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## **Modal Analysis of a GA Superconducting Magnet Subsystem for ALISS**

by

M. Lee  
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April 1997

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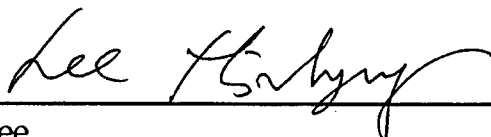
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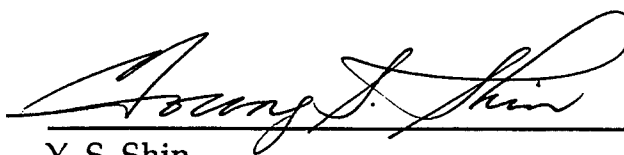
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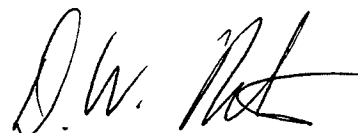
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## ABSTRACT

The modal analysis of a superconducting magnet subsystem designed by General Atomics (GA) has been performed to determine the natural frequencies and corresponding mode shapes. GA subsystem is a part of ALISS (Advanced Lightweight Influence Sweep System), which uses a superconducting magnet for magnetic mine sweeping. Any resonance condition must be avoided in an operational environment to ensure the no-quenching in the subsystem.

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# 1. INTRODUCTION

## A. OVERVIEW

There are two broad classifications of mines: contact mines and influence mines. [Ref. 1] Contact mines utilize the simplest technology and detonate only after coming into direct physical contact with targets. Influence mines detonate when they detect more characteristic ship or submarine signatures within range of the mines. The signatures are generated by acoustic noise, magnetic field variations, and hydrostatic pressure changes.

Mine hunting is the localization, identification, and neutralization of individual mines. There are two mine countermeasures (MCM) presently in use by the U.S. Navy for mine hunting and mine sweeping; a Current injection system and permanent magnetic system. [Ref. 2] The Current injection system creates magnetic signatures in sea water by passing a current through two separate electrodes. The permanent magnetic system composed of large steel pipe is towed by helicopters for shallow water sweeping. It is approximately a 30 foot length of 10 inch diameter steel pipe filled with Styrofoam and magnetized. Currently, there exists no capability in the U.S. Navy to sweep magnetic mines at speeds above 25 knots or in water shallower than 12 foot.

ALISS is an Advanced Technology Demonstration (ATD) to show how modules of relatively new, undeveloped technologies may be combined to provide the U.S. Navy with the capability to perform high-speed, shallow water mine countermeasures. [Ref. 3] There are three main elements to the magnetic sweeping module; a conductivity cooled superconducting magnet, a refrigeration system (cryocooler), and a cryostat. In this work, the vibration analysis is focused on the superconducting magnet and cryostat.

## B. RESEARCH OBJECTIVES

The use of a superconducting mine countermeasures system such as ALISS provides some advantages over present current injection and permanent magnet systems. Because of the small size and modularity of ALISS, it can be deployed onboard such vehicles as the Navy's LCAC (Landing Craft Air Cushing) or the Army's LACV (Landing Air Cushing Vehicle) classes of air-cushion landing craft at high-speed. Since ALISS is designed to operate while mounted to a moving vehicle, the vibration created in the system must be properly isolated within the system to ensure proper operation of the superconductor. Furthermore, ALISS is subjected to shock loads from underwater explosions (UNDEX). In this shock environment, it is possible for the superconducting magnet to become resistive (quenching). It is operationally unacceptable for the ALISS system to remain idle.

The purpose of this study is to build a finite element model of a candidate module developed by the General Atomics (GA) [Ref. 4] and perform modal analysis of the model.

## 2. FINITE ELEMENT METHOD

The finite element method is a numerical procedure for approximating the solution to many complex problems encountered in engineering. An approximate solution to the theoretical behavior of complex structures are obtained at a finite set of points in the model. The accuracy of a finite element solution depends on the way the finite element model is generated. That is, it depends on the number and type of elements used in the model.

Free vibration analysis is a method for predicting the undamped vibration characteristics of a structure. This vibration takes place in the absence of external excitation. The equation of motion of a discrete system is written in matrix form as,

$$[M]\{\ddot{q}\} + [K]\{q\} = \{0\}, \quad (1)$$

where,  $[M]$  is the structural mass matrix,  $\{\ddot{q}\}$  is the nodal acceleration vector,  $[K]$  is the structural stiffness matrix and  $\{q\}$  is the nodal displacement vector. Equation (1) is a system of coupled differential equations with  $n$ -independent unknowns, where  $n$  is the total number of degrees-of-freedom in the structure. By assuming a solution of the form as,

$$\{q\} = C\{\phi\}e^{j\omega t}, \quad (2)$$

an  $n$ -th order homogeneous eigenvalue problem is generated as,

$$[-\omega^2[M] + [K]]Ce^{j\omega t} = 0, \quad (3)$$

where,  $C$  is a constant and  $\{\phi\}$  is a spatial vector. The non-trivial solution to Equation (3) is,

$$\det[-\omega^2[M] + [K]] = 0 \quad (4)$$

This is the characteristic equation of the system. The roots of this equation are the eigenvalues,  $\lambda_i = \omega_i^2$ , where each  $\omega_i$  is a natural frequency of vibration.

For each natural frequency, there is a corresponding eigenvector  $\{\phi\}$  that is the mode shape associated with that frequency. Thus, the solution to the free vibration is  $n$  eigenpairs,  $\omega_n$  and  $\{\phi^n\}$ .

### 3. FINITE ELEMENT MODELING

The finite element (FE) model of the GA subsystem was built using *MSC/PATRAN* 6 code. The first step in finite element analysis was to build a solid model using the fabrication drawings provided by the manufacturer. Using the solid model as a geometric reference, a finite element model was built by manually creating nodes and elements. Certain features of the solid model such as bolt holes, scarf joints, and second stage sleeve were not transferred to the finite element model in order not to introduce large number of elements. Once a complete finite element model of the ALISS module was generated, physical and material properties of the various parts were then defined and a boundary condition was applied to the model. The modal analysis was carried out using *MSC/NASTRAN* [Ref. 5] code.

#### A. SOLID MODELING

This section provides a description of various parts modeled in the finite element analysis. The major components in cross section through cryostat are displayed in Figure 1. On the basis of structural design optimization determining that the lightest weight is achieved if the cylinders are smaller diameter than the magnetic coil, the structure is designed so it interfaces with the coil on its inside diameter. Innermost is the superconducting magnetic coil which contains NbTi conductor stabilized in

copper. The copper provides both mechanical and thermal stability to the superconductor.

Surrounding the coil is an aluminum overwrap and bobbin which provide for thermal conduction and support of the magnet. Since the overwrap is press-fit onto the coil, no slip is specified. Moving outward, the outer S-Glass cylinder which is attached to the bobbin circumferentially is connected to a titanium ring (10K). A middle E-Glass cylinder connects the titanium ring (10K) to a large titanium ring (40K). A outer shell of the aluminum thermal shield is connected to the titanium ring (40K). A inner E-Glass cylinder is made of the same material as the middle E-Glass cylinder and has similar construction. The inner E-Glass cylinder on the right side is connected to a vacuum vessel mount ring.

The parts previously described were generated in the modeling task by picking a basic shape from a catalog of primitives. Most of the primitives used were cylinders and rings. The parts that were modeled for this analysis were; overwrap, the magnetic coil, bobbin, outer S-Glass, titanium ring, middle E-Glass, thermal shield, and inner E-Glass. Figure. 2 is a solid representation of the finite element model.

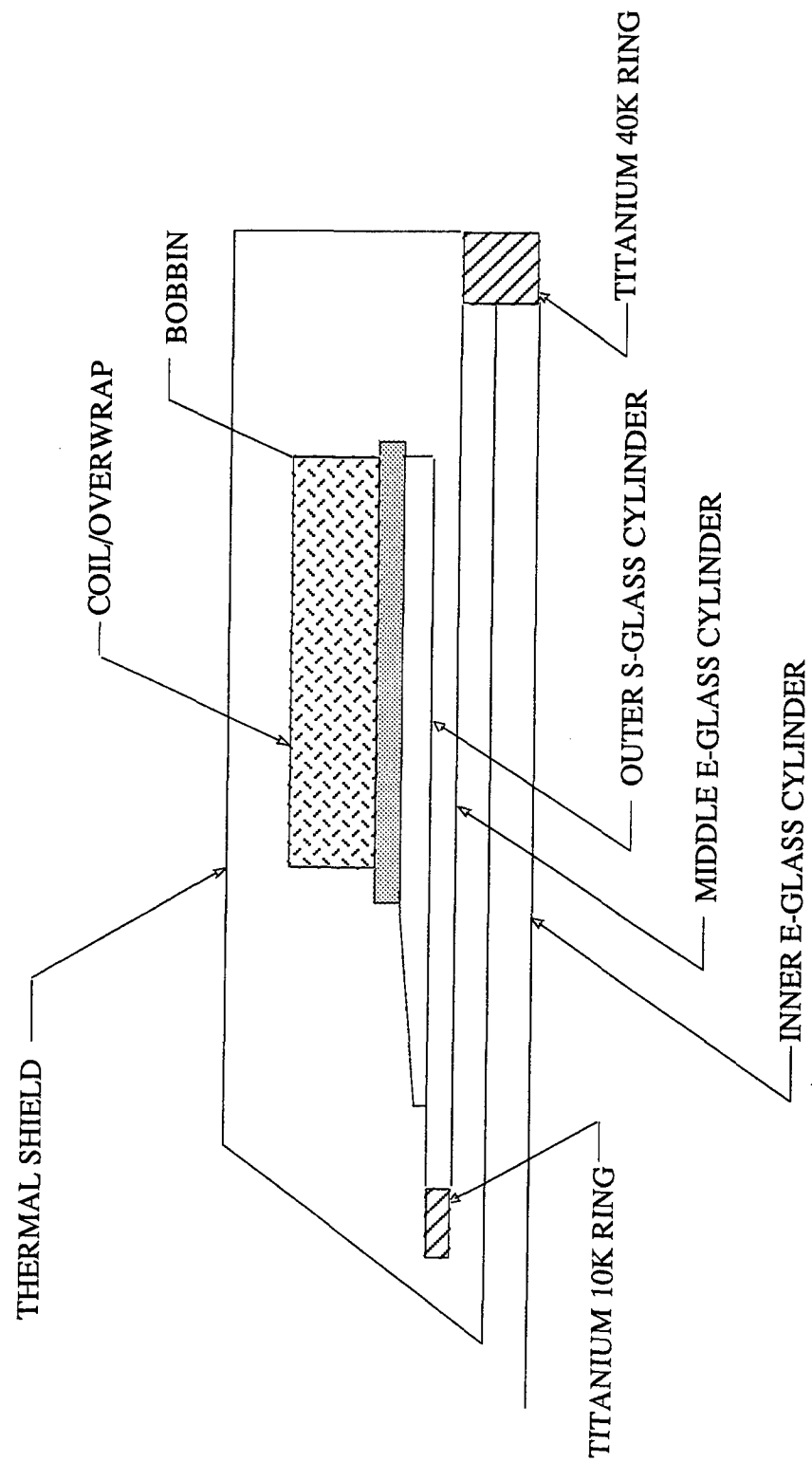
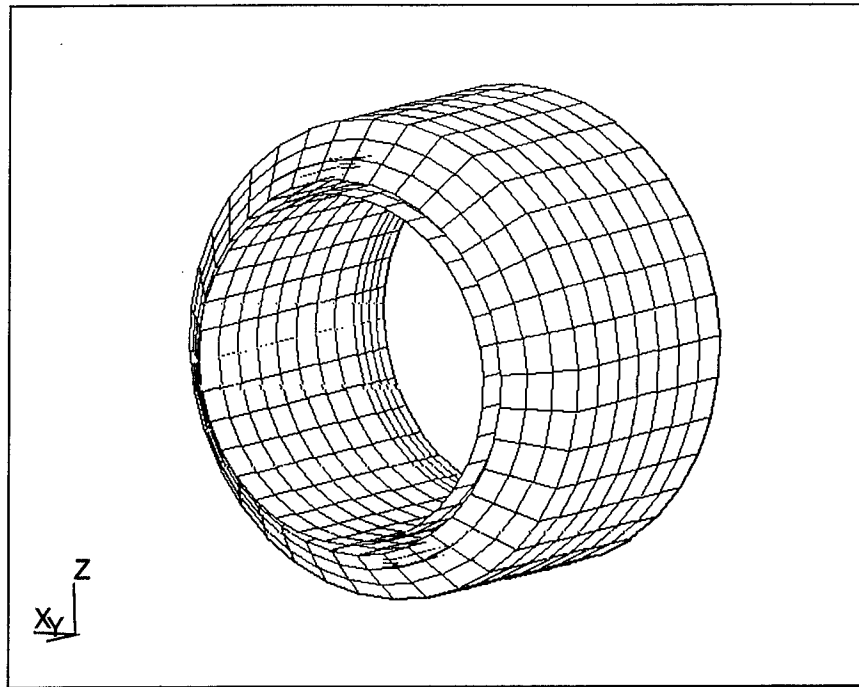
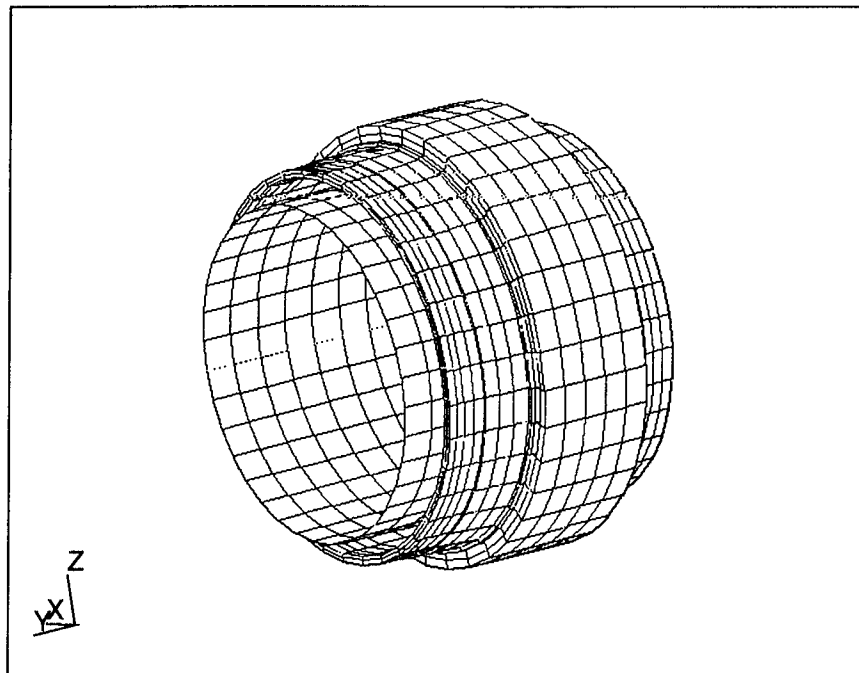


Figure 1. Cross Section of ALISS Magnetic Components [Ref. 4].



(a)



(b)

Figure 2. ALISS Module (a) with thermal shield, (b) without thermal shield.

## B. FINITE ELEMENT MODELING

A certain idealization had been made to keep the mathematical model as small as possible with minimum impact on the solution accuracy. Hence, small features were suppressed when transferring geometric information from the solid model to the finite element model. Once each part was discretized individually, the various finite element representations of the parts were appended to each other to make the entire assembly. Figure 3 displays the finite elements of GA subsystem model.

The total number of nodes in the finite element model is 4958. There are several types of elements to choose when making a finite element model. The proper choice depends on the geometry to be generated. Most elements were also manually generated by specifying the types of element and the node points belongs to them. Two types of elements were used in the current model of the GA subsystem; thin shell elements and solid elements. Thin shell elements were used to model structures that are thin compared to their length and width. Quadrilateral shell elements defined by four nodes were used to represent the inner E Glass cylinder, middle E Glass cylinder, and thermal shield. Solid elements are used to represent structures whose thickness is of the same order as their other dimensions. Brick elements defined by eight nodes were used to represent titanium rings, outer S Glass cylinder, bobbin, overwrap, and the magnetic coil. Actually, titanium rings are composed of solid elements for the ring section and thin shell elements for the cylinder section. The total number of elements in the model is 2700. Since most of the parts are cylinders, it is more realistic to look at each part individually. The finite elements of each parts modeled are displayed in Figure 4 and Figure 5.

Once the finite elements are generated, identification of duplicate nodes, duplicate elements, and missing elements must be conducted in order to find errors that may have occurred during the mesh generation. If the model is properly constructed, the free edge will show the model boundaries. If there exist missing elements or nodes, the highlighted line will indicate either hole or a crack in the model.

After the finite element model was generated, the physical and material properties of each elements were specified. Table I provides a list of the element thickness of the thin shell elements. Material properties must be also specified for each part of the model. The titanium ring, thermal shield, and bobbin are isotropic: that is, the material properties are directional. Table II lists the properties of the various materials used in the finite element model. Since titanium rings are represented as having rectangular cross section, there exists a difference between the actual mass and modeled mass. To take this into account, the density of the titanium is slightly reduced as shown in Table II.

Finally, boundary conditions were applied to the finite element model to determine the normal modes of vibration. The zero displacement restraint is specified along the edge of the inner E Glass cylinder which is connected to the vacuum vessel mounting ring. For a transient analysis, this boundary condition should be replaced with a excitation restraint.

Table I Physical Properties of Shell Element

| Part                    | Material  | Thickness (inch) |
|-------------------------|-----------|------------------|
| Inner E Glass Cylinder  | Composite | 0.43             |
| Middle E Glass Cylinder | Composite | 0.4              |
| Thermal Shield          | Aluminum  | 0.145            |

Table II List of Material Properties

| Name                    | E (radial) | E (hoop)<br>psi | E (axial) | Density<br>lb/cu in | Poisson's<br>Ratio |
|-------------------------|------------|-----------------|-----------|---------------------|--------------------|
| Inner E Glass Cylinder  | 2.0E+6     | 2.69E+6         | 3.47E+6   | 0.067               | 0.3                |
| Titanium Ring           | 1.8E+7     | 1.8E+7          | 1.8E+7    | 0.13                | 0.3                |
| Thermal Shield          | 1.1E+7     | 1.1E+7          | 1.1E+7    | 0.098               | 0.3                |
| Middle E-Glass Cylinder | 3.0E+6     | 4.19E+6         | 4.88E+6   | 0.067               | 0.23               |
| Outer S-Glass Cylinder  | 3.0E+6     | 6.63E+6         | 3.0E+6    | 0.067               | 0.23               |
| Bobbin                  | 1.1E+7     | 1.1E+7          | 1.1E+7    | 0.098               | 0.3                |
| Coil/Overwrap           | 3.52E+6    | 1.3E+7          | 5.32E+6   | 0.19                | 0.3                |

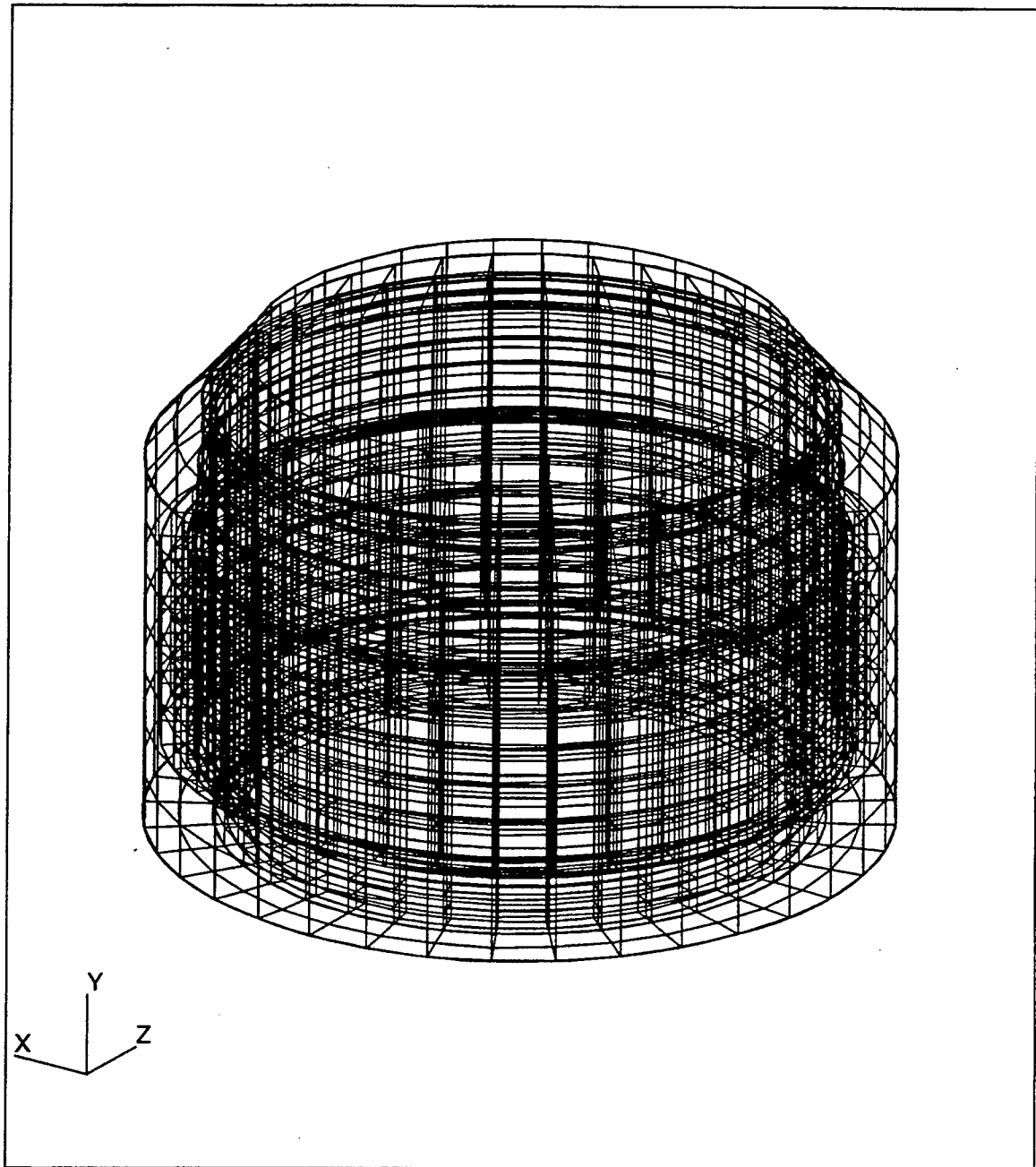


Figure 3. Finite Element Model of Magnetic ALISS Module.

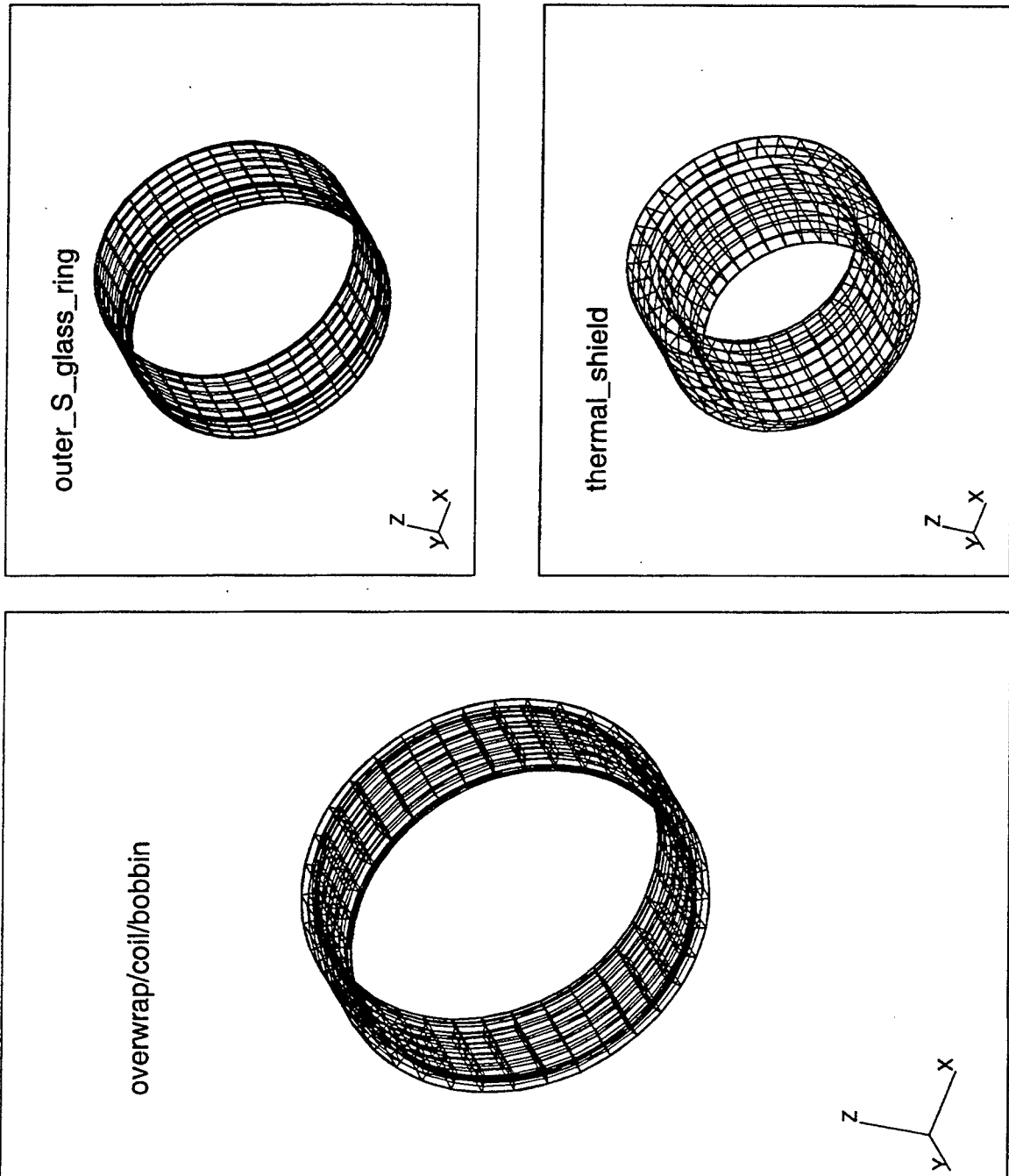


Figure 4. Finite Element Model of Each Parts.

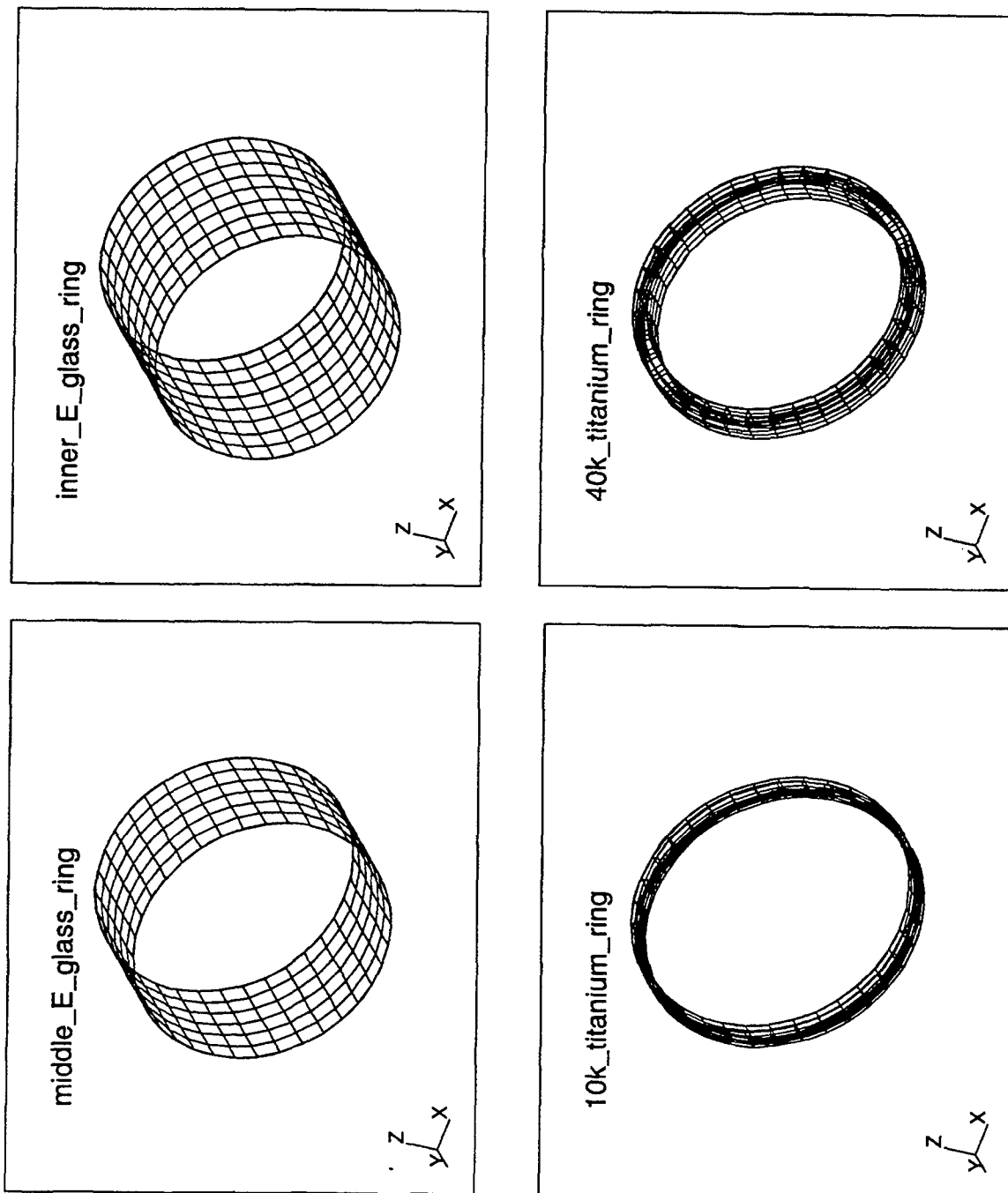


Figure 5. Finite Element Model of Each Parts.

## 4. NORMAL MODE ANALYSIS

The normal modes of vibration of the model were solved using *MSC/NASTRAN* finite element structural code. The solutions are the system undamped natural frequencies and the mode shapes.

The first 10 modes of the model were obtained and the natural frequencies are provided in Table III. Due to the connectivity of each part in the finite element model, resonant frequencies of one component have effects on the other parts to some degrees. In the following discussion, thus, the mode shapes are depicted by describing the motions of the parts that exhibit the greatest deformation value from the eigenvector. The deformation shown in the figures are not to scale with the parts.

Table III. Natural Frequencies.

| Mode Natural Frequency (Hz) |        |
|-----------------------------|--------|
| 1                           | 47.44  |
| 2                           | 47.44  |
| 3                           | 62.97  |
| 4                           | 64.54  |
| 5                           | 64.58  |
| 6                           | 75.50  |
| 7                           | 75.50  |
| 8                           | 86.15  |
| 9                           | 101.96 |
| 10                          | 101.97 |

Only the modes that have significant deformations of a part are described here. Appendix A gives complete characteristics of the first 10 modes of this model.

The major participant in Mode 1 at 47.44 Hz is the magnetic coil. Figure 4 shows this mode. The magnetic coil translates axially and laterally. There is

also a slight rocking motion of the coil. Mode 2 occurs at the same frequency and has the same shapes as Mode 1, which is also displayed in Figure 7.

Mode 3, which occurs at 62.97 Hz, is characterized by coil and outer S Glass cylinder deforming in a breathing fashion. The maximum deformations of the coil and outer S Glass cylinder caused by this mode are shown in Figure 8 and Figure 9, respectively.

The primary motion of Modes 4 (64.54 Hz) and 5 (64.58 Hz) are bending of the coil and outer S Glass cylinder. The maximum deformations of the coil and outer S Glass cylinder caused by this mode are shown in Figure 10 and Figure 11, respectively.

The natural frequency of Mode 6 is 75.50 Hz. This mode is identified by the rocking and bending motions in coil and outer S Glass cylinder. The maximum deformations of the coil caused by this mode are shown in Figure 12. Mode 7 vibrates at nearly the same frequency and the deformation of the outer S Glass cylinder caused by this mode are displayed in Figure 13.

The primary participant in Mode 8, which occurs in 86.15 Hz are the coil and outer S Glass cylinder. The motion of these parts is axial translational motion. The deformations of the coil and outer S Glass cylinder caused by this mode are shown in Figure 14 and Figure 15, respectively.

The major parts in Mode 9 at 101.96 Hz are Titanium Ring (10K), middle E Glass cylinder, outer E Glass cylinder, and coil. They exhibit the twisting motions. The deformations of the Titanium Ring and coil caused by this mode are shown in Figure 16 and Figure 17, respectively. Figure 18 shows the combined bending motion of the coil occurring at 101.97 Hz.

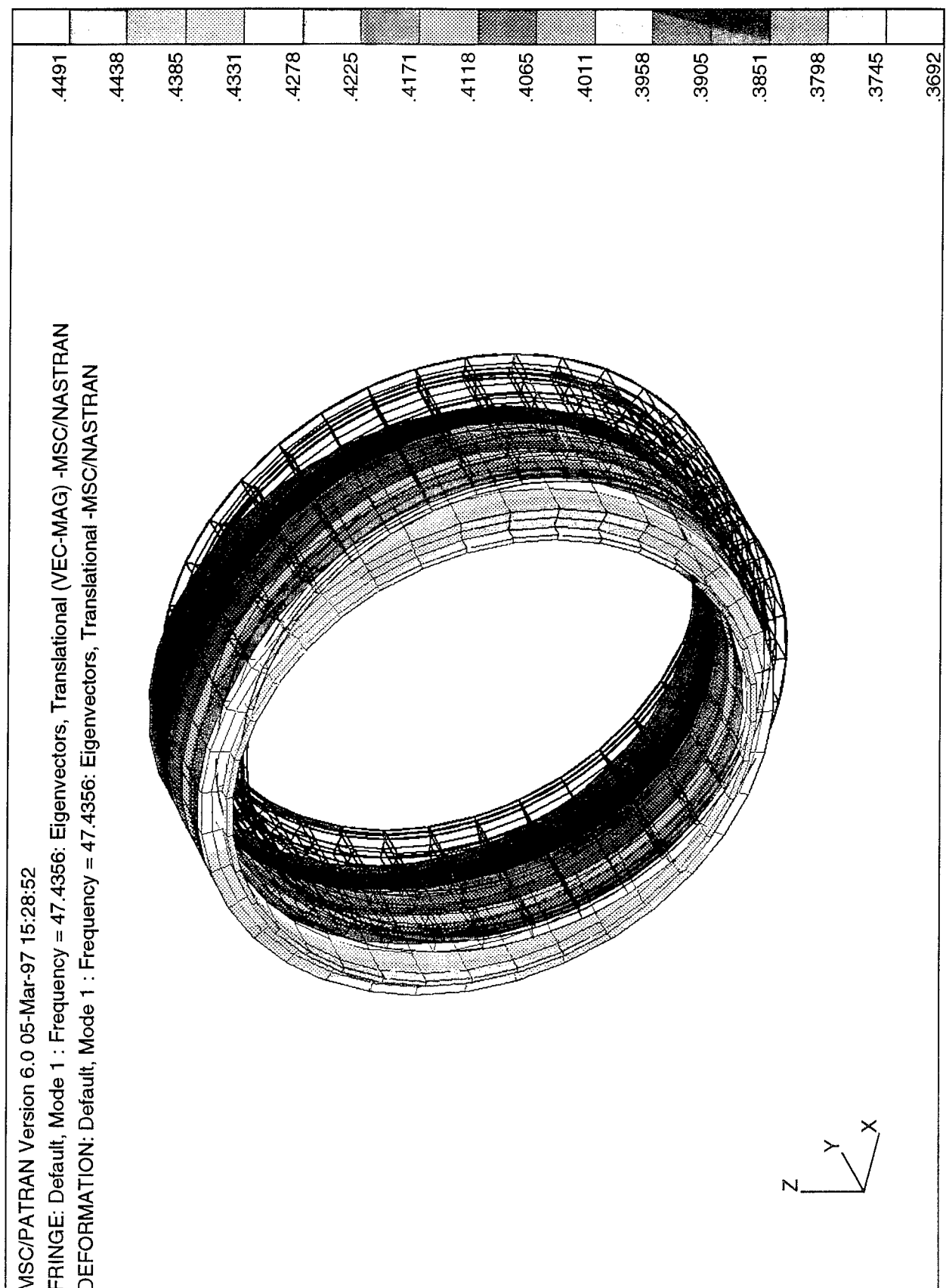


Figure 6. Mode 1, 47.44 Hz, Axial and Lateral Translation. Coil.

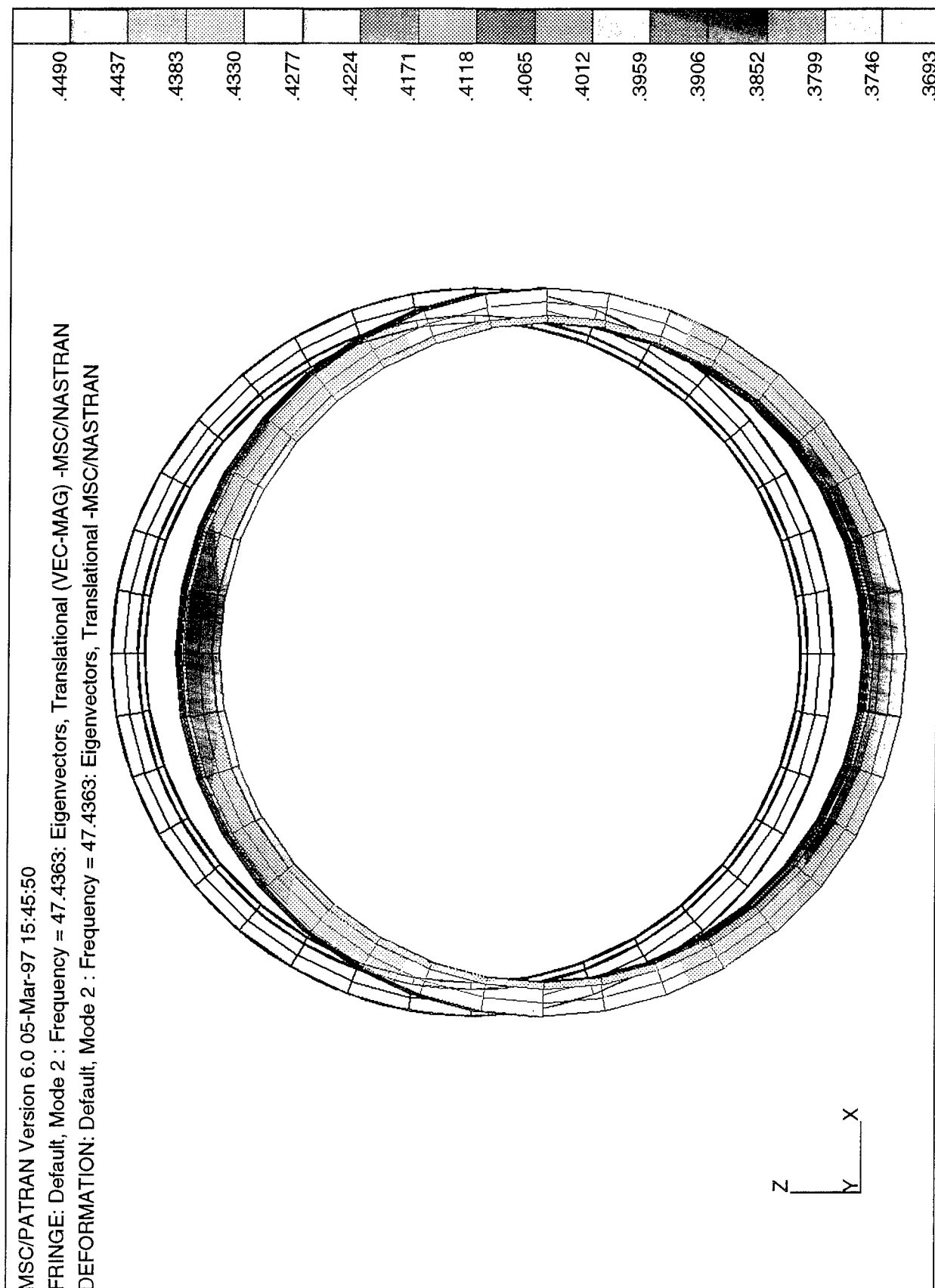


Figure 7. Mode 2, 47.44 Hz, Same as 1st Mode. Coil.

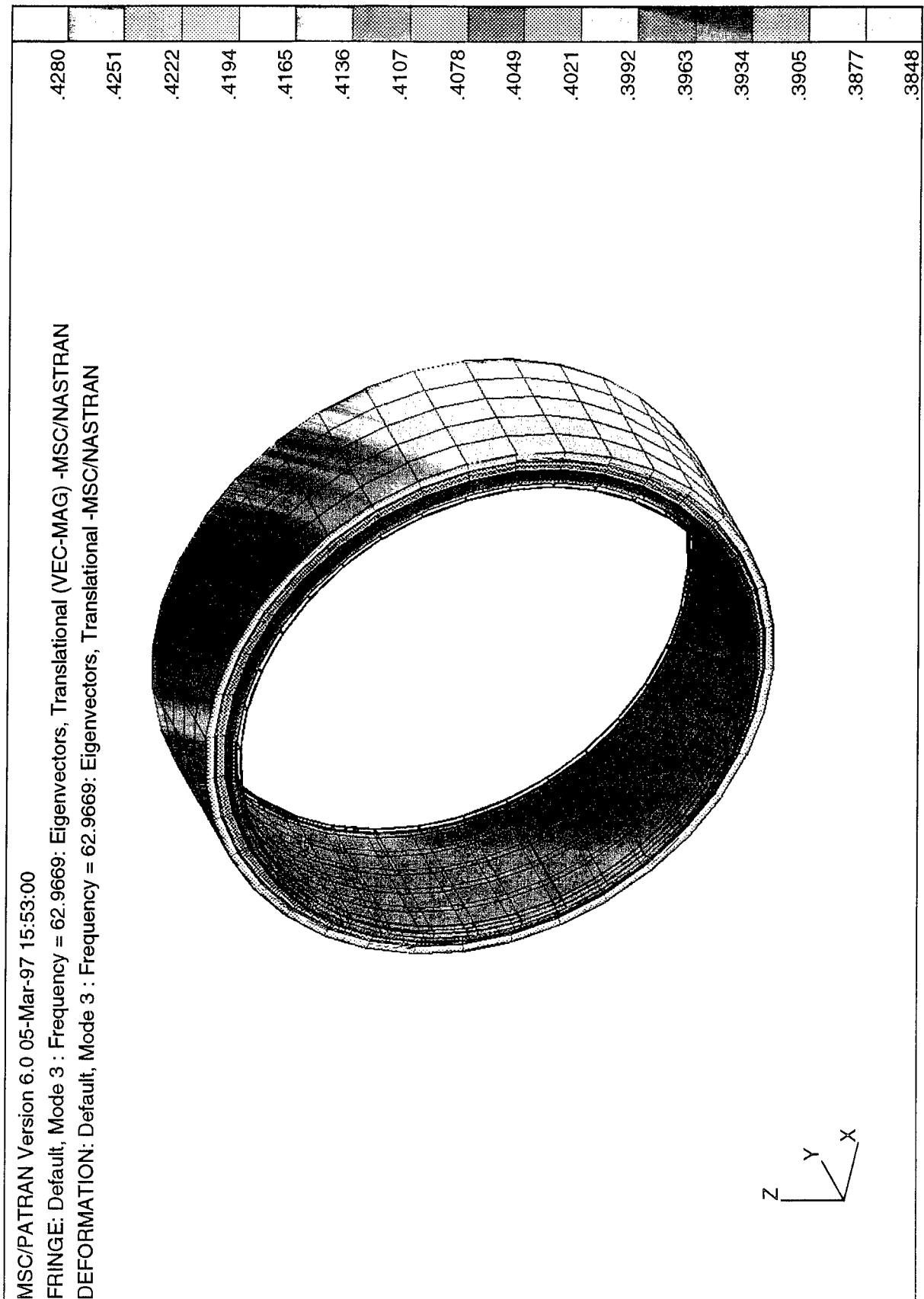


Figure 8. Mode 3, 62.97 Hz, Breeding Mode. Coil.

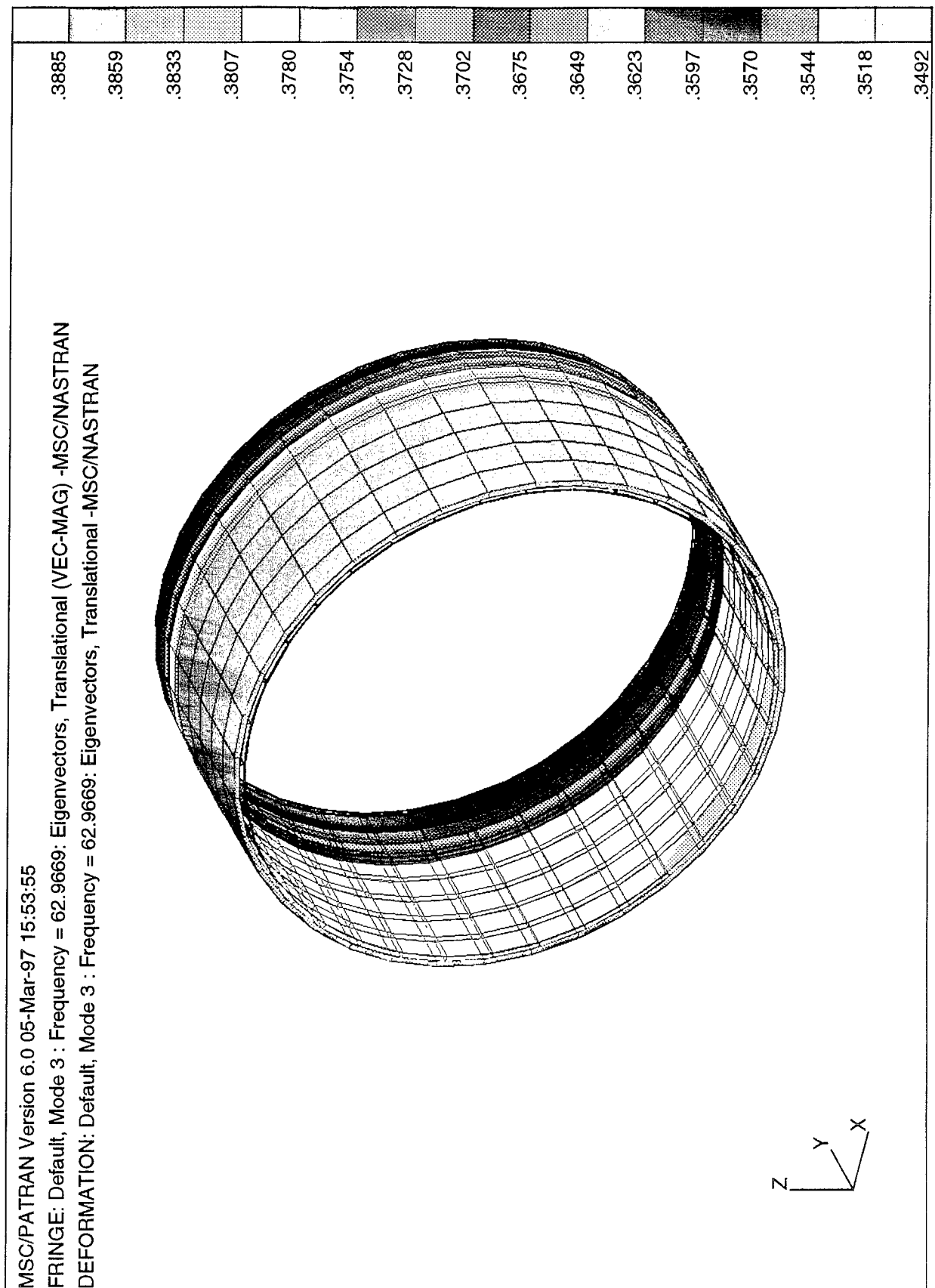


Figure 9. Mode 3, 62.97 Hz, Breeding Mode. Outer S Glass.

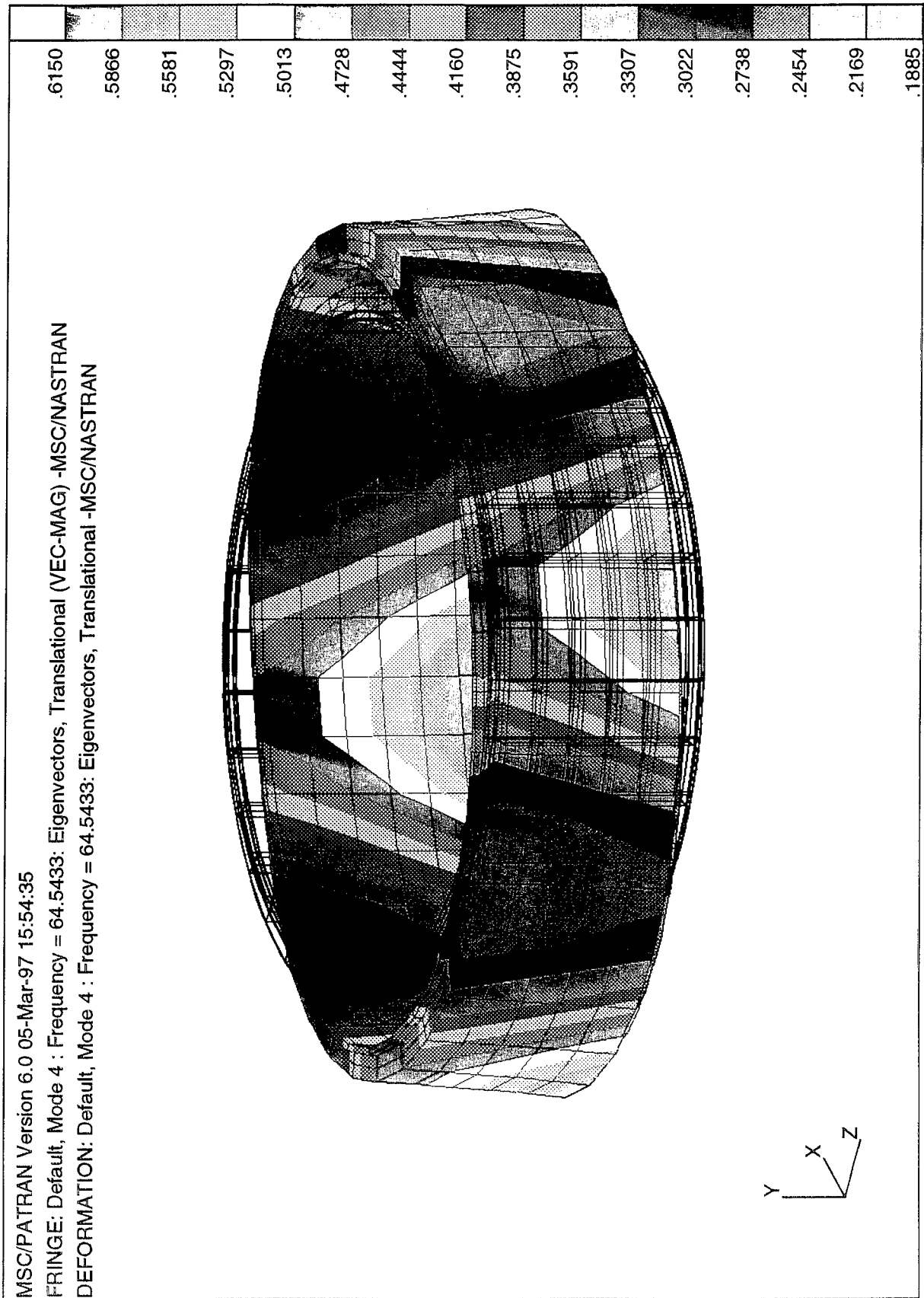


Figure 10. Mode 4, 64.54 Hz, Bending Mode. Coil.

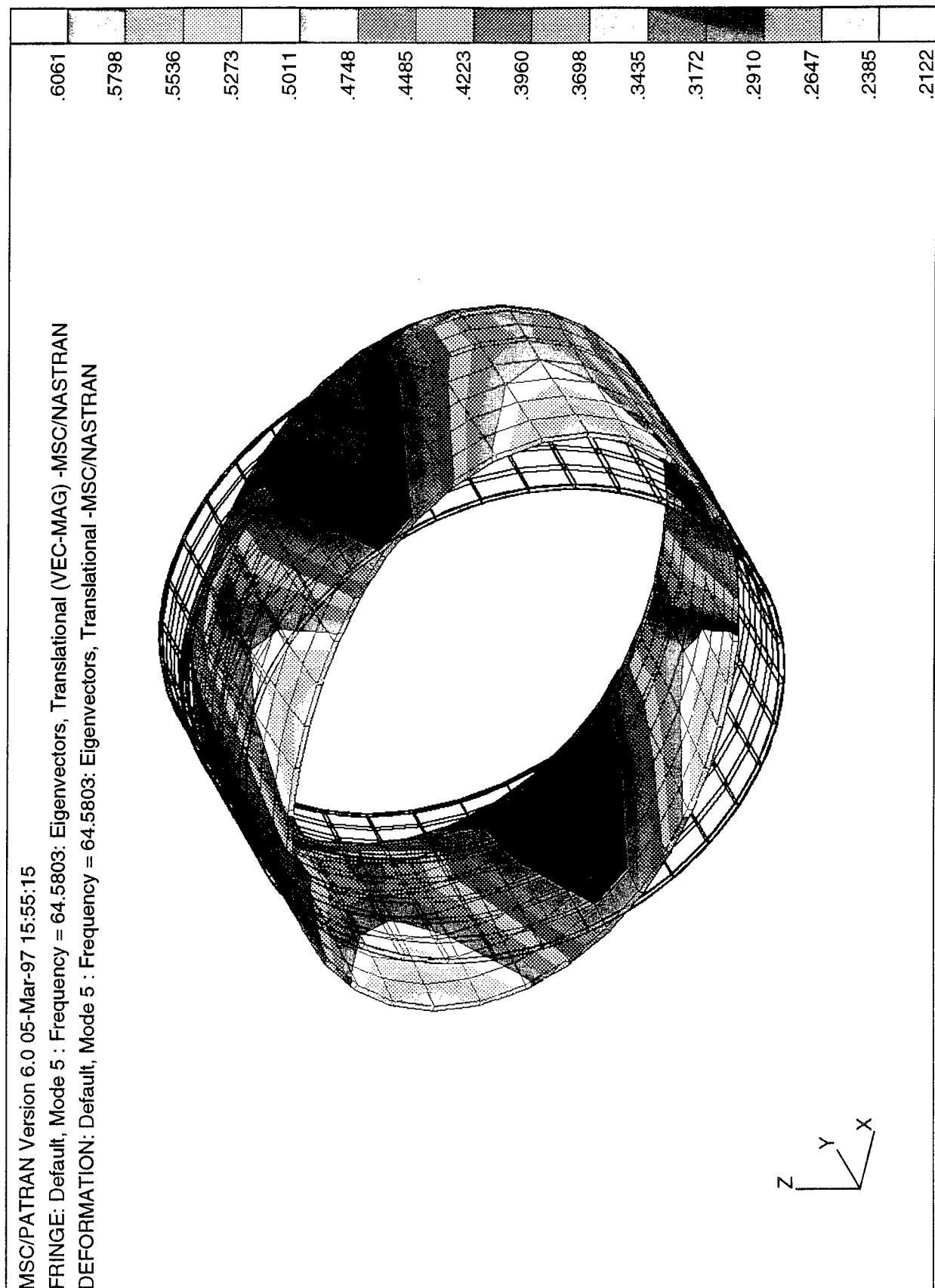


Figure 11. Mode 5, 64.58 Hz, Same as 4th Mode. Outer S Glass.

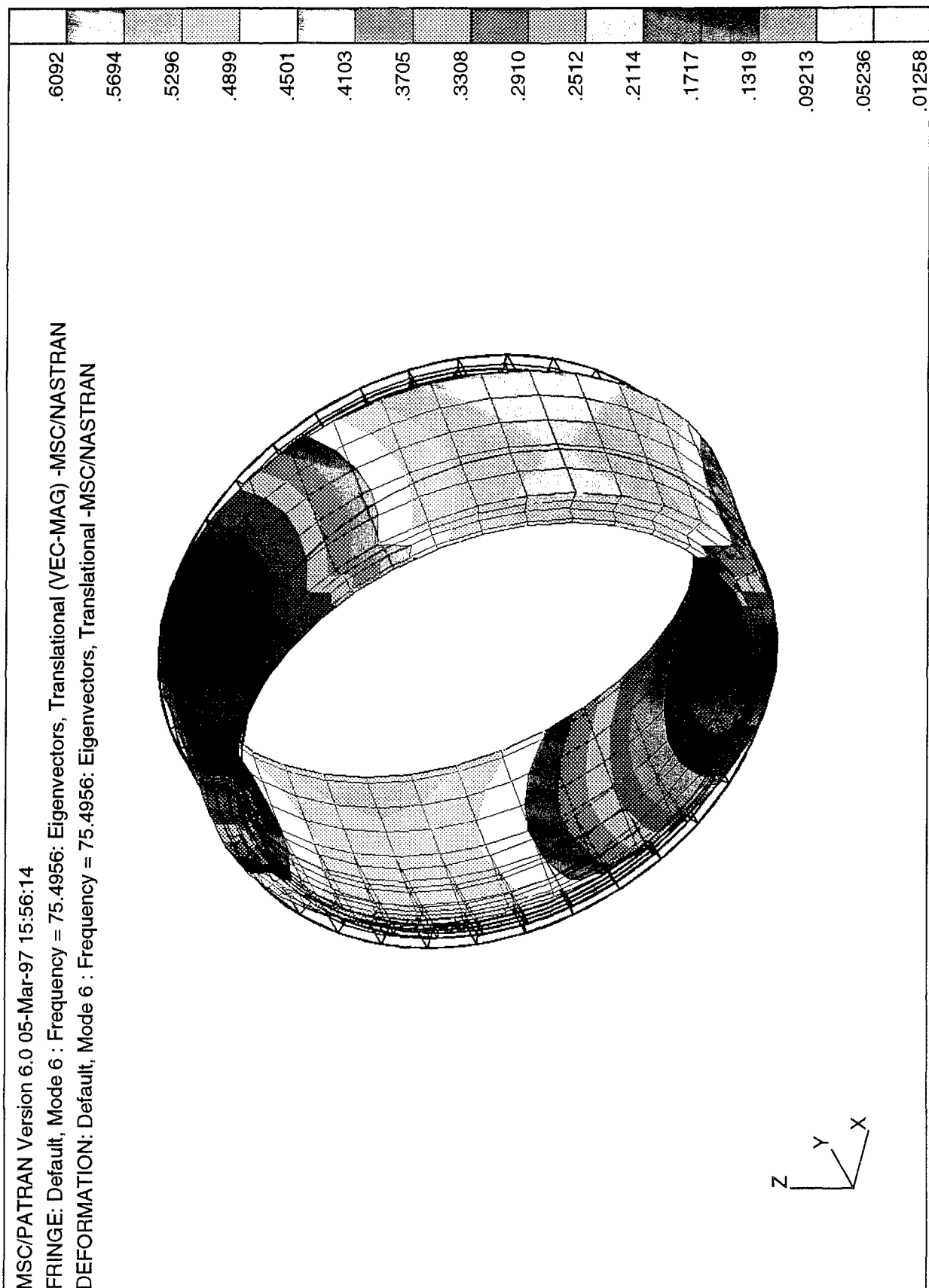


Figure 12. Mode 6, 75.50 Hz, Rocking & Bending Mode. Coil.

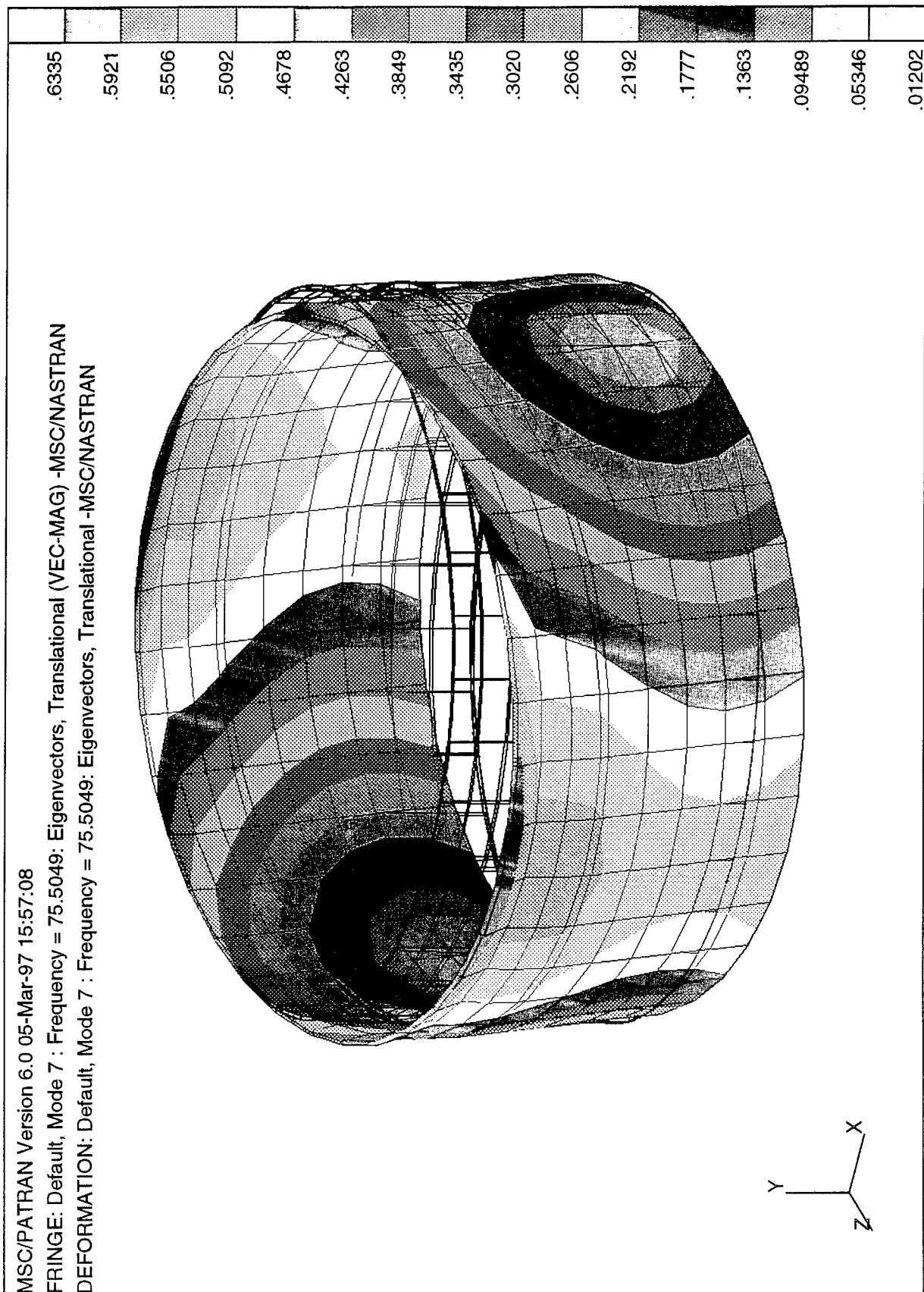


Figure 13. Mode 7, 75.50 Hz, Same as 6th Mode. Outer S Glass.

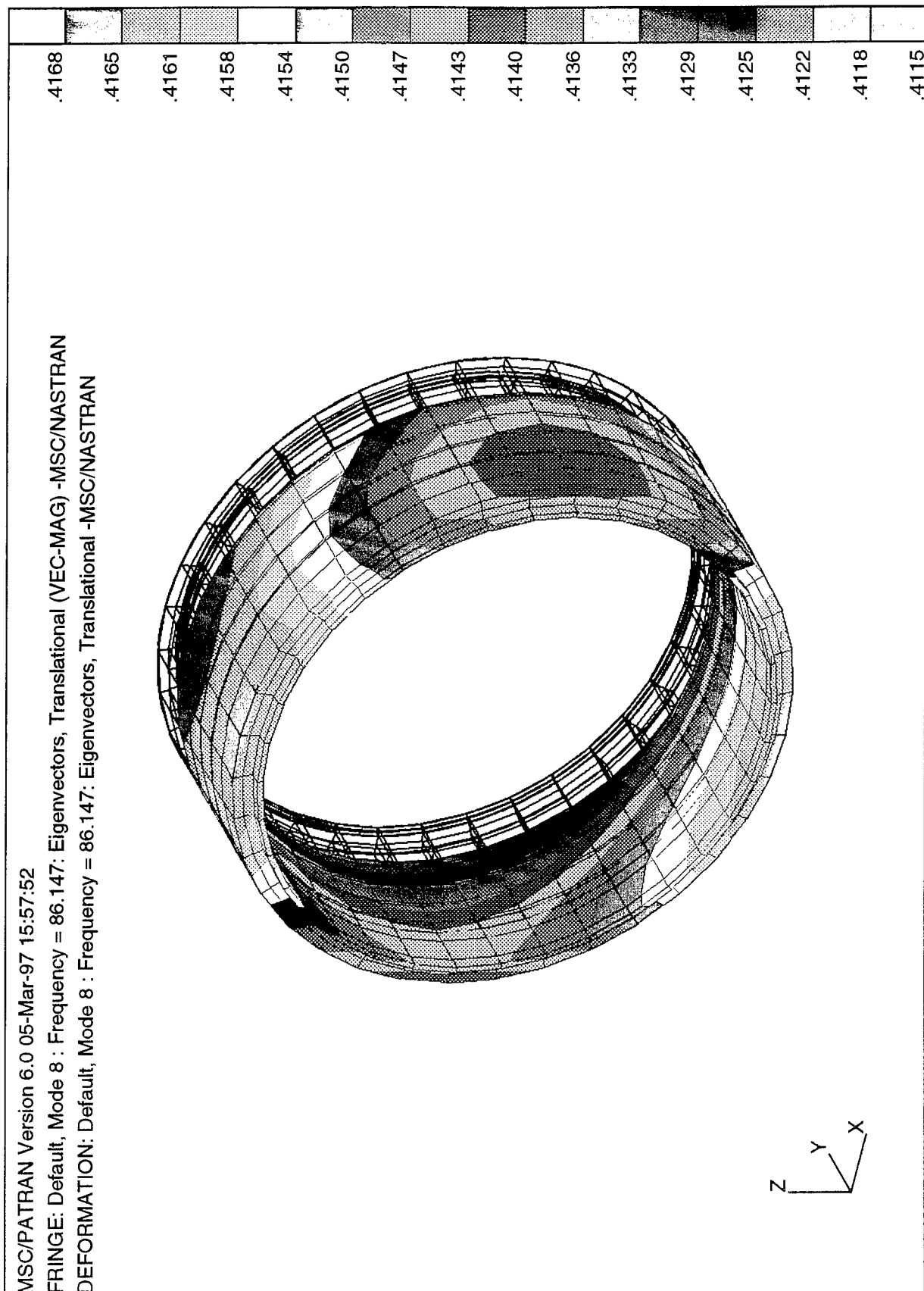


Figure 14. Mode 8, 86.15 Hz, Axial Translation. Coil.

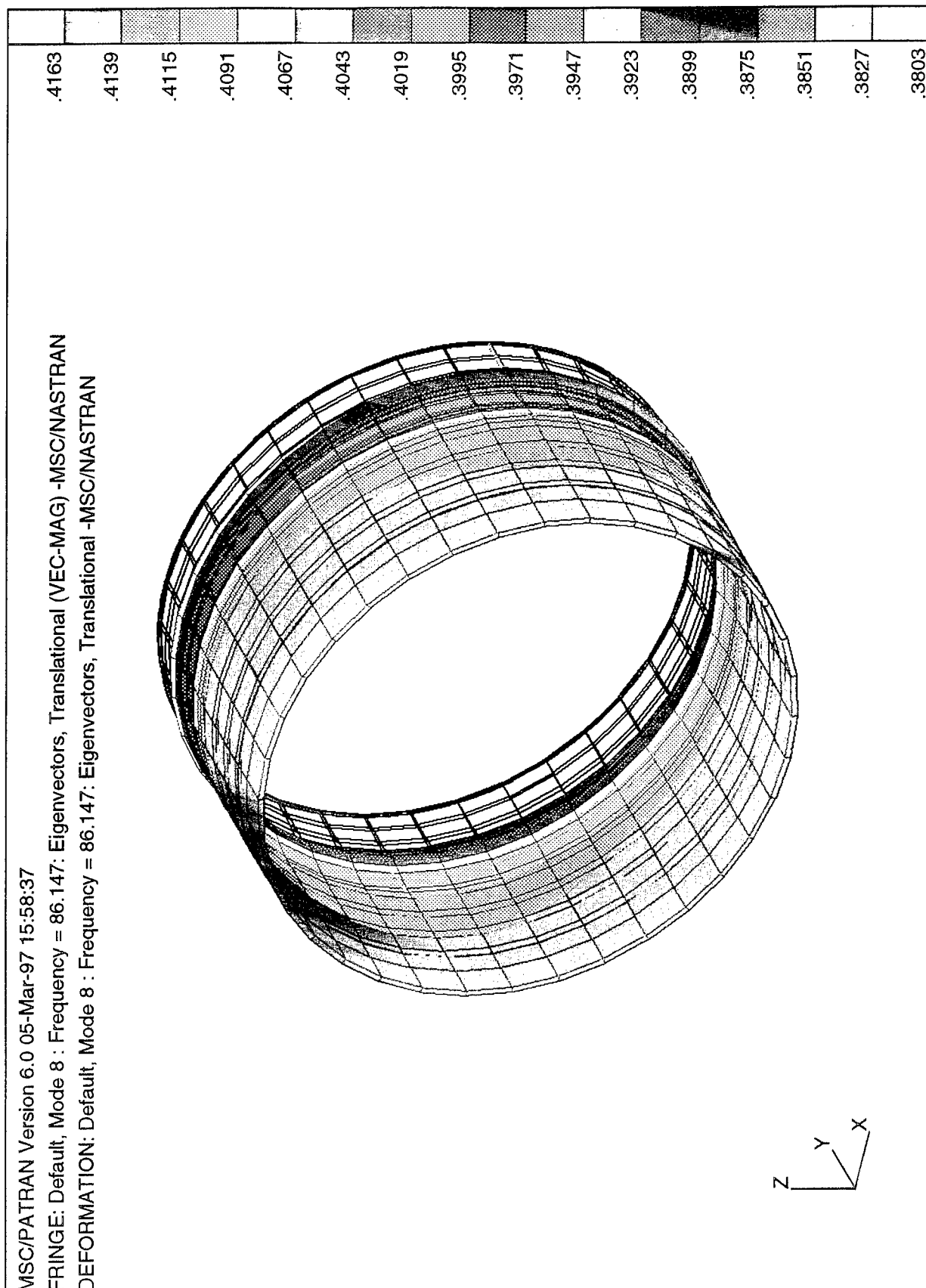


Figure 15. Mode 8, 75.50 Hz, Axial Translation. Outer S Glass.

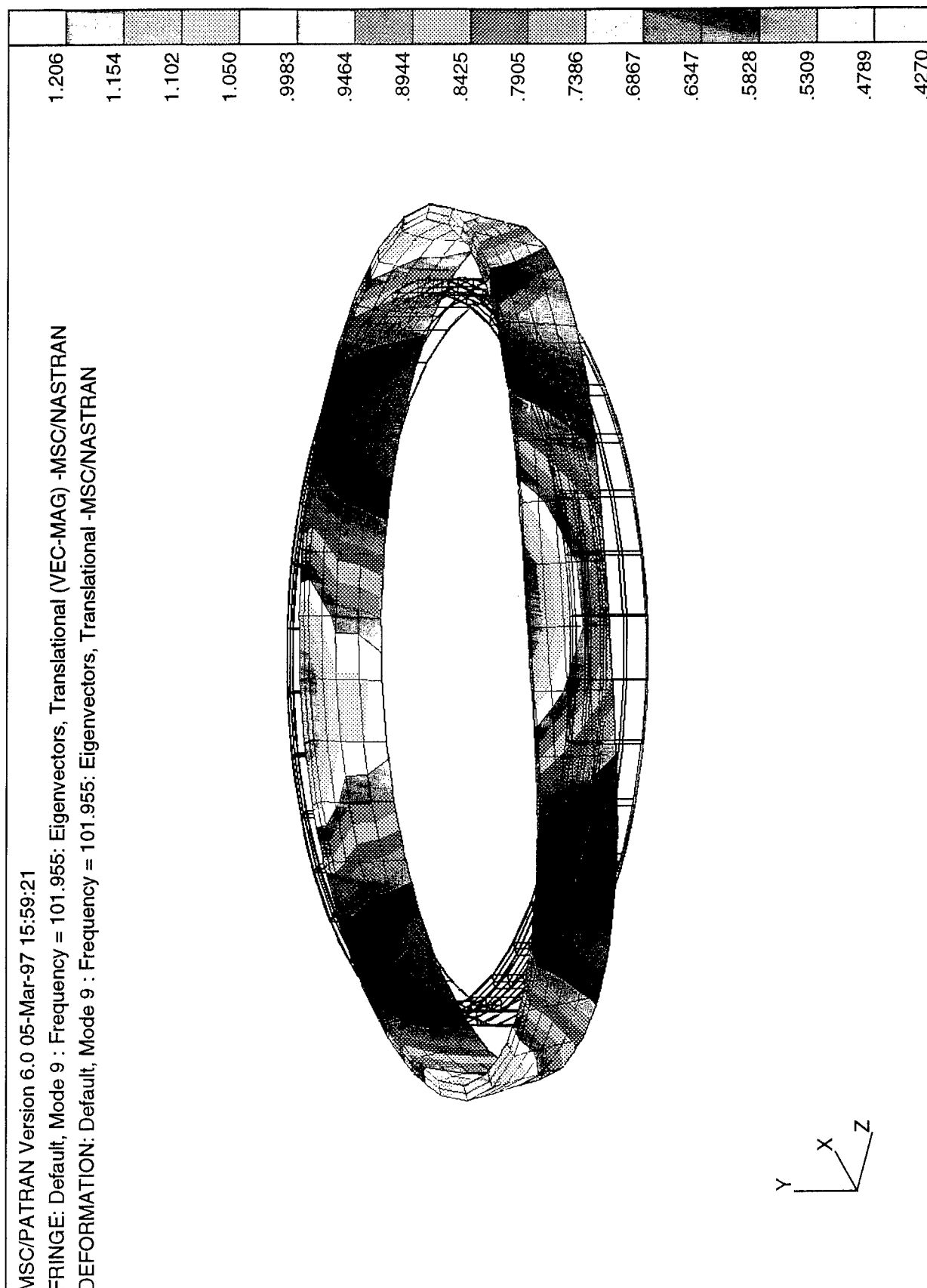


Figure 16. Mode 9, 101.96 Hz, Twisting Mode. Titanium ring (10K).

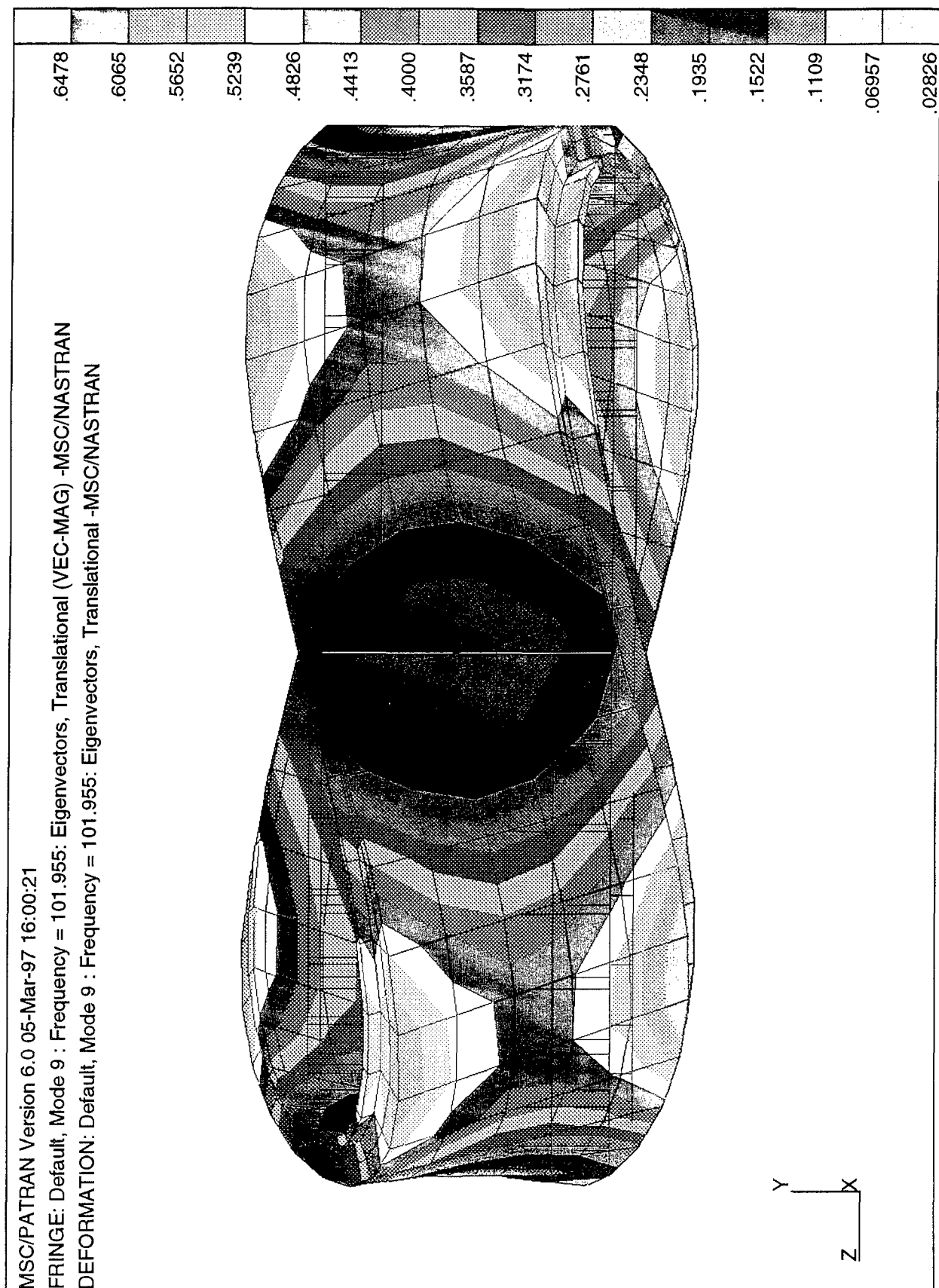


Figure 17. Mode 9, 101.96 Hz, Twisting Mode. Coil.

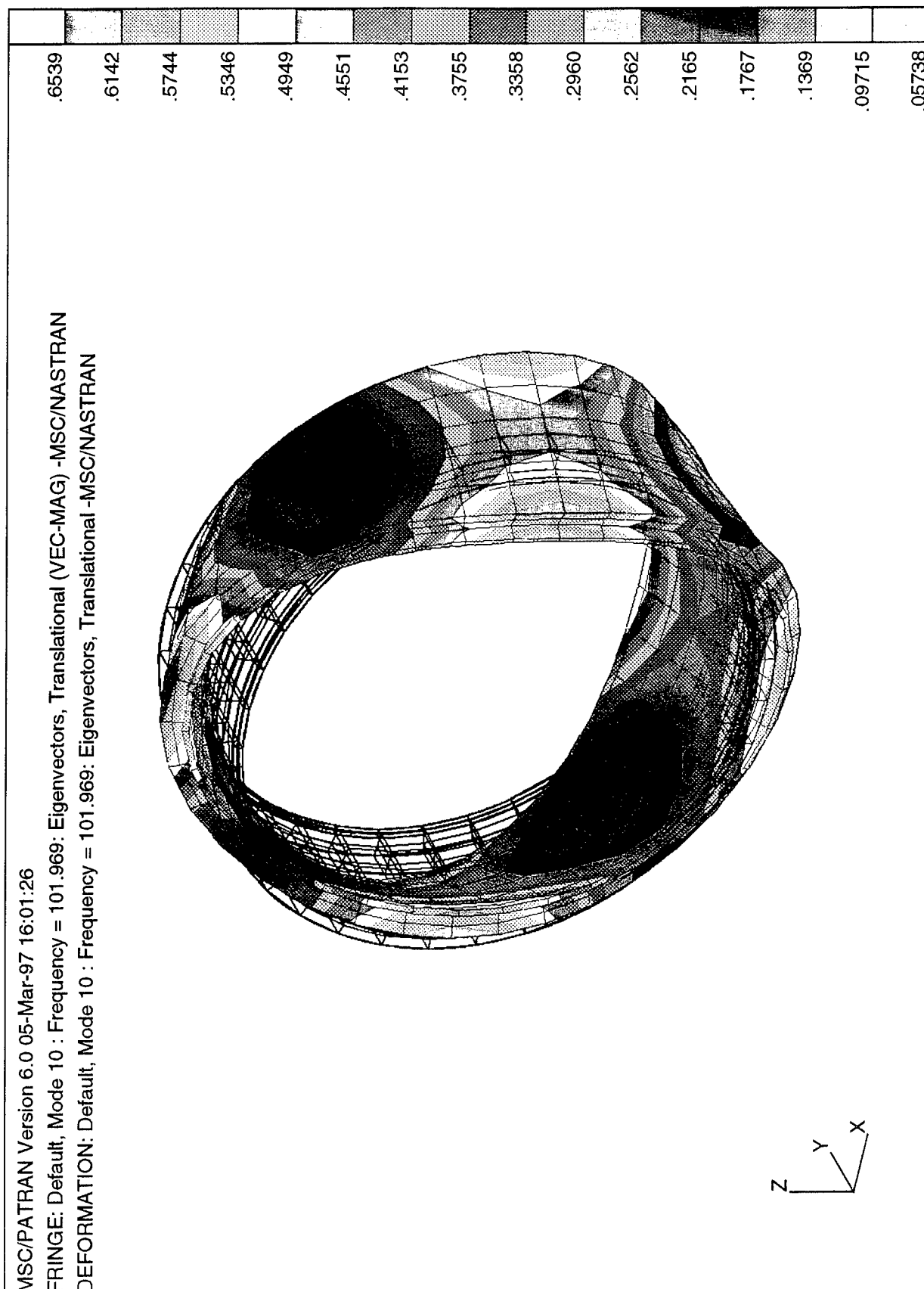


Figure 18. Mode 10, 101.97 Hz, Combined Bending Mode. Coil.

## 5. DISCUSSIONS

The use of small size and low power requirements of magnetic ALISS may provide significant capability in the area of magnetic mine sweeping. Due to the small size, it can be employed in a variety of platforms, including advanced design surface ships and aircraft. However, the potential advantages are offset by the risks inherent in the use of immature technologies in the unknown operational environment. Since ALISS is designed to operate while mounted to a moving vehicle, the vibration created in the system must be properly isolated within the system to ensure proper operation of the superconductor. Furthermore, ALISS is subjected to shock loads from underwater explosions (UNDEX). In this shock environment, it is possible for the superconducting magnet to become resistive. The goal of this work has been to construct a finite element model of the magnetic ALISS module, and perform the modal analysis for the purpose of providing recommendations for the shock and vibration design criteria of ALISS.

Once the normal mode analysis of the ALISS model was conducted, a transient response of the model will be analyzed using a base excitation function. For a transient input, half sine-wave acceleration with maximum amplitude and duration from ship shock detonation data can be used. It may be more realistic to consider a function of several sine waves with decaying amplitude as a transient excitation.

To understand the ALISS system and inter-relation of its components, it is also necessary to perform the sensitivity analysis by changing one property as a time. First, a damping sensitivity need to investigate by increasing the damping extant in the system. The results can be used to determine the actual structural damping when a test data obtained from the prototype is available.

Second, dimensional sensitivity must be performed by changing certain parts of the model, most notable the shell thicknesses. This will determine what effect different shell thicknesses would have on the vibration characteristics of the module.

The General Atomics is building a prototype magnetic module that will be operationally tested for shock and vibration. When the results of these tests become available, they should be compared with the data obtained from this work.

## APPENDIX A. MODE SHAPES OF ALISS

The origin is located at the centroid of the magnet, the Y-axis is the bore axis of the magnet, the X-axis and Z-axis are vertical and transverse directions, respectively. "MAX" parameter used in the table is not physical dimensional value, but relative quantity and not to be scaled.

### MODE 1 AND 2    FREQUENCY: 47.44 Hz

| PART                    | MAX    | DESCRIPTION                             |
|-------------------------|--------|-----------------------------------------|
| Coil/Overwrap           | 0.4491 |                                         |
| Outer S-Glass Cylinder  | 0.440  |                                         |
| Middle E-Glass Cylinder | 0.3056 |                                         |
| inner E-Glass cylinder  | 0.2406 | Axial, lateral translation, and rocking |
| Thermal Shield          | 0.2599 |                                         |
| 10K Titanium Ring       | 0.3461 |                                         |
| 40K Titanium Ring       | 0.2611 |                                         |

### MODE 3    FREQUENCY: 62.97 Hz

| PART                    | MAX    | DESCRIPTION                       |
|-------------------------|--------|-----------------------------------|
| Coil/Overwrap           | 0.4280 |                                   |
| Outer S-Glass Cylinder  | 0.3885 |                                   |
| Middle E-Glass Cylinder | 0.3276 |                                   |
| inner E-Glass cylinder  | 0.2169 | Breeding mode in radial direction |
| Thermal Shield          | 0.3045 |                                   |
| 10K Titanium Ring       | 0.3494 |                                   |
| 40K Titanium Ring       | 0.2487 |                                   |

MODE 4 AND 5    FREQUENCY: 64.54 Hz

| PART                    | MAX    | DESCRIPTION  |
|-------------------------|--------|--------------|
| Coil/Overwrap           | 0.6150 |              |
| Outer S-Glass Cylinder  | 0.5984 |              |
| Middle E-Glass Cylinder | 0.4224 |              |
| inner E-Glass cylinder  | 0.1382 | Bending mode |
| Thermal Shield          | 0.1910 |              |
| 10K Titanium Ring       | 0.4693 |              |
| 40K Titanium Ring       | 0.1382 |              |

MODE 6 AND 7    FREQUENCY: 75.50 Hz

| PART                    | MAX    | DESCRIPTION            |
|-------------------------|--------|------------------------|
| Coil/Overwrap           | 0.6092 |                        |
| Outer S-Glass Cylinder  | 0.6321 |                        |
| Middle E-Glass Cylinder | 0.5131 |                        |
| inner E-Glass cylinder  | 0.1770 | Rocking & Bending mode |
| Thermal Shield          | 0.4148 |                        |
| 10K Titanium Ring       | 0.7100 |                        |
| 40K Titanium Ring       | 0.3321 |                        |

MODE 8 FREQUENCY: 86.15 Hz

| PART                    | MAX     | DESCRIPTION              |
|-------------------------|---------|--------------------------|
| Coil/Overwrap           | 0.4168  |                          |
| Outer S-Glass Cylinder  | 0.4163  |                          |
| Middle E-Glass Cylinder | 0.2844  |                          |
| inner E-Glass cylinder  | 0.1266  | Axial Translation motion |
| Thermal Shield          | 0.42344 |                          |
| 10K Titanium Ring       | 0.3935  |                          |
| 40K Titanium Ring       | 0.2344  |                          |

MODE 9 FREQUENCY: 101.96 Hz

| PART                    | MAX    | DESCRIPTION     |
|-------------------------|--------|-----------------|
| Coil/Overwrap           | 0.6478 |                 |
| Outer S-Glass Cylinder  | 0.9134 |                 |
| Middle E-Glass Cylinder | 1.0360 |                 |
| inner E-Glass cylinder  | 0.1189 | Twisting motion |
| Thermal Shield          | 0.5535 |                 |
| 10K Titanium Ring       | 1.2060 |                 |
| 40K Titanium Ring       | 0.2061 |                 |

MODE 10 FREQUENCY: 101.97 Hz

| PART                    | MAX    | DESCRIPTION           |
|-------------------------|--------|-----------------------|
| Coil/Overwrap           | 0.6539 |                       |
| Outer S-Glass Cylinder  | 0.9212 |                       |
| Middle E-Glass Cylinder | 1.0440 |                       |
| inner E-Glass cylinder  | 0.1198 | Combined bending mode |
| Thermal Shield          | 0.5580 |                       |
| 10K Titanium Ring       | 1.2170 |                       |
| 40K Titanium Ring       | 0.2085 |                       |

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