LIGO

FACILITIES STUDY

(Foundation Response and Local Optical Lever Performance)

performed as part of the LIGO

ALIGNMENT SENSING/CONTROL DESIGN TASK

Presented at the

LIGO Integration Meeting, 9 February 1995

by

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G950128-00-D

OBJECTIVE

To determine the mechanical stability of the LIGO corner and end station foundations and their suitability for supporting a local optical lever system capable of initial lock acquisition of the fabry-perot cavities.

To estimate the mechanical viability of the local optical lever system as a long-term alignment tool for maintaining alignment of the cavities.

SOLUTION APPROACH

The FINITE ELEMENT METHOD is useful for the solution of various classes of problems.

- Eigen Value Problems

  The frequencies and mode shapes of natural vibration of a body, such as an elastic foundation resting on an elastic soil, are the eigen values and eigen vectors of the system, respectively. The dynamic response of such a system to an input function is soluable using the spectral-decomposed stiffness matrix once damping is applied.

- Propagation Problems

  The time evolution of the temperature field that gives rise to thermal gradients that distort the earth's surface and structures attached to it, such as the diurnal thermal distortions of the soil and foundation, are solved.

- Steady-State Problems

  Load application does not vary with time or load appliction is a very slow process, without lags, (pseudo steady-state) and can be approximated as steady-state. The diurnal tidal expansion / contraction of the earth's crust can be modeled as a pseudo steady-state system.

MECHANICAL LOADING

- Seismic Random Vibration Input

  Standard LIGO input spectrum defined at the Washington state site. Three orthogonal directions of uncorrelated input are applied to the foundation through the soil upon which it rests. Input applied on time scales greater than 10s do not significantly contribute to the foundation's vibration response.

- Solar Radiation-Induced Thermal Input

  Solar flux assumed to irradiate soil in the vicinity of corner and end stations. Soil convects to ambient air and conducts through and underneath wall footings to the foundation whose upper surface convects to constant room temperature facilitated by the air conditioning system and whose lower surface is held constant at the soil temperature.

- Tidal Force-Induced Terrestrial Crust Strains

  Strain rates of the earth's surface, as measured by wide-band interferometers, are modeled as though they were isotropic thermal expansion of the soil in the vicinity of the corner and end station facilities. The foundation is assumd to rest (in a coupled sense) on the expanding soil.

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THE FINITE ELEMENT METHOD

Segmenting a continuum into a discrete system of elements possessing a finite number of degrees of freedom whose state variable solution can be numerically managed.

Procedure

- System Idealization: Creating an element assemblage (model).
- Element Equilibrium: Requiring equilibrium equations, written in terms of state variables, be satisfied on the element scale.
- Assemblage Connectivity: Element interconnection requirements establish simultneous equations in terms of the state variables (continuity).
- Response Solution: Simultaneous equations are solved for the state variables subject to the element equilibrium requirements and boundary conditions such that the response of each element of the model is known.

FINITE ELEMENT MODELS

Eigen Value Problem (Modes and Frequencies)

2D Model: Isoparametric, 9-node shell elements describe foundation characteristics and 2D springs describe soil characteristics. Analytical treatment of soil parameters and foundation "foot print" on an elastic medium are used to determine spring rates.

3D Model: Solid, 20-node elements describe the foundation and the soil out to an extent where boundary conditions can be applied to the soil nodes without constraining the foundation behavior. Coupled modes are well described.

Propagation Problem (Heat Transfer)

2D Model: Isoparametric, 4-node elements describe foundation and soil thermal and mechanical characteristics. Time-varying solar heat flux impinges upon soil elements whereas the foundation surface is assumed to convect to air at constant temperature. Wall footings are mechanically and thermally isolated from the foundation thus acting as partial thermal barriers.

3D Model: Solid, 8-node elements describe the foundation and the soil. Thermal gradients from solar heat flux are well described by this model leadng to an accurate displacement solution for foundation surface nodes at the cost of long run times (iterative solutions are required and execution time scales as system DOFs**2).

Steady-State Problem (Tidal Distortions)

3D Model: Solid, 20-node elements describe the foundation and soil. The slowly time-varying load is described by its initial and final states. The maximum strain rate of the crust is modeled as isotropic thermal expansion leading to 2E-7 strain at the location of the foundation.

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MODEL PARAMETERS

- Monolithic, reinforced-concrete foundation with dimensions of 50m x 50m x 1m.

- Optical lever dimensions of 40m length and 4m base (2x2m).

- Foundation and Soil parameters.

	Foundation	Soil
Elast. modulus:	31E9 Pa	230E6 Pa
Poisson ratio:	0.18	0.37
Mass density:	2.3E3 kg/m3	1.52E3 kg/m3
Therm. cond.	0.93 W/m/k	0.33 W/m/k
Therm. expan.	12.6E-6 /k	12.6E-6 /k
Specific heat	653 J/kg/k	800 J/kg/k

- Facility walls are thermally and vibrationally well isolated from the foundation (wind loading and air conditioning system equipment do not augment the LIGO input vibration spectrum appreciably). Wall footings offer some resistance to heat flow from the soil to the foundation.

- Facility air conditioning system operates continuously.

FINITE ELEMENT MODEL BOUNDARY CONDITIONS

Eigen Value Problem

2D Model: Vertical and Transverse springs fixed at ends in 6 mechanical DOFs

3D Model: Soil elements fixed at bottom in 3 translational DOFs

Propagation Problem

2D Model: Soil at foundation lower surface fixed at ~10 C
Soil elements fixed at bottom in 6 mechanical DOFs

Special Parameters:
Convective film coefficient from foundation to air space, 20 $W/m^2/C$
Convective film coefficient from soil to ambient air, 20 $W/m^2/C$
Thermal conductivity between soil and foundation edge, ~0.1 W/m/C

3D Model: Identical to 2D model excepting soil elements fixed in 3 trans. DOFs

Steady-State Problem

3D Model: Soil elements fixed at bottom in 3 translational DOFs
Soil surface defined to assume 2e-7 isotropic strain

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REFERENCE MATERIALS

Input parameters, analytical treatments, and solution comparisons were afforded by the following sources.

Eigen Value Problem

- Dames and Moore, "Report of Geotechnical Survey , LIGO Project, Hanford, WA," 1993.
- R. V. Whitman and F. E. Richart, "Design Procedures for Dynamically Loaded Foundations," 1967.
- H. B. Seed et al., "Soil Moduli and Damping Factors for Dynamic Response Analyses," 1970.
- K. J. Bathe, "Finite Element Procedures in Engineering Analysis," 1982.

Propagation Problem

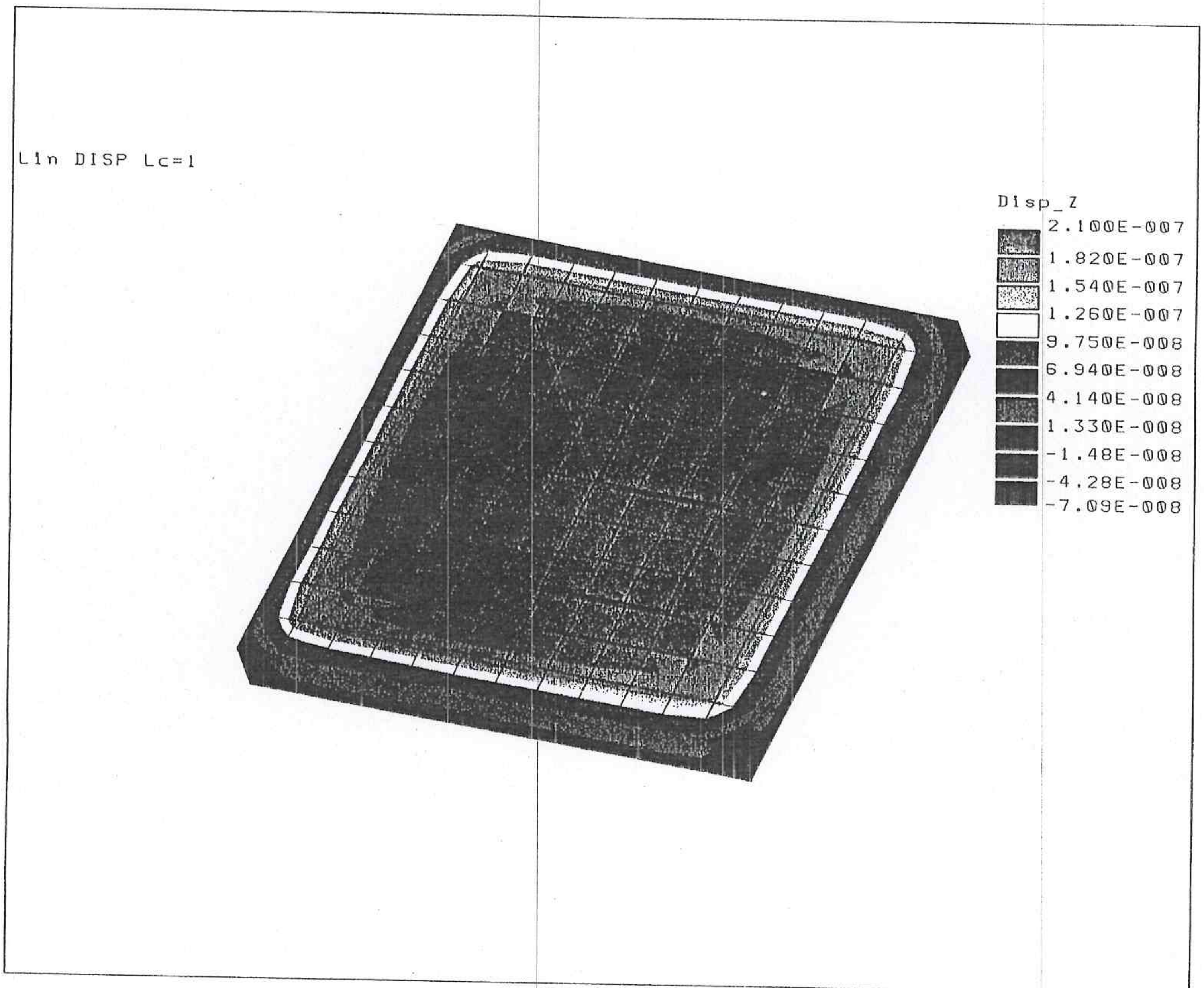
- F. Krieth, "Principles of Heat Transfer," 1967.
- R. V. Dunkle and J. T. Gier, "Selected Spectral Characterisitics of Solar Collectors," Transactions of the Tucson Conference on Applied Solar Energy, 1957.
- R. Weiss, memorandum to W. E. Althouse, memo# THERMAL121788.tex, 1988.
- 1993 ASHRAE Handbook- Fundamentals, SI Edition.
- R. Sugahara et al., "Measurement of the Seismic Motion and the Displacement of the Floor in the TRISTAN Ring," 1993.

Steady-State Problem

- J. Berger and J. Levine, "The Spectrum of the Earth Strain from 10E-8 to 10E-2," 1974.
- J. N. Brune and J. Oliver, "The Seismic Noise of the Earth's Surface," 1967.
- R. Weiss, memorandum to W. E. Althouse, memo# THERMAL121788.tex, 1988.
- V. Braginsky, memoranda to R. Vogt and S. Whitcomb and private communications, 1994.

STEADY-STATE PROBLEM

(Tidal Effects)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1.330E-008
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-7.09E-008

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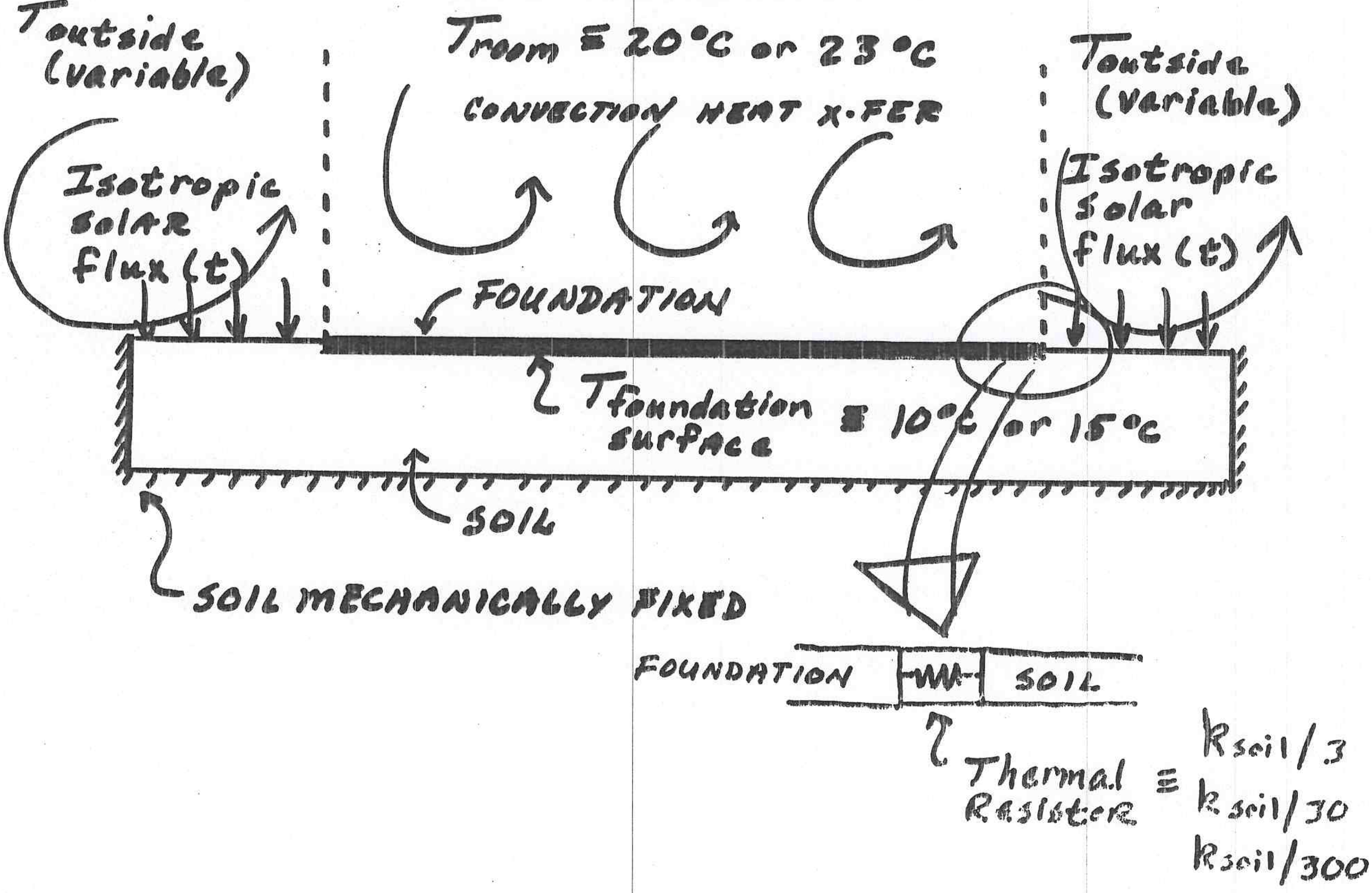
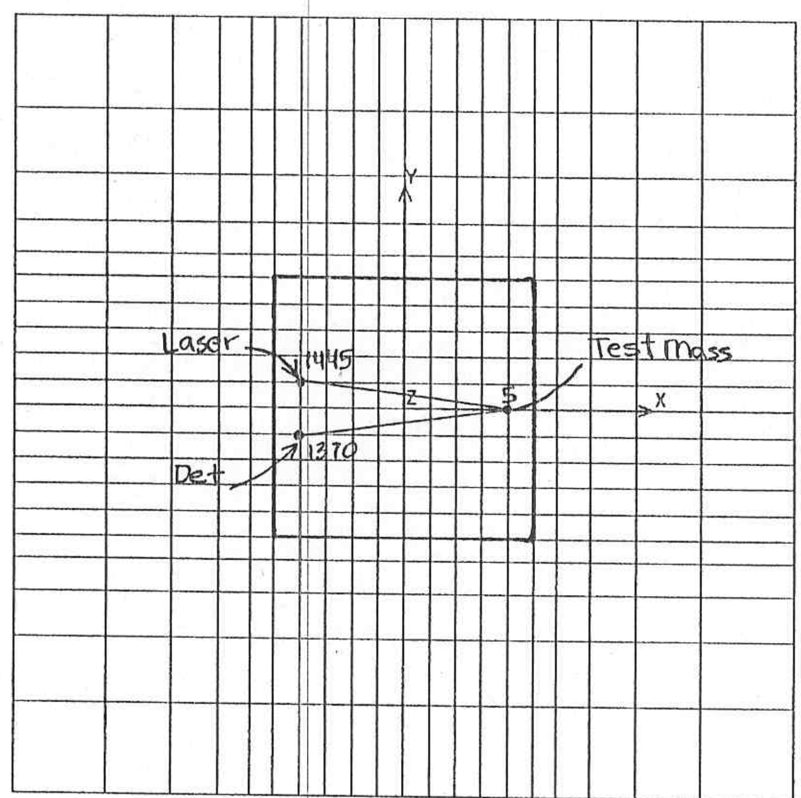
PROPAGATION PROBLEM

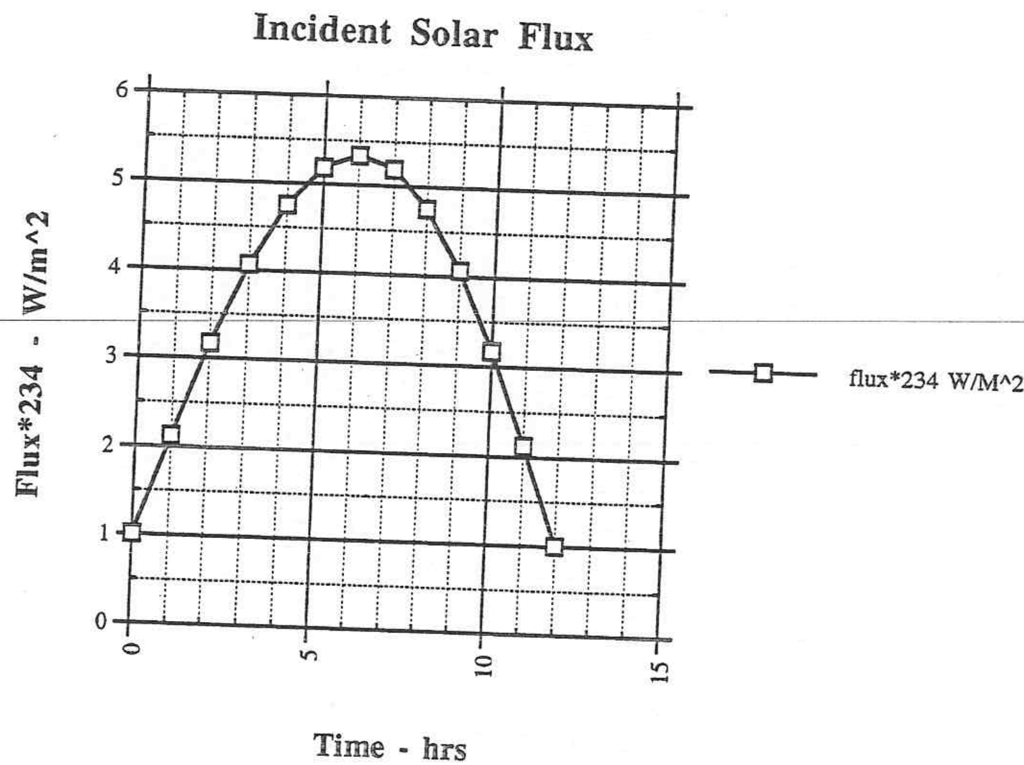
(Solar Heat Transfer)

FINITE ELEMENT MODEL SCHEMATIC





Y
Laser
1445
Z
5
Test Mass
X
1370
Det



Incident Solar Flux
Flux*234 - W/m^2
Time - hrs
flux*234 W/M^2
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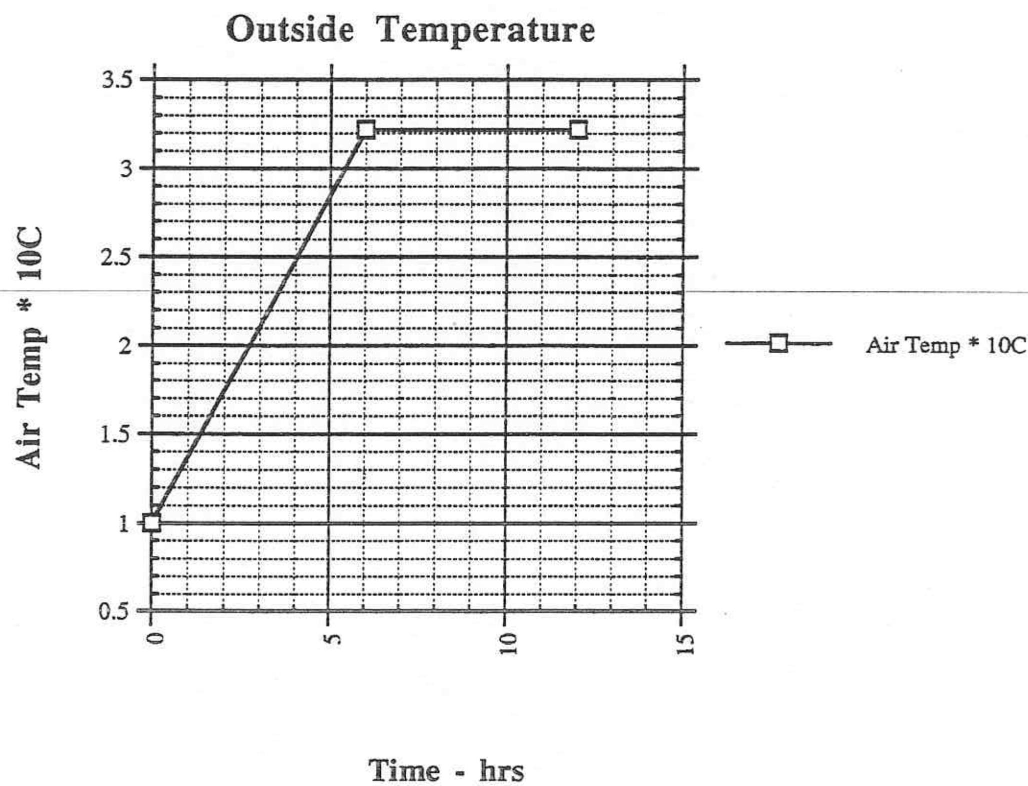
1
2
3
4
5
6
0
5
10
15


Outside Temperature
Air Temp * 10C
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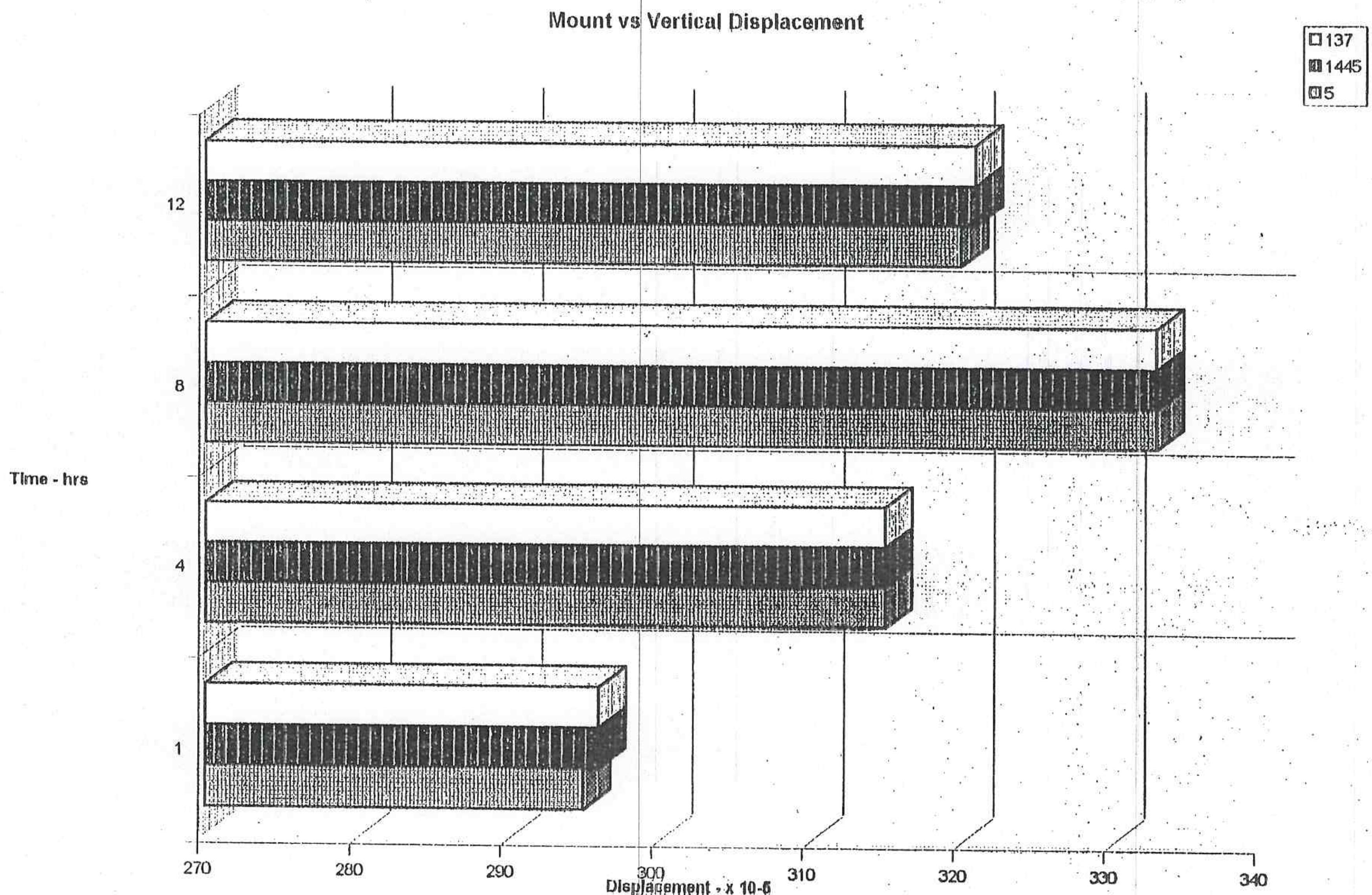
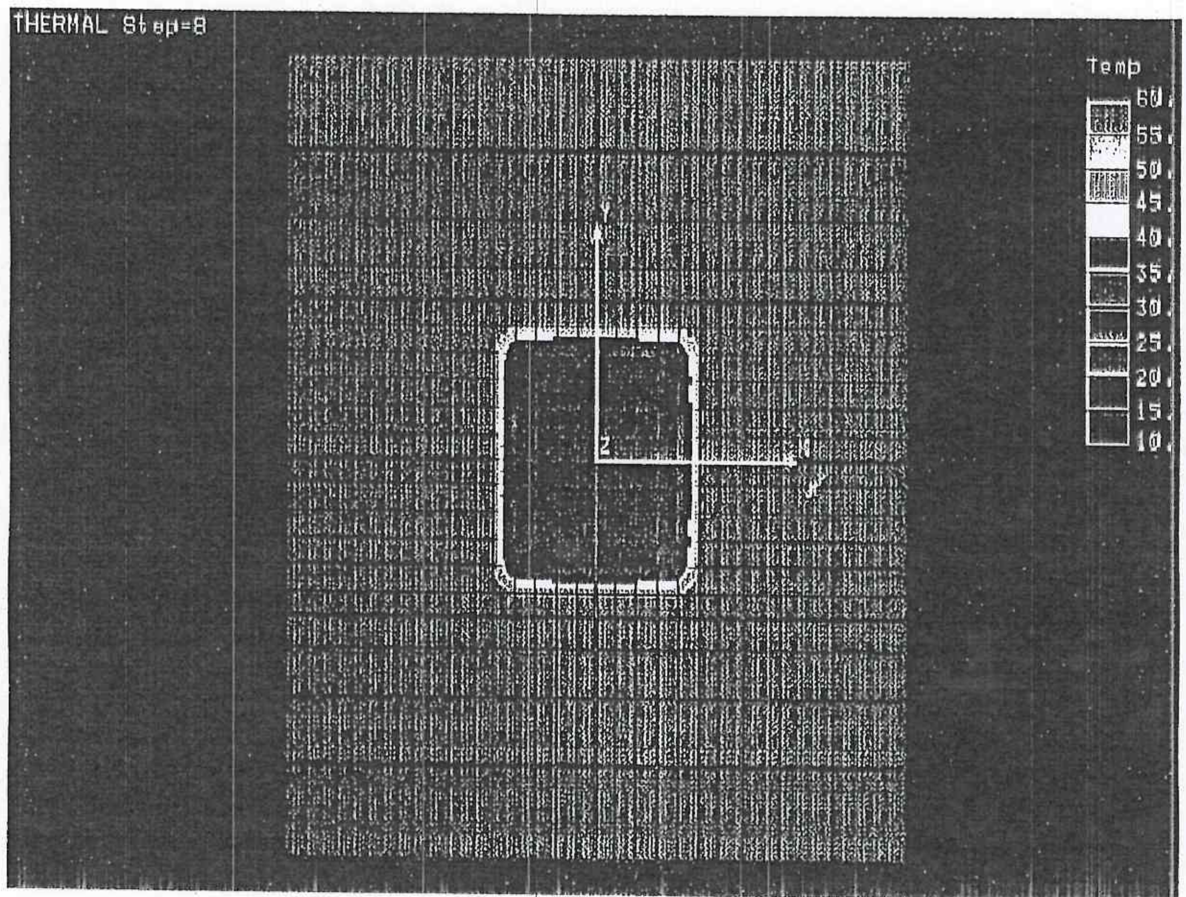
3
2.5
2
1.5
1
0.5
0
5
10
15
Time - hrs
Air Temp * 10C



Mount vs Vertical Displacement
137
1445
5
Time - hrs
12
8
4
1
270
280
290
300
310
320
330
340
Displacement - x 10-6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55.
50.
45.
40.
35.
30.
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20.
15.
10.

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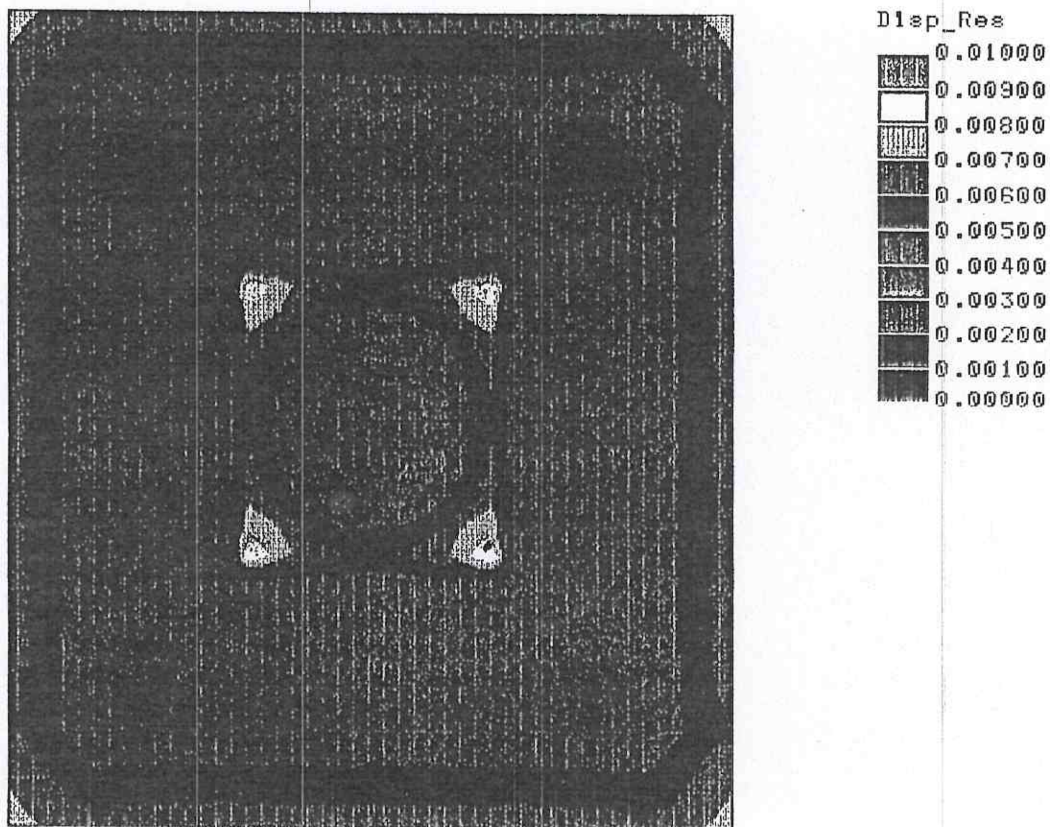
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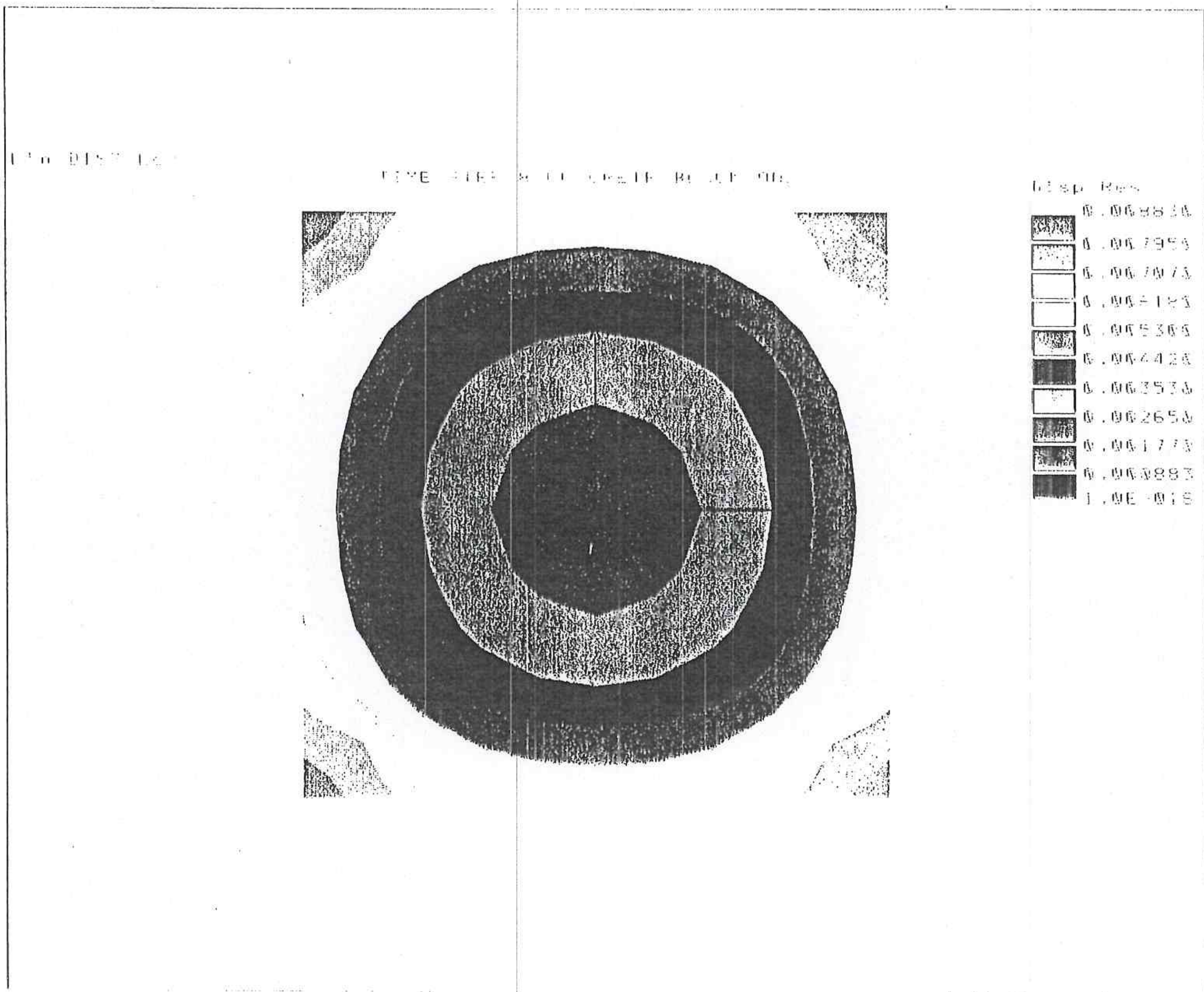
0.00000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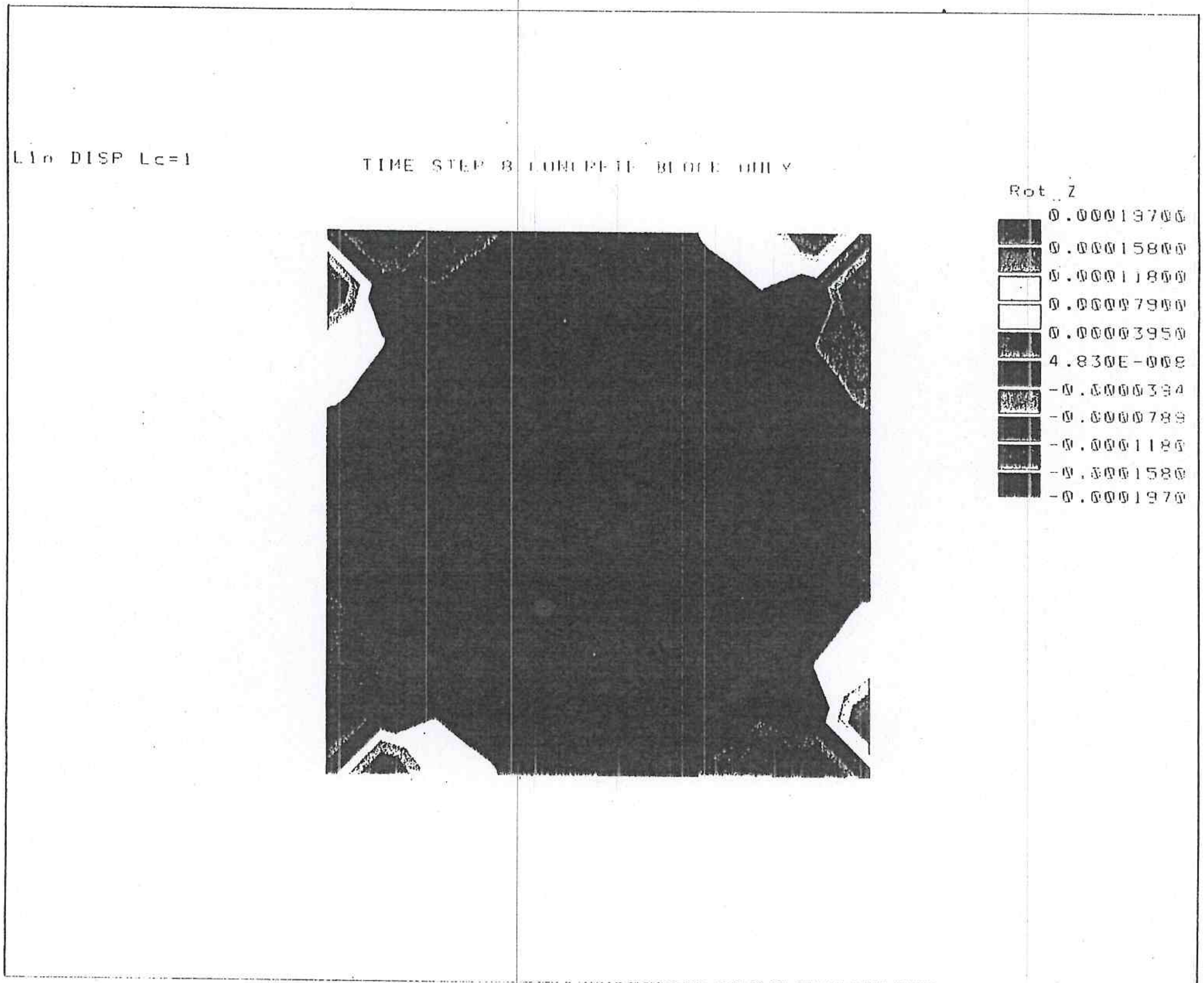
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TIME STEP 8
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-0.0001970

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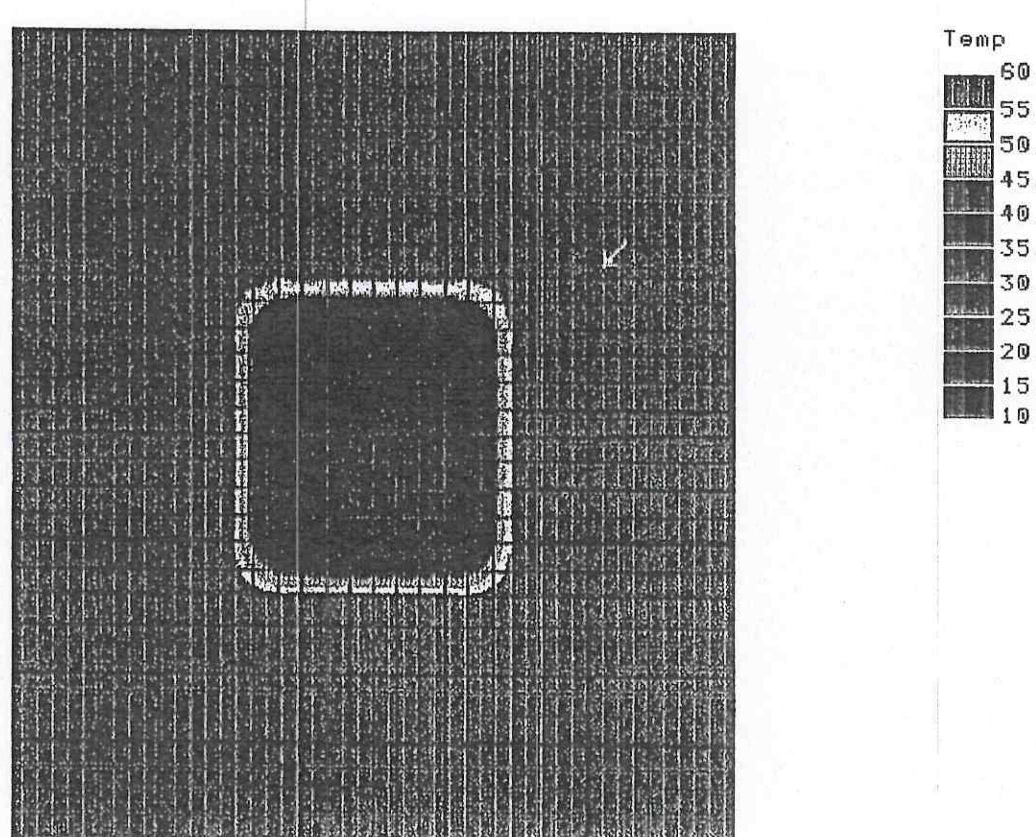


EIGEN VALUE PROBLEM

(Vibration Modes and Frequencies)

INPUT / OUTPUT QUANTITIES

INPUT POWER SPECTRUM

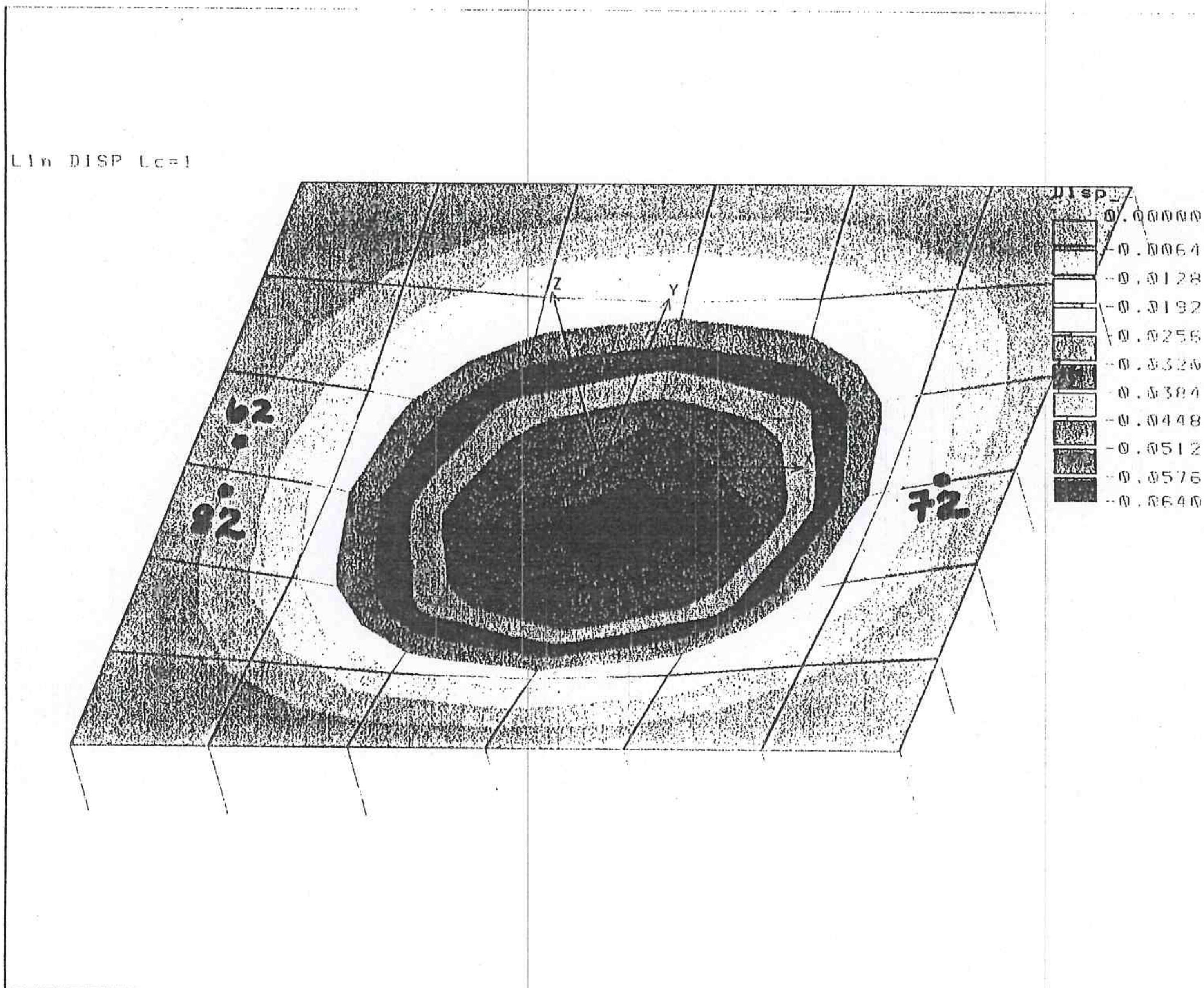
- Hanford site ambient ground spectrum
- Displacement power
- Acceleration power
- Standard power units e.g. [$microns^2/Hz$]

TRANSFER FUNCTION

- ABSOLUTE acceleration frequency response function, H(f)
- Plotted values are $/H(f)/^2$

OUTPUT POWER SPECTRA

- RELATIVE displacement power { $Szz(f) = Syy(f) - Sxx(f)$ }
- Standard units [$microns^2/Hz$]



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-0.0192
-0.0255
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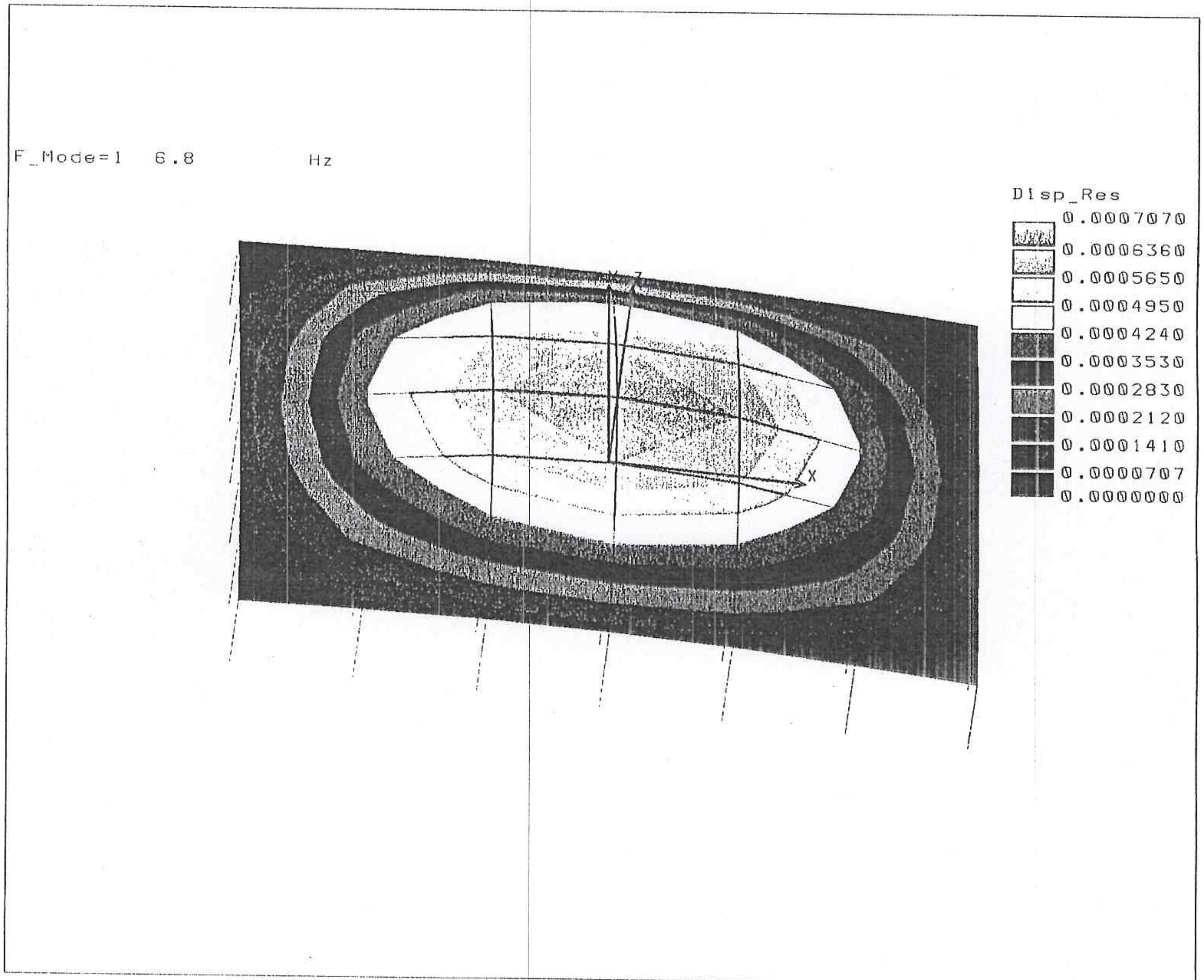
-0.0640
Z
Y
X
62
82
72



F_Mode=1 6.8 Hz
Disp_Res
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0.0006360
0.0005650
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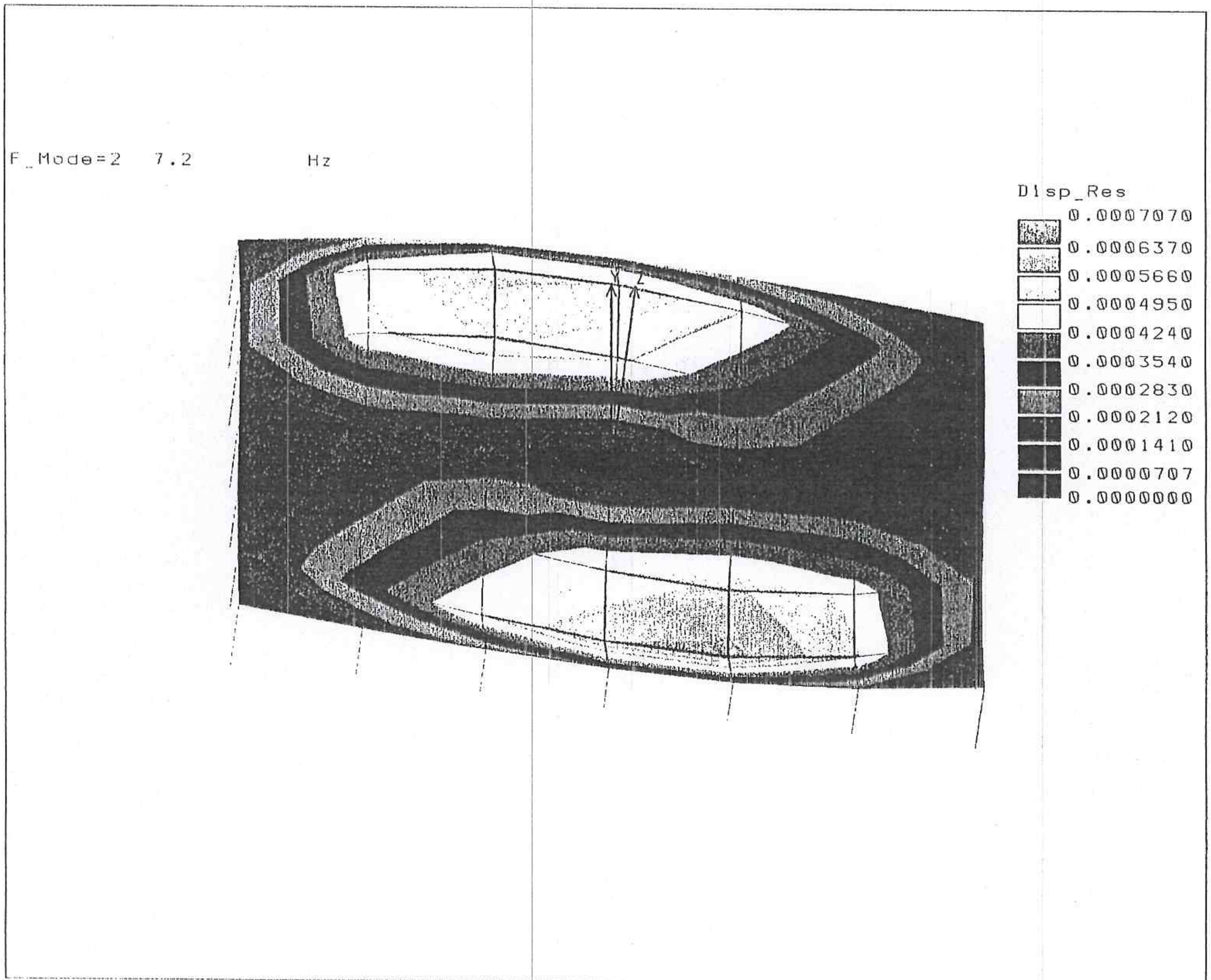
0.0002120
0.0001410
0.0000707
0.0000000
X
Y
Z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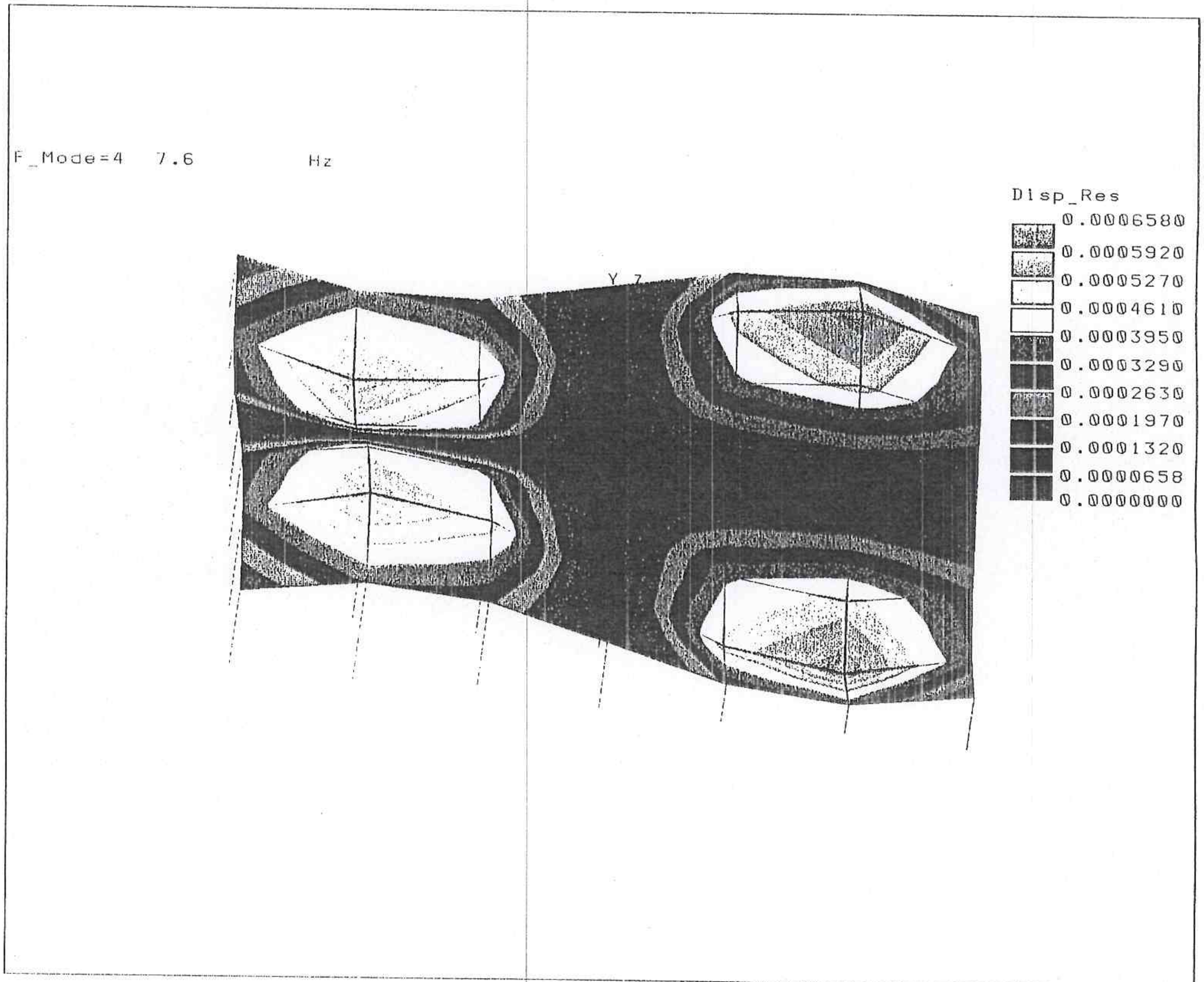
0.0001410
0.0000707
0.0000000
Y
Z



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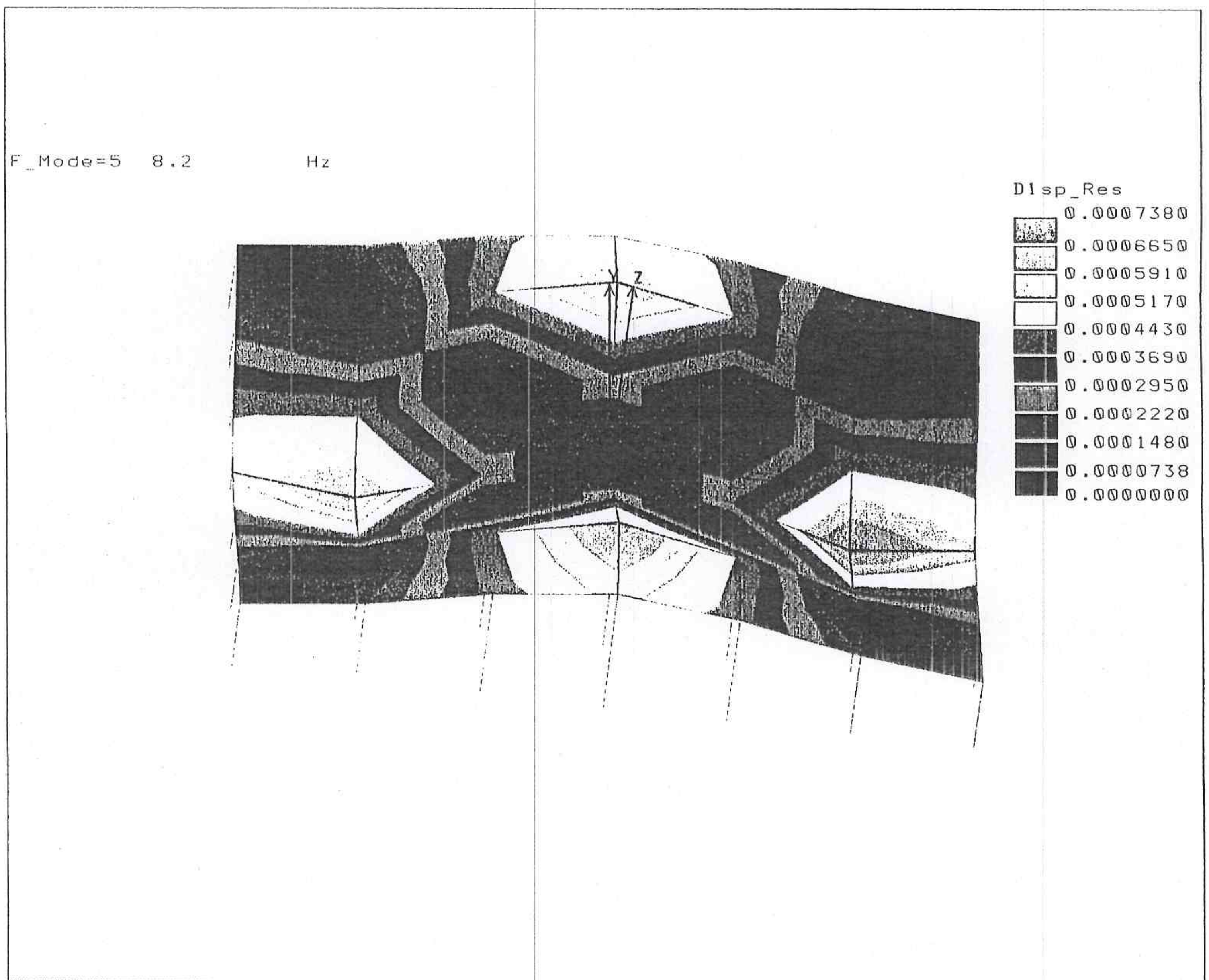

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Disp_Res
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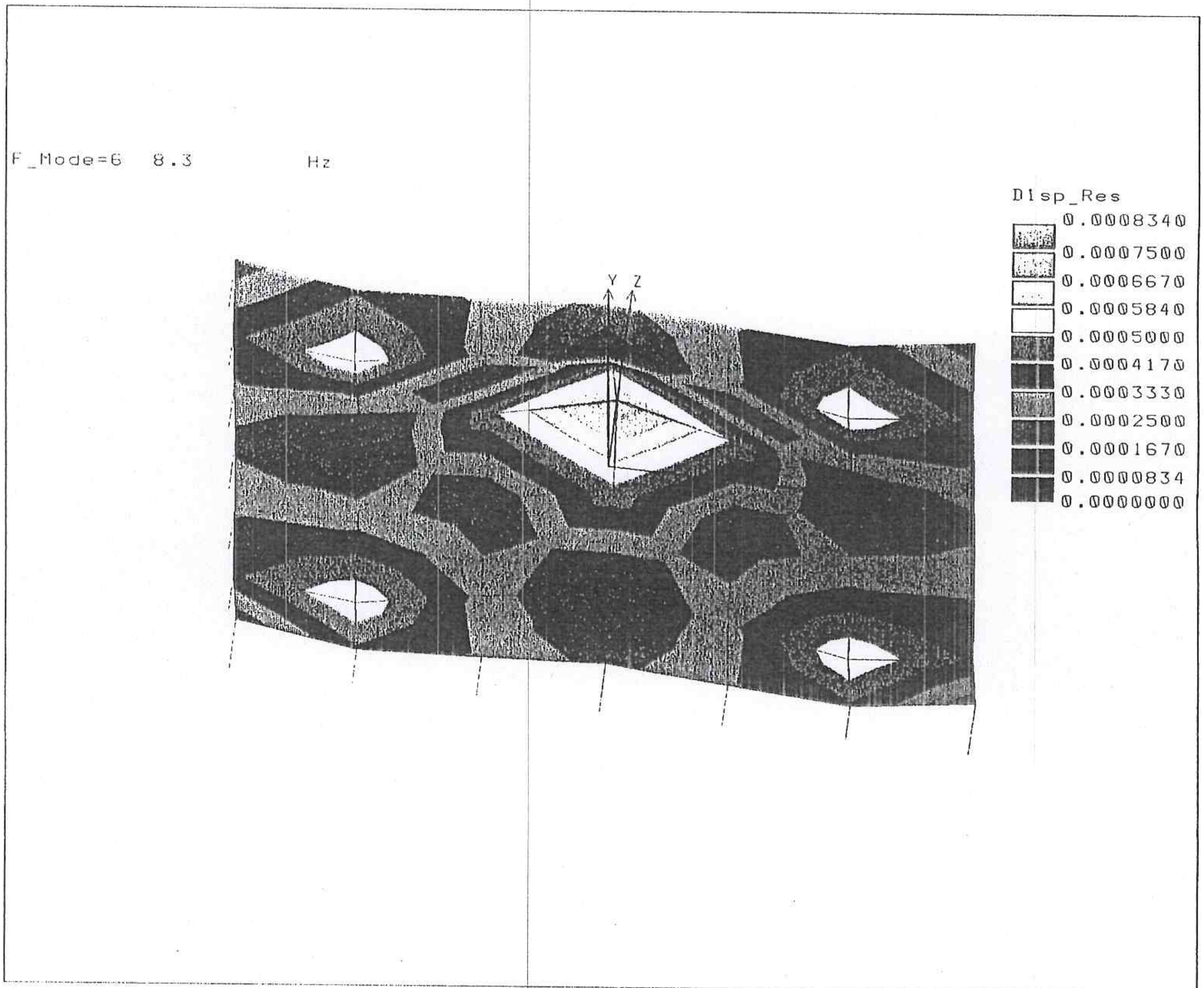
0.0000000
Y
Z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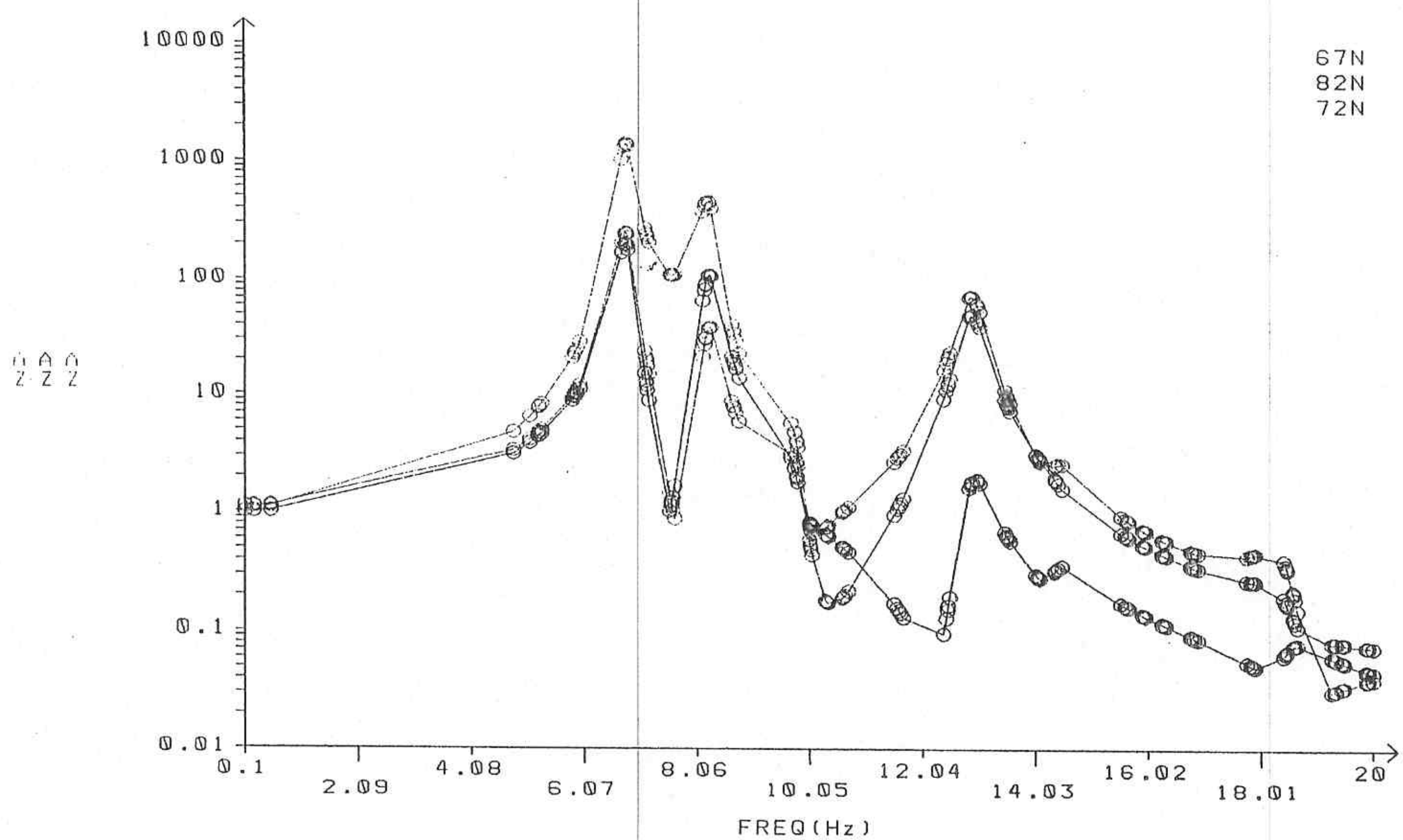
0.0000000
Y
Z



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100
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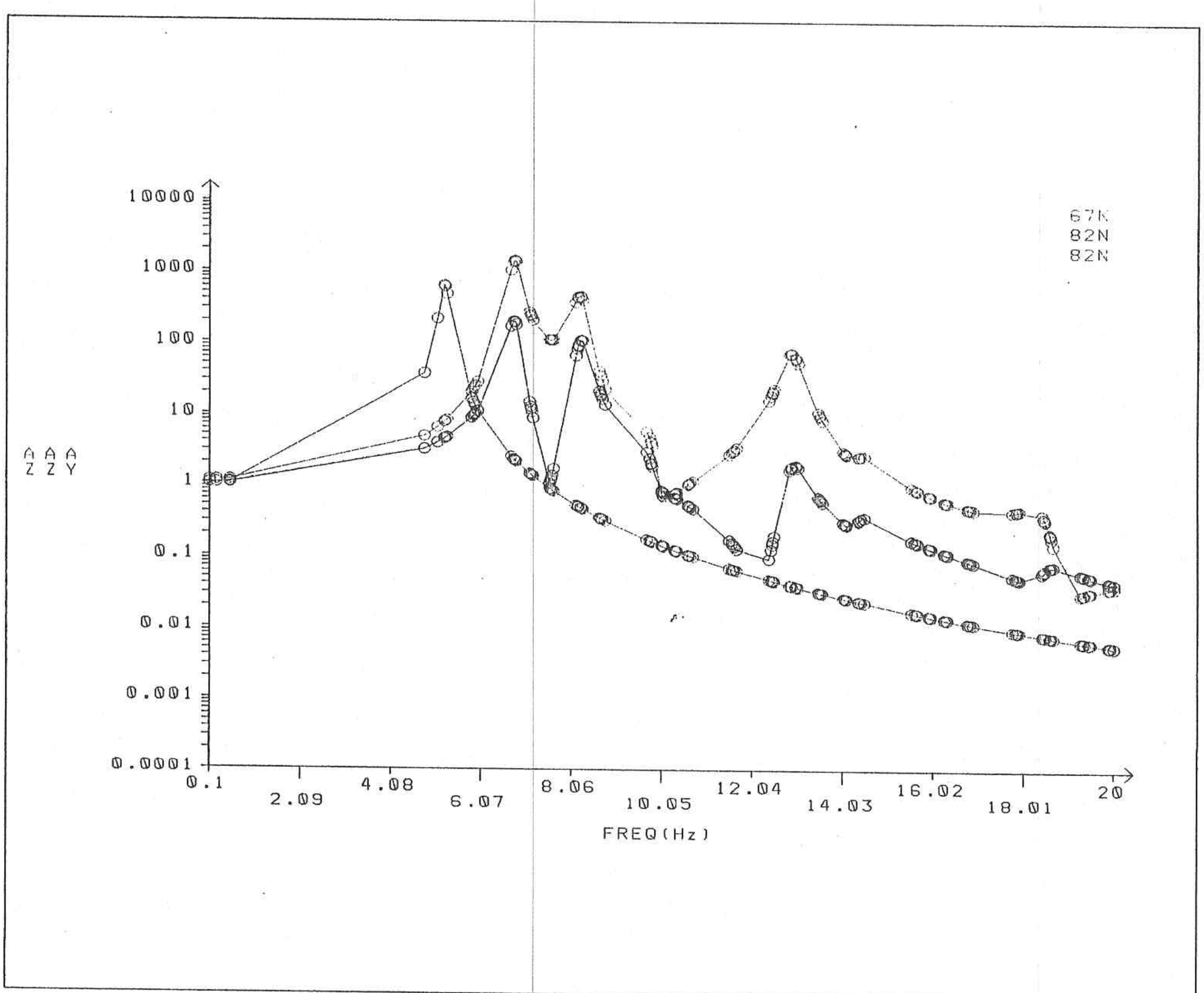
1
0.1
0.01
0.1
2.09
4.08
6.07
8.06
10.05
12.04
14.03
16.02
18.01
20
FREQ(Hz)
67N
82N
72N



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82N
82N
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10
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0.01
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0.0001
A A A
Z Z Y
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6.07
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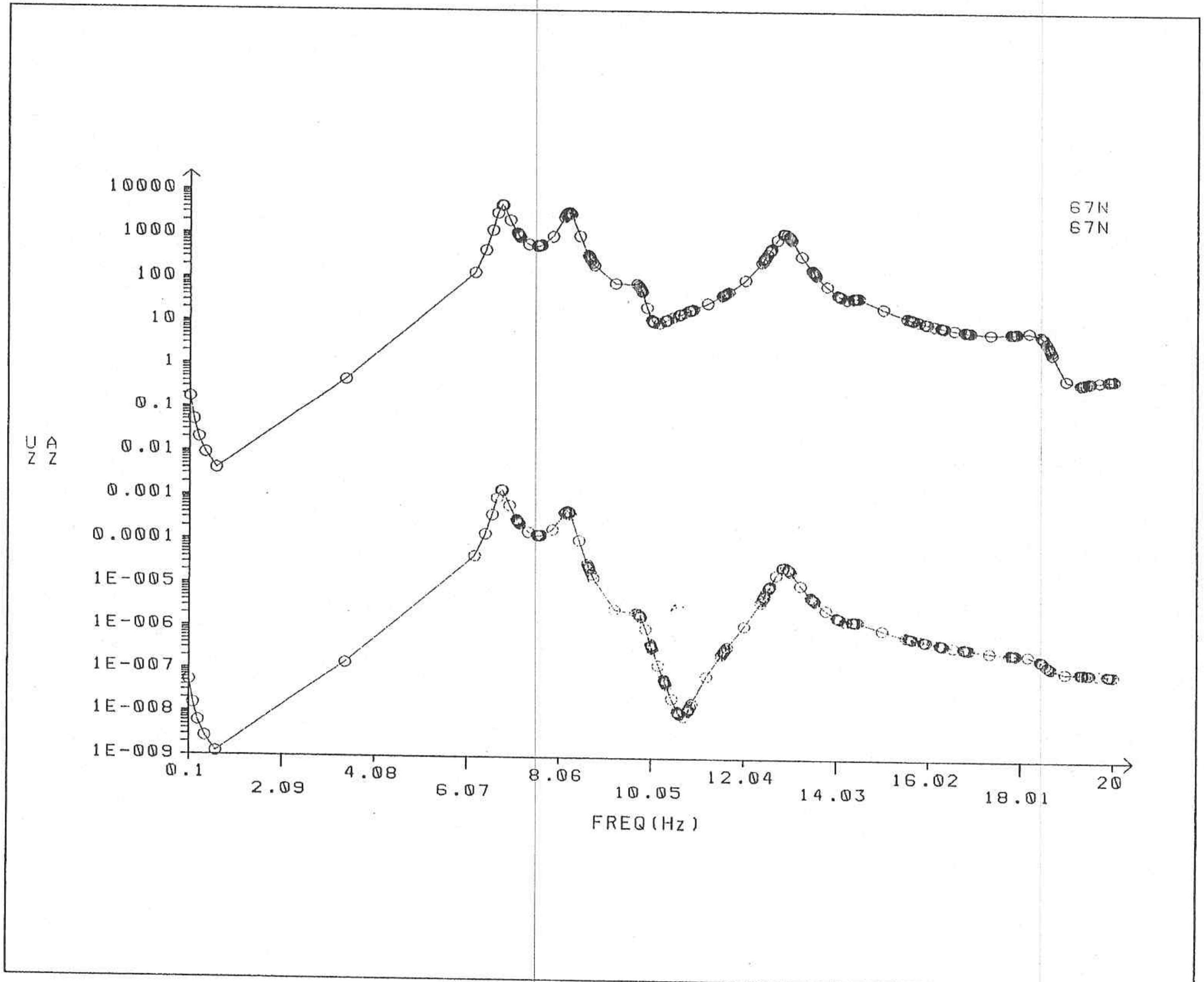
12.04
14.03
16.02
18.01
20
FREQ(Hz)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UA
ZZ
67N
67N
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4.08
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16.02
18.01
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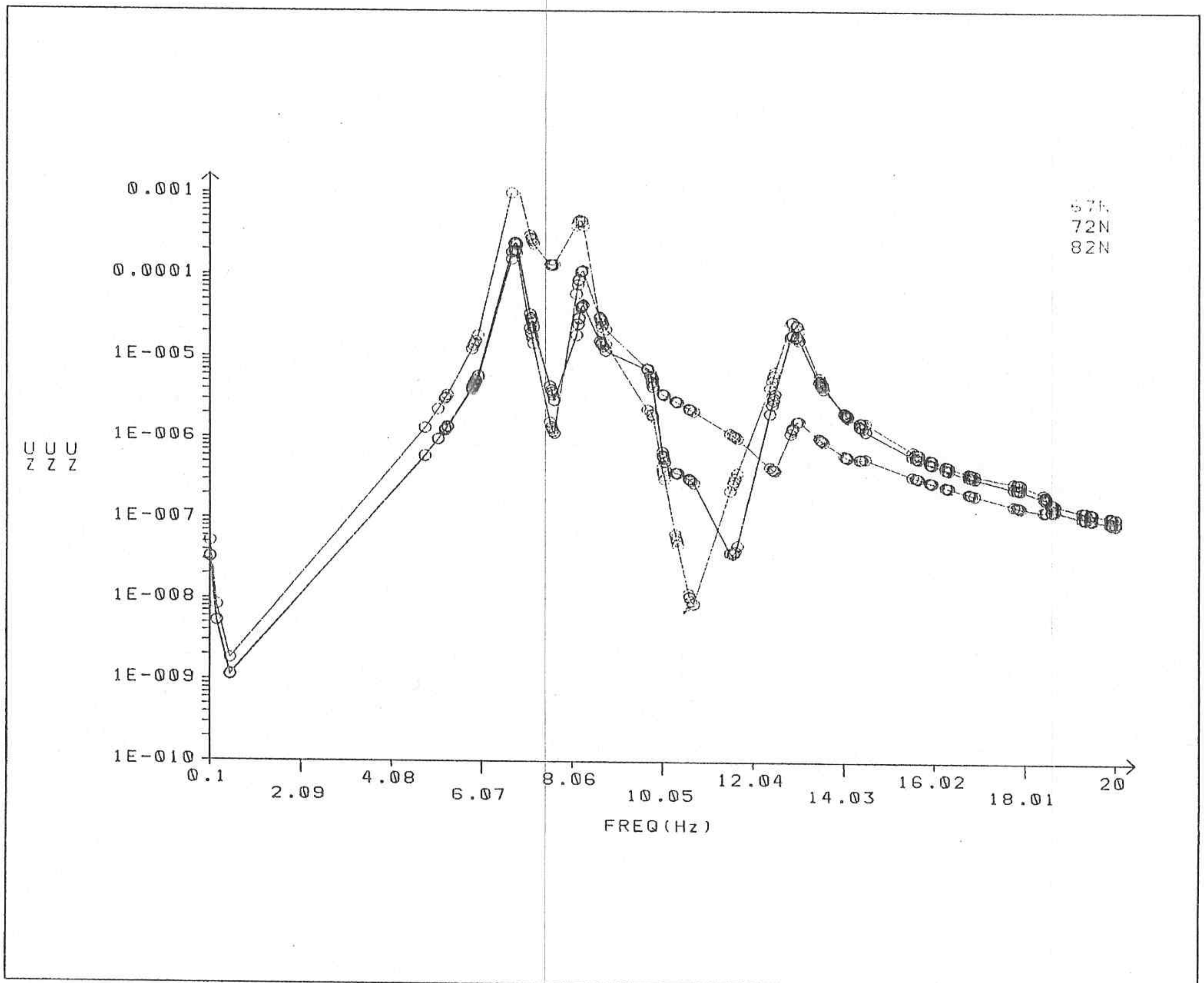
FREQ(Hz)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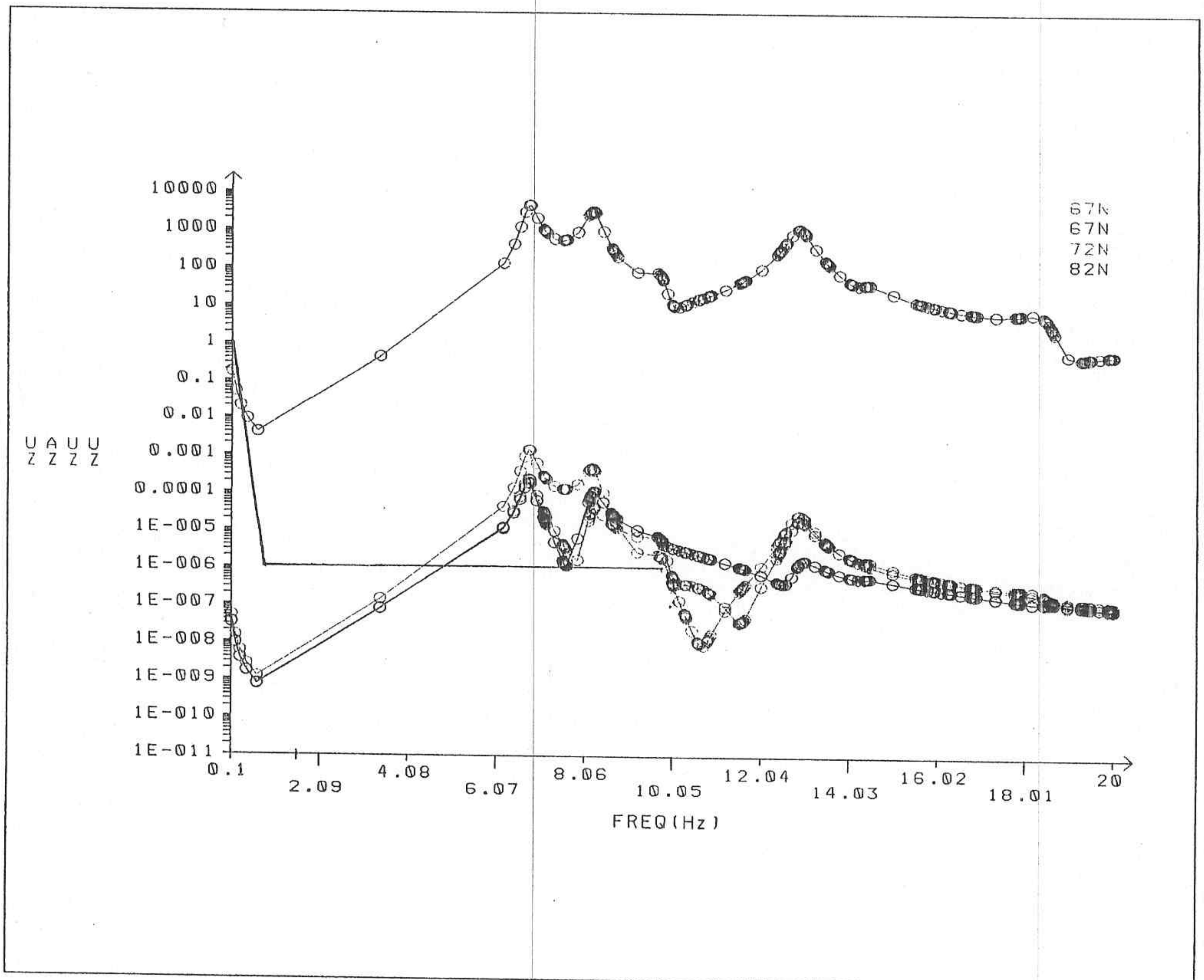
18.01
20
FREQ(Hz)
72N
82N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4.08
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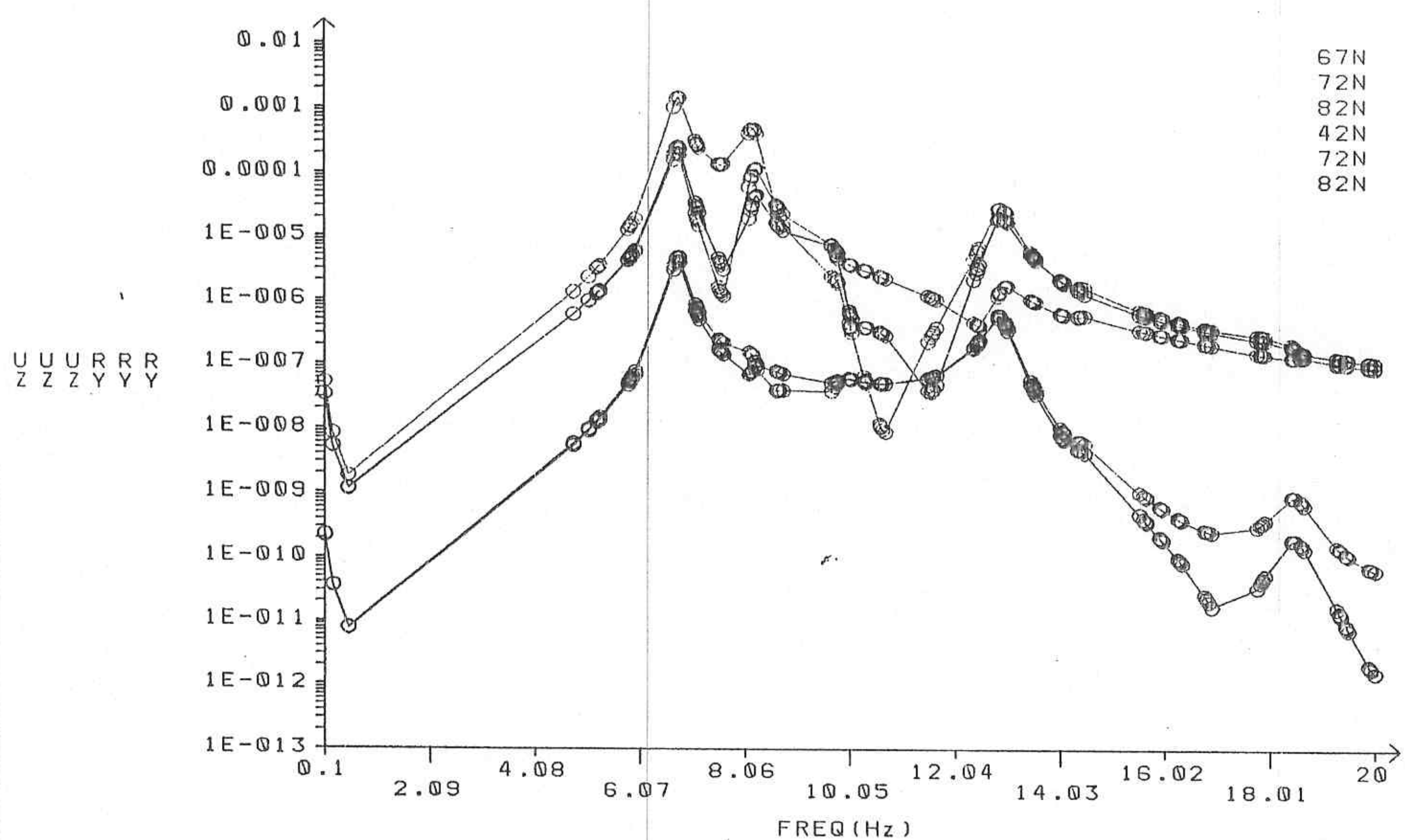
FREQ(Hz)
67N
67N
72N
82N



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2.09
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FREQ(Hz)
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72N
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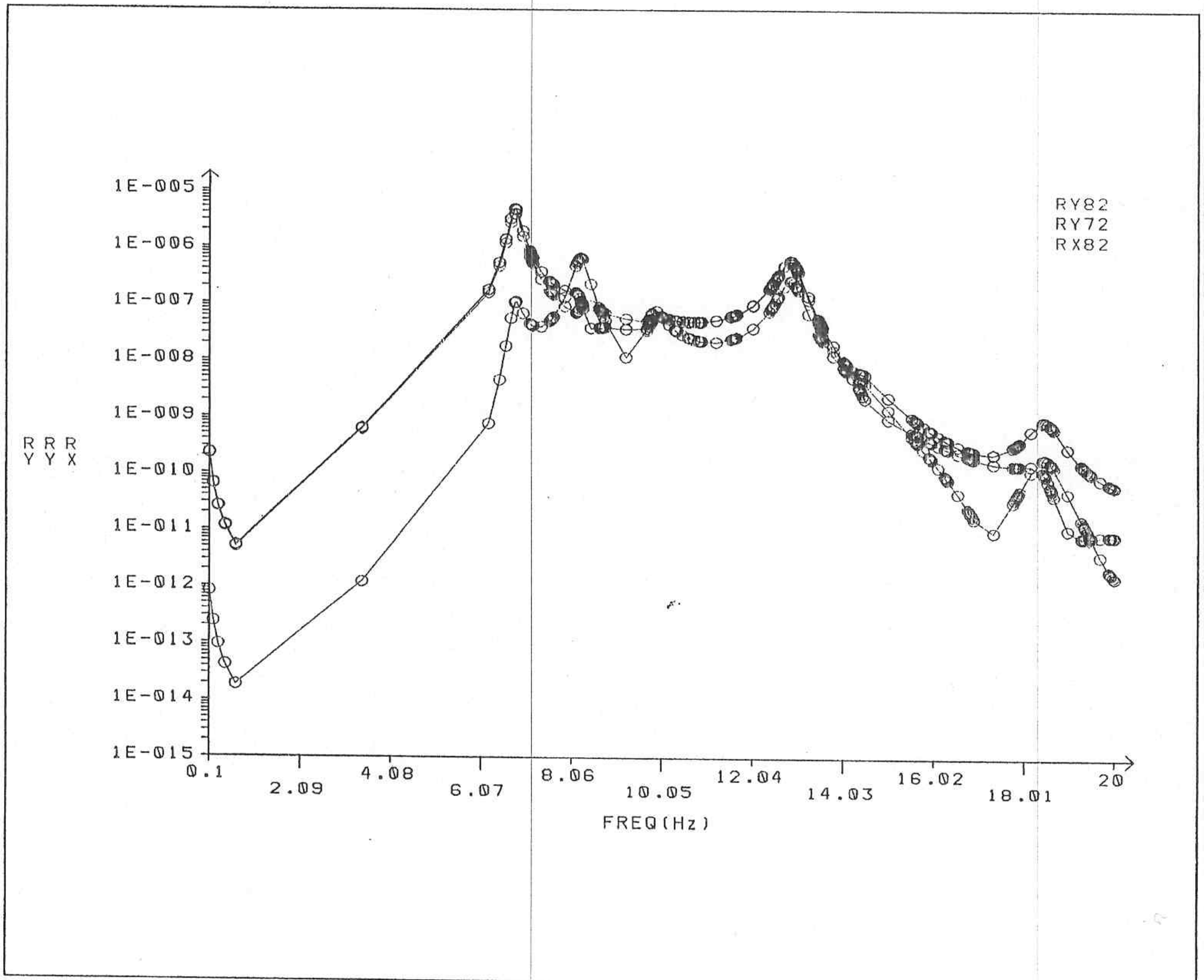
82N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R R R
Y Y X
0.1
2.09
4.08
6.07
8.06
10.05
12.04
14.03
16.02
18.01
20
FREQ(Hz)
RY82
RY72
RX82

RESULTS of FOUNDATION RESPONSE

Eigen Value	Freq.(Hz)	Max Relative Ang. Disp.(rad)	Max Relative Vert. Disp.(m)
2D Model	f1= 6.9	3e-10	3e-9
	f2= 7.3	negligible	negligible
	f4= 7.9	negligible	negligible
	f5= 8.2	8e-10	4e-9
3D Model	f1= 6.6	not calculated	not calculated
	f2= 6.9		
	f4= 7.5		
	f5= 7.9		

Propagation	Max Foundation Surface Temp.(C)		
2D Model	20	7e-6	3e-4 (absol.)
3D Model	25	40e-6	4e-4 (absol.)

Steady-State	Strains(m/m)		
3D Model	2e-7	negligible	negligible

FOUNDATION RESPONSE RESULTS DISCUSSION

- **Tidal forces acting on the earth**, and subsequently on the subject foundation, would not appear to adversely affect the performance of the local optical lever system. The mechanically stiff foundation tends to follow the expansion and contraction of the earth's crust very much as a rigid body, reaching a peak absolutely random heave of a few millimeters at 12 hr intervals.

- **Seismic vibration-induced foundation response** would not appear to adversely affect the performance of the local optical lever system. Neither the low frequency rocking mode nor the highest Q resonance modes (the first two bending modes) result in relative angle changes between the alignment laser, test mass, and quad detector exceeding 1e-8 rad, the working tolerance assumed for this study. The time scale for these responses is the order of 0.1 s. This dynamic affect would be worse were the structure excited by an input spectrum characteristic of an operating facility.

- **Solar heat flux-induced foundation response** would appear to adversely affect the performance of the local optical lever system. This effect is superposed with a near steady-state thermal response of upward bowing, on the order of millimeters, promoted by the thermal gradient between the foundation's upper and lower surfaces. Heat flow from the surrounding soil into the foundation's perimeter induces a temporally varying bowing of the foundation center, inducing OL pointing errors of more than 1e-8 rad within minutes and a total upward deformation of the center on the order of 100s of microns on a time scale of hours. Should excellent thermal isolation of the foundation's edges from their surroundings be realized, the time varying effect would be minimized promoting a thermally stable foundation.

CONCLUSIONS

- The foundation thickness of approximately 1 m, envisioned for LIGO corner and end stations, appears reasonable.

- The inherent stability of this foundation with respect to tidal distortions appears to be adquate to support local optical lever performance on the order of 1e-8 rad.

- The inherent vibratory stability of this foundation apears to be adequate to support local optical lever performance on the order of 1e-8 rad. This result is a very strong function of the optimistic input spectrum assumed to charcterized the operational LIGO facility.

- The inherent thermal stability of this foundation, or an arbitrarily thicker one, appears inadequate to support local optical lever performance on the order of 1e-8 rad for more than minutes. This result is a very strong function of the solar flux-induced heat transfer from the surrounding soil to the foundation edges. Careful facility design and fabrication could most likely minimize this effect leaving only a steady-state offset value associated with the thermal gradient from the foundation's upper and lower surfaces.

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FUTURE WORK

The impact of tidal, thermal, and seismic vibratory inputs on the subject foundation have been addressed to assess the capability of the foundation to support local optical lever performance on the order of 1e-8 rad of pointing accuracy. This analysis was not based upon detailed facility / optical lever design information and hence, is only an order of magnitude study. As detailed designs for these are made available, a much more accurate analysis can be produced.

Further, the response of the foundation to these loadings may have a substantial impact on the performance of the integrated LIGO that is of greater interest than that of the local optical lever, whose primary mission is to assist in intial interferometer lock acquisition.

Recommended future work would include:

- Assessing the effect of foundation rigid body modes on the integrated LIGO performance
- Assessing the impact of the particular facility design and local/global optical lever designs, once they are generated, on the integrated LIGO performance
- Assessing the response of the foundation and facility when subjected to an input spectrum characteristic of an operating facility. Such a spectrum would include information for operational air handling systems, wind loading on the exterior, operational rotating machinery, vehicles operating in the near-field etc.