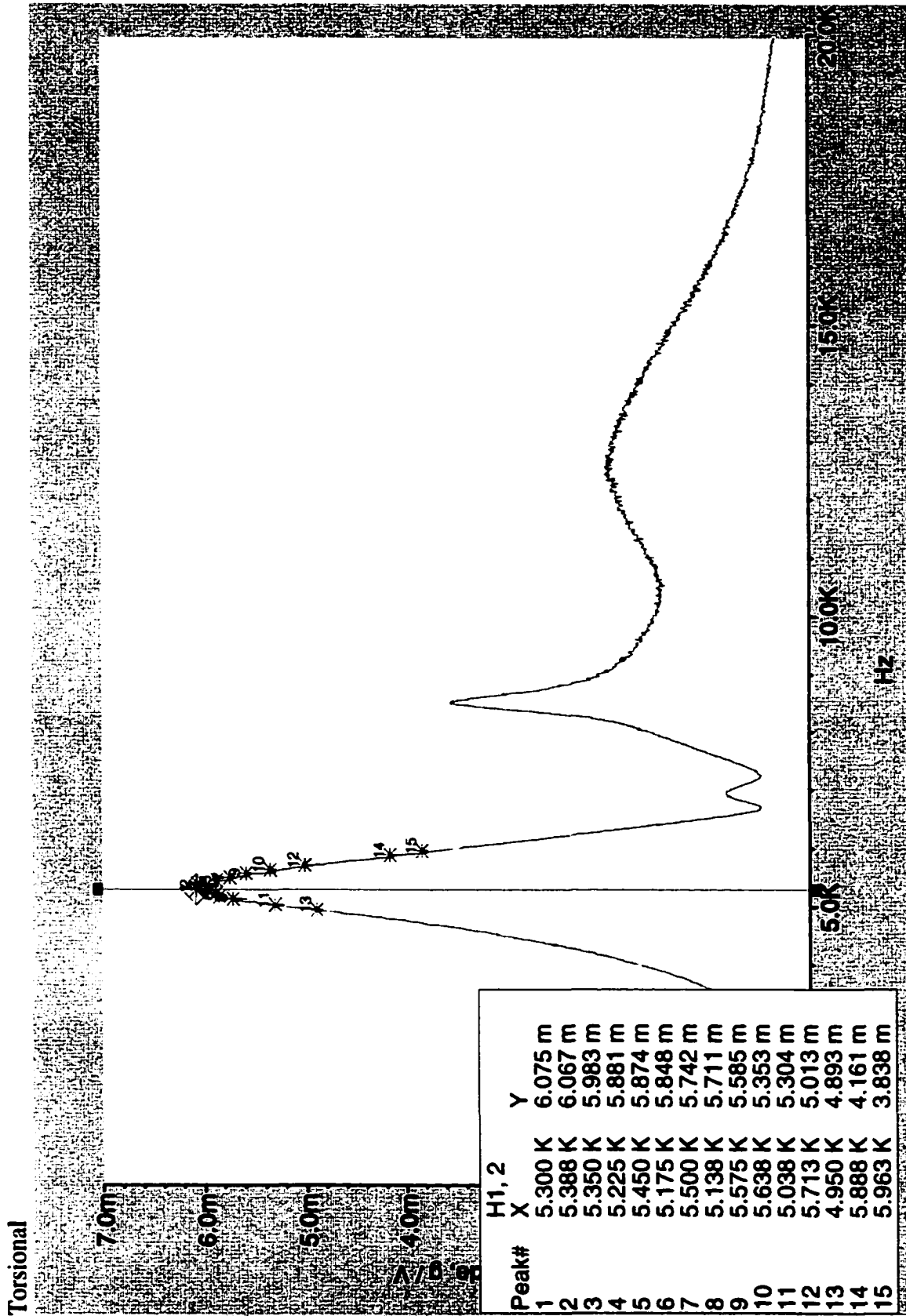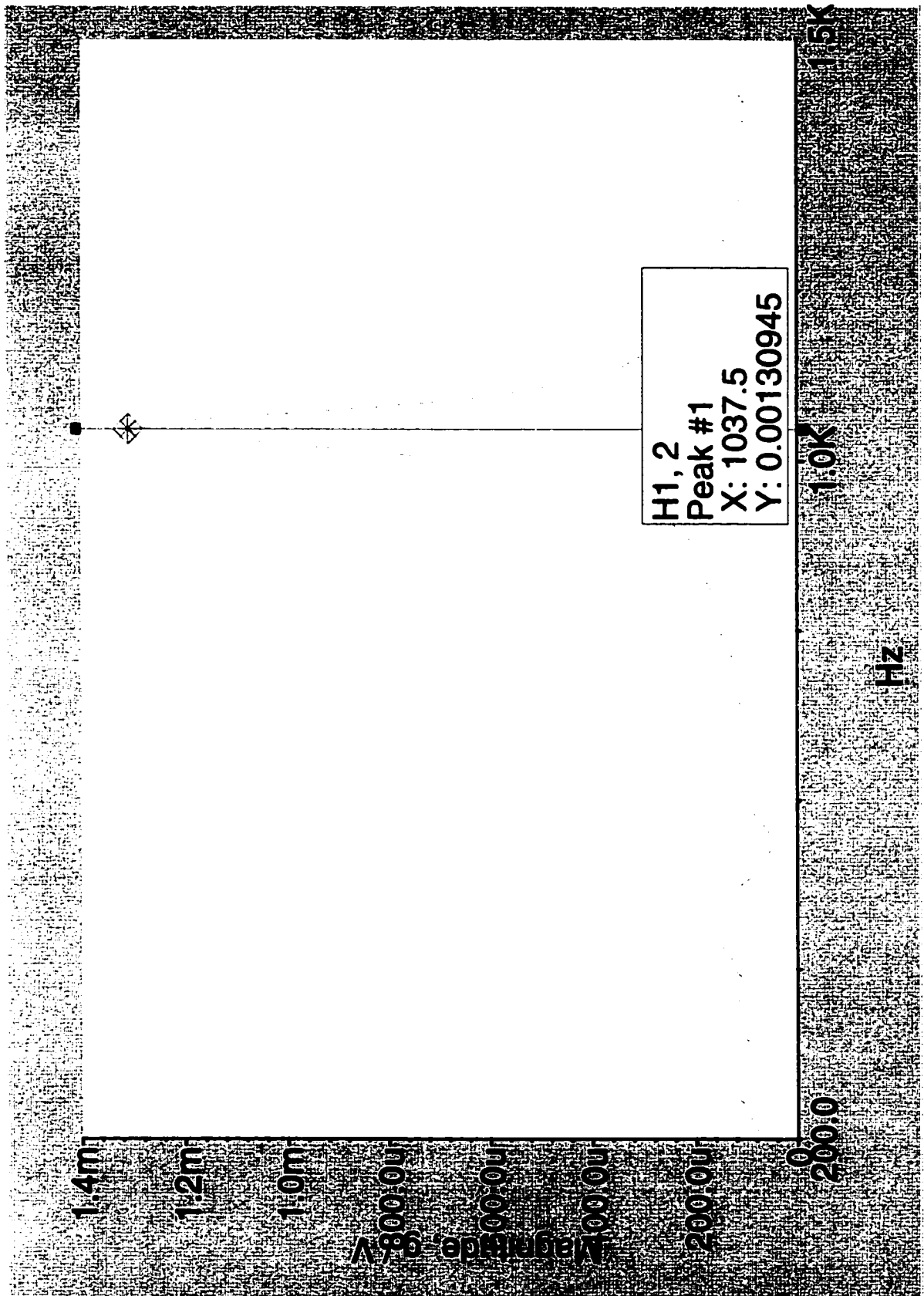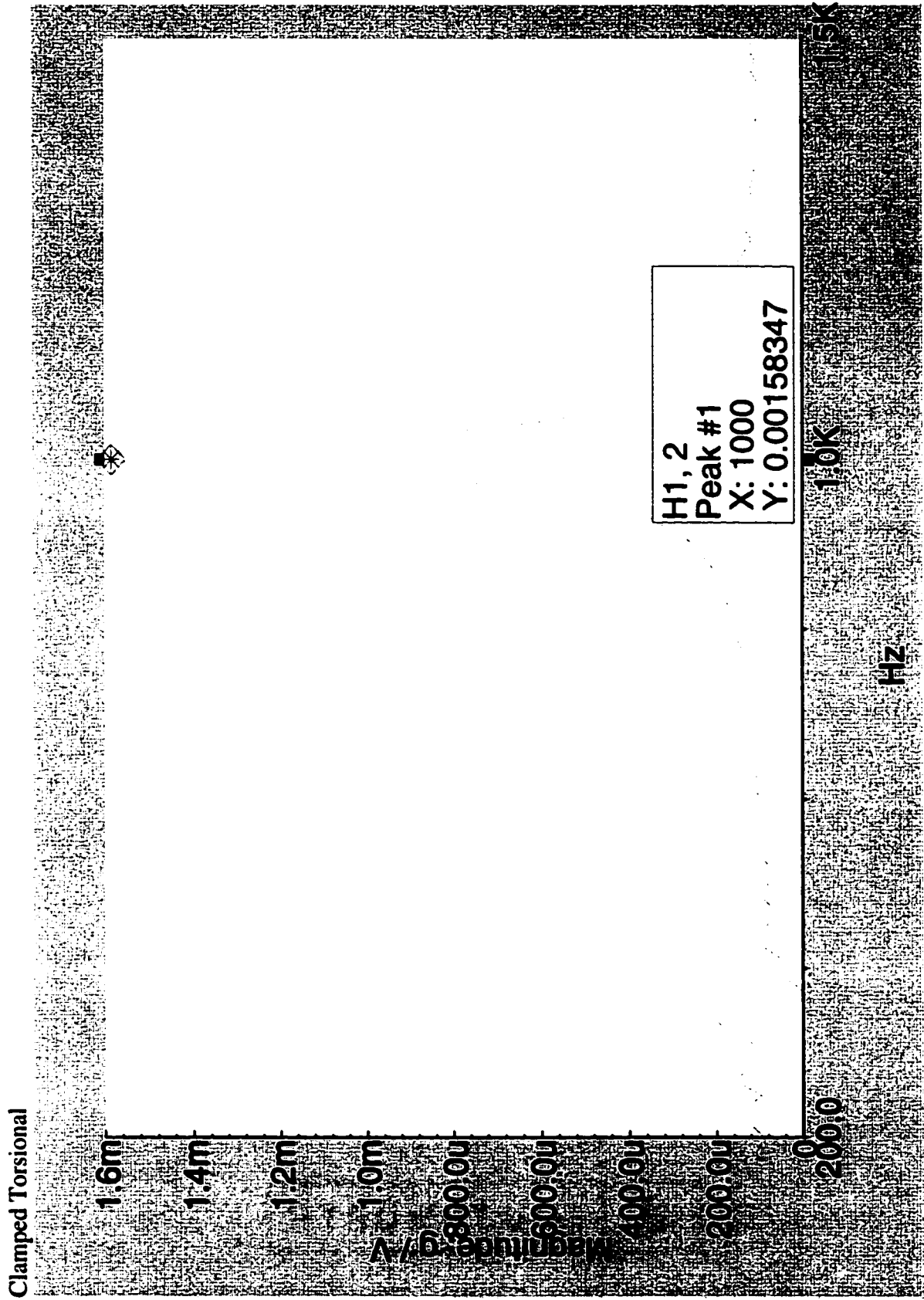
Hz

H1, 2
Peak #1
X: 975
Y: 0.0014499

Clamped Torsional

H1, 2
Peak #1
X: 950
Y: 0.00154128

Full Threaded Mount #4 Axial

Peak#	H1, 2		
	X	Y	
1	7.112 K	16.037 m	
2	7.138 K	15.969 m	
3	7.075 K	15.808 m	
4	7.000 K	15.582 m	
5	7.200 K	15.401 m	
6	7.288 K	15.037 m	
7	7.413 K	13.907 m	
8	7.450 K	13.839 m	
9	7.500 K	13.653 m	
10	7.538 K	13.211 m	
11	7.612 K	13.149 m	
12	8.412 K	13.041 m	
13	8.350 K	12.994 m	
14	7.663 K	12.858 m	
15	7.750 K	12.524 m	

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H1, 2
Peak #1
X: 1050
Y: 0.0001167391

Magnitude q/V

Hz

200.0   1.0K   1.5K

20.0u
40.0u
60.0u
80.0u
100.0u
120.0u
140.0u
160.0u
180.0u

Torsional

Peak#	H1, 2	
	X	Y
1	5.300 K	6.075 m
2	5.388 K	6.067 m
3	5.350 K	5.983 m
4	5.225 K	5.881 m
5	5.450 K	5.874 m
6	5.175 K	5.848 m
7	5.500 K	5.742 m
8	5.138 K	5.711 m
9	5.575 K	5.585 m
10	5.638 K	5.353 m
11	5.038 K	5.304 m
12	5.713 K	5.013 m
13	4.950 K	4.893 m
14	5.888 K	4.161 m
15	5.963 K	3.838 m

H1, 2
Peak #1
X: 1037.5
Y: 0.00130945

15K

1.0K

Hz

200.0

1.4m

1.2m

1.0m

800.0u

600.0u

400.0u

200.0u

200.0u

Magnitude, q.6 V

Clamped Torsional

H1, 2
Peak #1
X: 1000
Y: 0.00158347

Axial Clamped

H1, 2
Peak #1
X: 8637.5
Y: 0.0089578

148

Half Threaded Case See Picture for details. Axial

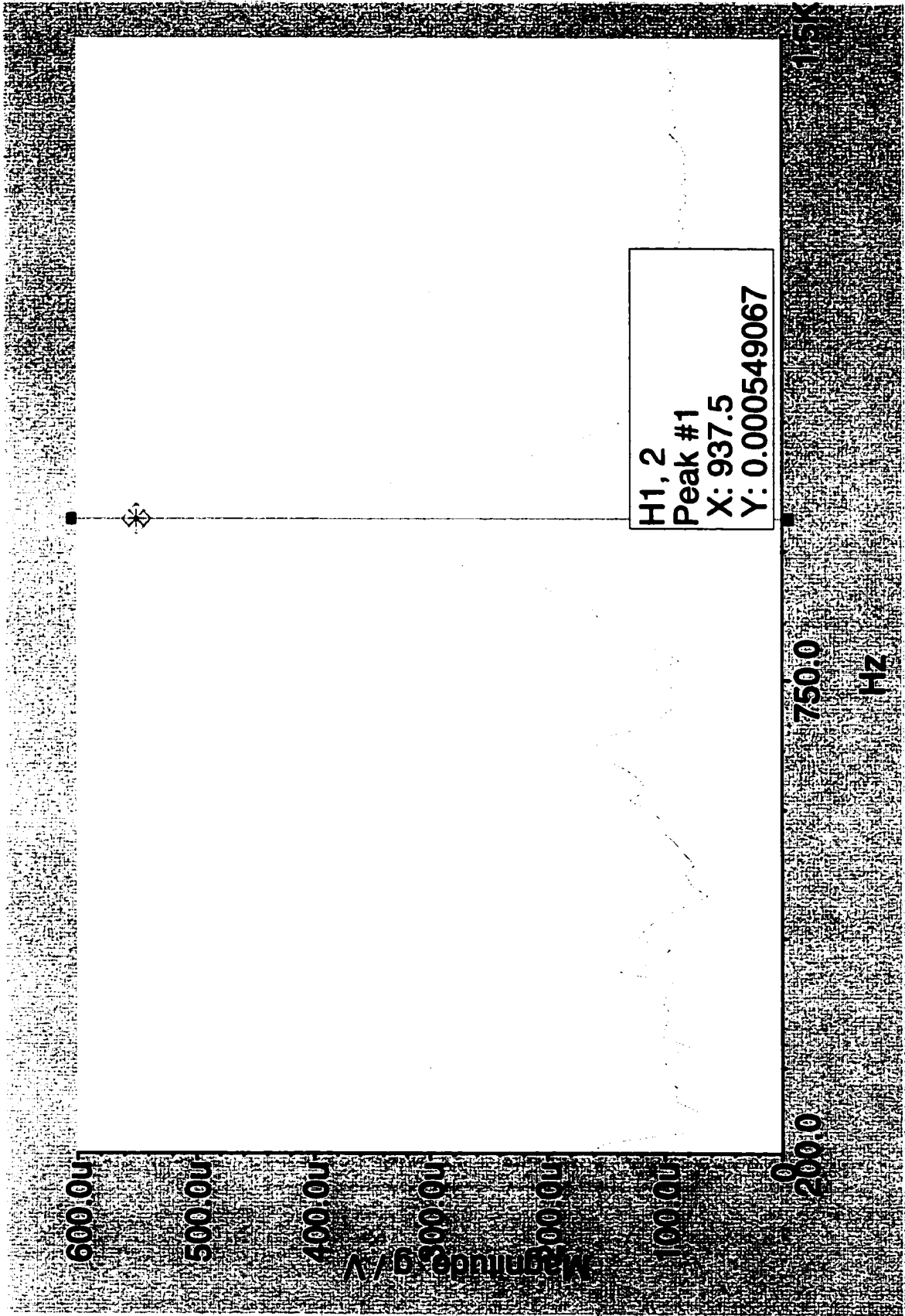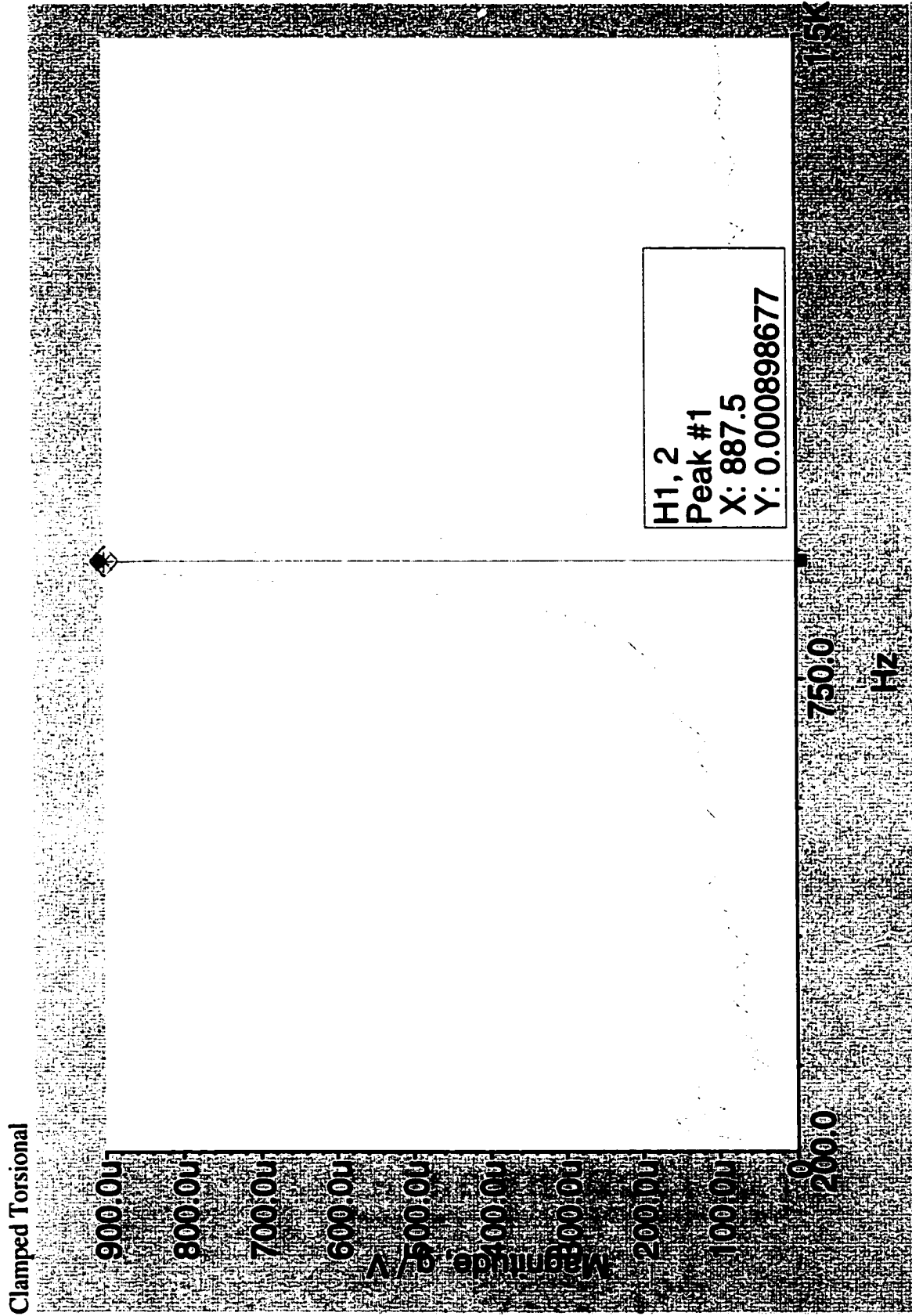| Peak#	H1, 2 X	Y
1	5.725 K	13.242 m
2	5.800 K	12.529 m
3	6.563 K	12.340 m
4	6.600 K	12.236 m
5	6.663 K	11.177 m
6	5.987 K	9.651 m
7	6.038 K	8.963 m
8	6.138 K	7.705 m
9	6.325 K	7.563 m
10	6.925 K	7.280 m
11	6.275 K	7.195 m
12	6.225 K	7.169 m
13	7.088 K	6.080 m
14	7.138 K	5.782 m
15	7.250 K	5.325 m

149

Peak #1
X: 937.5
Y: 0.0001105984
H1,2

Magnitude g/V

120.0u
100.0u
80.0u
60.0u
40.0u
20.0u
200.0

750.0   15K
Hz

150

Torsional

Peak#	H1, 2	
	X	Y
1	3.988 K	3.865 m
2	5.575 K	3.269 m
3	5.513 K	3.220 m
4	5.650 K	3.151 m
5	5.450 K	3.052 m
6	18.988 K	2.854 m
7	19.038 K	2.846 m
8	18.938 K	2.828 m
9	19.113 K	2.823 m
10	18.900 K	2.802 m
11	7.413 K	2.755 m
12	19.150 K	2.726 m
13	7.663 K	2.723 m
14	7.575 K	2.718 m
15	7.737 K	2.712 m

Clamped Torsional

H1, 2
Peak #1
X: 887.5
Y: 0.000898677

Magnitude θ/V

900.0u
800.0u
700.0u
600.0u
500.0u
400.0u
300.0u
200.0u
100.0u

200.0   750.0   1.5K

Hz

APPENDIX E

MATHCAD SOLUTION FOR THEORETICAL VALUES

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Torsional Vibration Theoretical Calculation

Material Properties of the Aluminum

$$Ga := 26 \cdot 10^9 \cdot Pa \qquad pa := 2700 \cdot \frac{kg}{m^3}$$

$$L := 0.515 in \qquad\qquad L1 := .2 \cdot in$$

ro := .096·in **The radius of the beam.**   R1o := .375·in **The radius of the disk.**

$$Jo := \left[\frac{1}{2} \cdot \pi \cdot \left(ro^4 \right) \cdot L \right] \qquad\qquad Jo1 := \frac{1}{2} \cdot \pi \cdot \left(R1o^4 \right) \cdot L1$$

$$Jo = 7.264 \times 10^{-13} m^5 \qquad\qquad Jo1 = 6.568 \times 10^{-11} m^5$$

$$ca := \sqrt{\frac{Ga}{pa}} \qquad ca = 3.103 \times 10^3 \frac{m}{s} \qquad \beta := \frac{Jo}{Jo1}$$

$$\alpha_2 := 3.1448 \qquad \alpha_1 := .1 \qquad \beta = 0.011$$

1 mode $\qquad \omega_n := \frac{1}{2 \cdot \pi} \frac{ca}{L} \cdot \sqrt{\frac{Jo}{Jo1}}$ $\qquad$ $\boxed{\omega_n = 3.971 \times 10^3 \, Hz}$

2 mode $\qquad \omega_n := \frac{\alpha_2}{2 \cdot \pi} \frac{ca}{L}$ $\qquad$ $\boxed{\omega_n = 1.187 \times 10^5 \, Hz}$

Transverse Vibration Thoeretical Calculation

Material properties of Aluminum

$$Ga := 26 \cdot 10^9 Pa \quad \rho a := 2700 \cdot \frac{kg}{m^3} \quad v := 0.33$$

$$Ea := 69 \cdot 10^9 \cdot Pa$$

$$L := .515 \cdot in \quad ro := .096 \cdot in \qquad L1 := .2 \cdot in \quad Rlo := .375 \cdot in$$

The Area of the Beam   **The Area of the Disk**

$$Ar := \pi \cdot ro^2$$ $$Ad := \pi \cdot Rlo^2 - (0.179 \cdot in \cdot .125 in) - (0.174 \cdot in \cdot 0.125 \cdot in)$$

$$Adf := Ad - \left[\frac{1}{2} \cdot (0.021 \cdot in \cdot 0.125 \cdot in) \right] - \frac{1}{2} \cdot (0.034 \cdot in \cdot 0.125 \cdot in)$$

$$I := \frac{1}{4} \cdot \pi \cdot ro^4$$ $$M := \rho a \cdot Adf \cdot L1$$

$$Mb := \rho a \cdot Ar \cdot L$$ $$M = 3.488 \times 10^{-3} kg$$

$$Mb = 6.597 \times 10^{-4} kg$$ $$\beta := \frac{M}{\rho a \cdot Ar \cdot L} \qquad \beta = 5.288$$

The Longtitude Vibration

$$c := \sqrt{\frac{Ea}{\rho a}} \qquad L2 := .515 \cdot in$$

$$\beta 2 := \frac{Mb}{M} \qquad \beta 2 = 0.189$$

$$\omega_1 := \frac{1}{2 \cdot \pi} \cdot \frac{c}{L2} \cdot \sqrt{\beta 2}$$

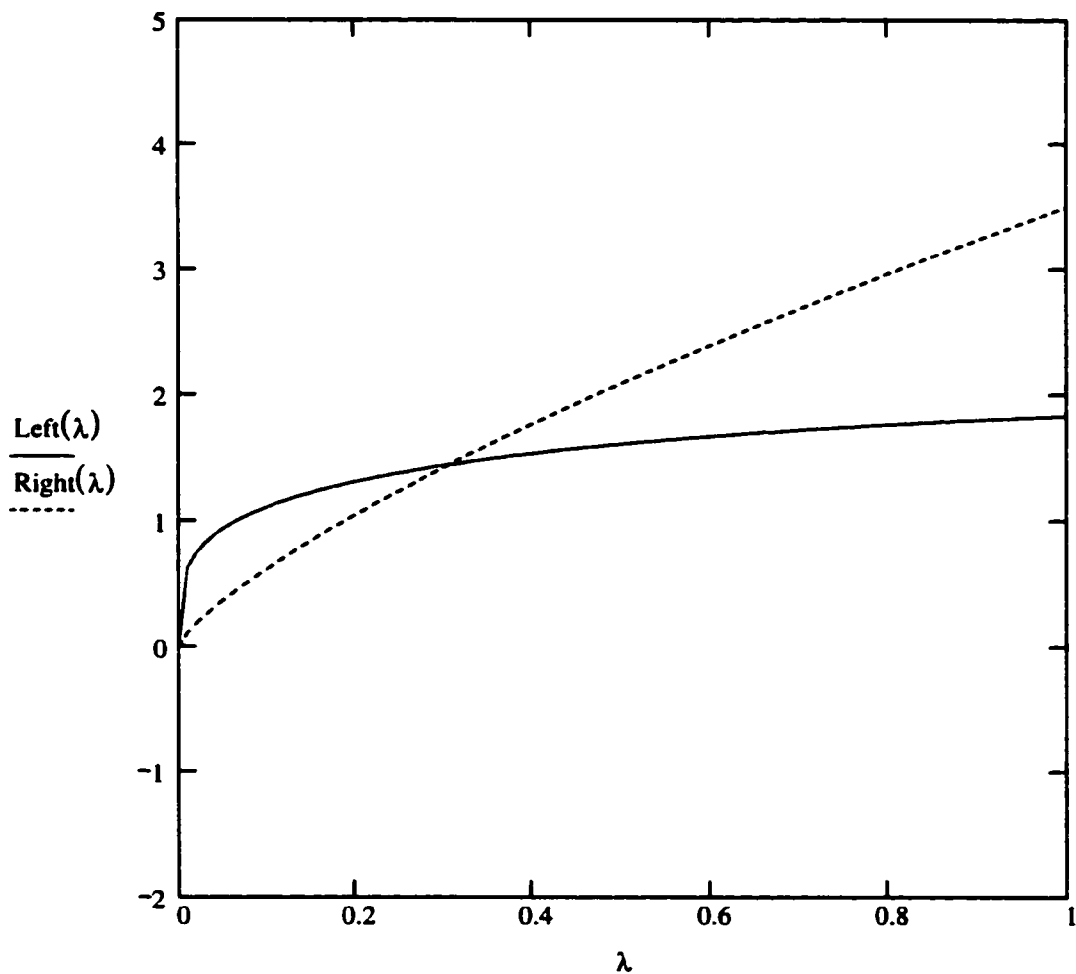$$\boxed{\omega_1 = 2.675 \times 10^4 Hz}$$

Solving for λ for β=5.288.

$$\lambda := 0, 0.01 .. 1000$$

$$Left(\lambda) := \sqrt[4]{\lambda} \cdot \left(\cos\left(\sqrt[4]{\lambda}\right) \cdot \cosh\left(\sqrt[4]{\lambda}\right) + 1 \right)$$

$$Right(\lambda) := -\beta \cdot \left[\left(\cos\left(\sqrt[4]{\lambda}\right) \right) \sinh\left(\sqrt[4]{\lambda}\right) - \cosh\left(\sqrt[4]{\lambda}\right) \cdot \sin\left(\sqrt[4]{\lambda}\right) \right]$$

$$\frac{Left(\lambda)}{Right(\lambda)}$$

A graph of the first λ1 of bending Vibration

Beams with Concentrated Mass
Bending Vibration

$$\lambda_1 := 0.306 \qquad \lambda_3 := 3099.483 \qquad \lambda_5 := 36985.658$$

$$\lambda_2 := 308.74 \qquad \lambda_4 := 12989.139$$

$$\omega_1 := \frac{\sqrt{\lambda_1}}{2 \cdot \pi} \cdot \sqrt{\frac{Ea \cdot I}{\rho a \cdot Ar \cdot L^4}} \qquad \boxed{\omega_1 = 3.171 \times 10^3 \, Hz}$$

$$\omega_2 := \frac{\sqrt{\lambda_2}}{2 \cdot \pi} \cdot \sqrt{\frac{Ea \cdot I}{\rho a \cdot Ar \cdot L^4}} \qquad \boxed{\omega_2 = 1.007 \times 10^5 \, Hz}$$

$$\omega_3 := \frac{\sqrt{\lambda_3}}{2 \cdot \pi} \cdot \sqrt{\frac{Ea \cdot I}{\rho a \cdot Ar \cdot L^4}} \qquad \boxed{\omega_3 = 3.192 \times 10^5 \, Hz}$$

$$\omega_4 := \frac{\sqrt{\lambda_4}}{2 \cdot \pi} \cdot \sqrt{\frac{Ea \cdot I}{\rho a \cdot Ar \cdot L^4}} \qquad \boxed{\omega_4 = 6.534 \times 10^5 \, Hz}$$

$$\omega_5 := \frac{\sqrt{\lambda_5}}{2 \cdot \pi} \cdot \sqrt{\frac{Ea \cdot I}{\rho a \cdot Ar \cdot L^4}} \qquad \boxed{\omega_5 = 1.102 \times 10^6 \, Hz}$$

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