LIGO Laboratory

☑ California Institute of Technology
MC 18-34, 1200 E. California Blvd.
Pasadena CA 91125 USA
TEL: 617.395.2129
FAX: 617.304.9834
www.ligo.caltech.edu

☐ LIGO Livingston Observatory
P.O. Box 940
Livingston LA 70754 USA
TEL: 225.686.3100
FAX: 225.686.7189
www.ligo-la.caltech.edu

☐ LIGO Hanford Observatory
P.O. Box 159
Richland WA 99352 USA
TEL: 509.372.8106
FAX: 509.372.8137
www.ligo-wa.caltech.edu

☐ Massachusetts Institute of Technology
MIT NW22 – 295, 185 Albany St.
Cambridge MA 02139 USA
TEL: 617.235.4824
FAX: 617.253.7014
www.ligo.mit.edu

Date:	24 March 2009	Refer to:	T0900120-v2
Subject:	Dynamics of the Damper Suspension for the ETM Transmission Telescope/Monitor		
To:	Mike Smith		
From:	Dennis Coyne		

Revision History:
v1 Initial release which simply demonstrates that the ring (upper) stage yaw (torsional) mode has a high frequency. There were 3 errors in v1: (1) the magnet plate mass was only 3 kg, (2) the ring was comprised of a stainless steel tubes, not aluminum as intended and (3) the pendulum length was set to the full TransMon length (optics table to optical axis length of 1742 mm), but should be shorter in order to interface to the top of the main TransMon assembly.
v2 Some preliminary sizing to achieve high frequency modes.

Introduction

A suspended magnet plate serves to eddy current damp the adjacent suspended ETM Telescope and transmitted beam monitor assembly (aka TransMon). Eddy current damping requires a different frequency for the reaction/damping suspension than the main suspension, in order to develop relative velocities between the suspension chains. A recent concept is to effectively half the length of the reaction/damping suspension by using a stiff "wire structure" which is about half the full pendulum length and then a compliant suspension for the magnet plate hanging from this stiff "wire structure". The wire structure was proposed to support a stiff triangular ring with two wires splayed out from each corner of the ring to the optics table.

It is likely that all modes of the magnet plate suspension must either be < ~10 Hz or > 150 Hz, in order to stay sufficiently below or above the upper unity gain frequency of the BSC ISI control. It is possible that modal frequencies in the range of 10 to 150 Hz could be acceptable if the associated modal mass is low and/or the interaction of the mode with the compliance of the BSC optics table is slight; This aspect is not discussed in this memo.

The intent of this memo is to roughly determine the parameters of a magnet plate suspension which meets (or comes close to) the desired dynamics.

Suspension Geometry and Properties

The payload for the ETM Transmission Telescope and monitor (aka "TransMon") is depicted in Figure 1. The optics bench is approximately 1.05 m by 0.6 m (from the Zemax file, D0900446-v2). The depth of the off-axis, parabolic reflective telescope is 0.3 m. (also from

D0900446-v2). The distance from the optics table to the center of the ETM is 1742 mm and to the center of the aperture of the large telescope[1] is ~1742 mm.
The TransMon is suspended from the BSC optics table with a single pendulum suspension. The intent is to passively damp this suspension with another suspension which supports a plate with a set of magnets (no concept sketches were found in the DCC).

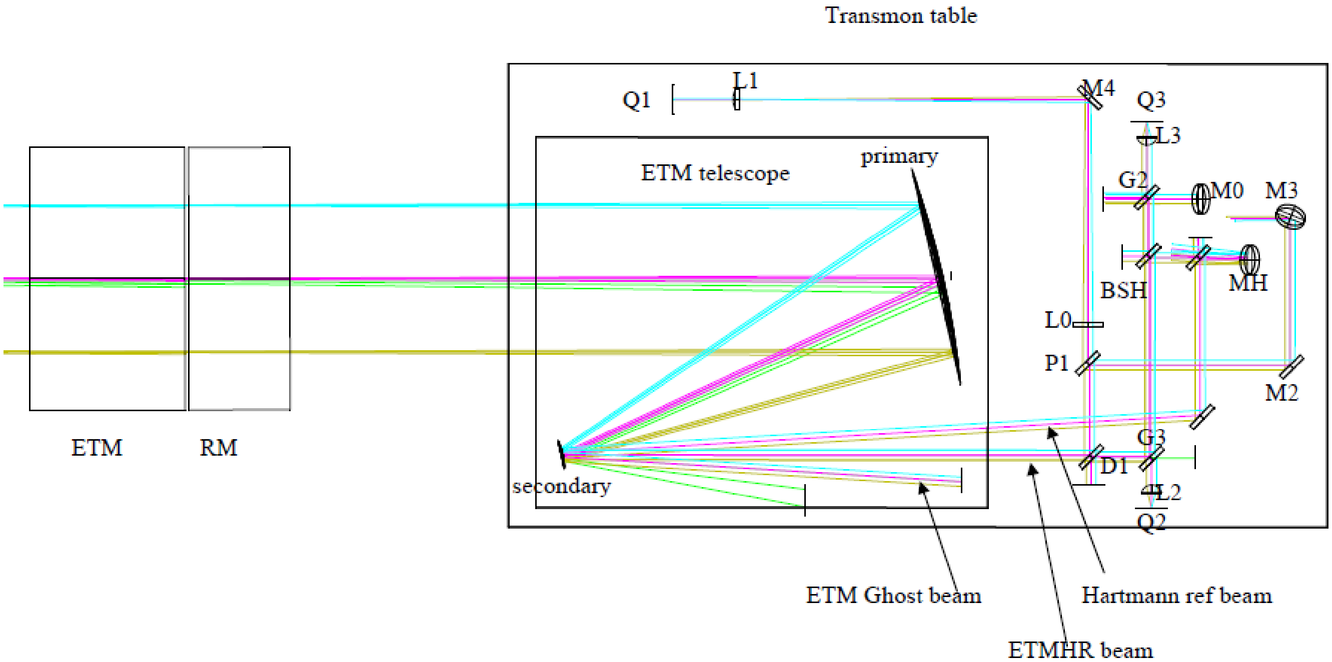


Figure 1: Transmon Table, Zemax Layout (2008-12-04 email from M. Smith, "ETM Transmon") [approximately consistent with zemax file D0900446-v2]

I choose to represent the reaction/damper suspension in ANSYS with:

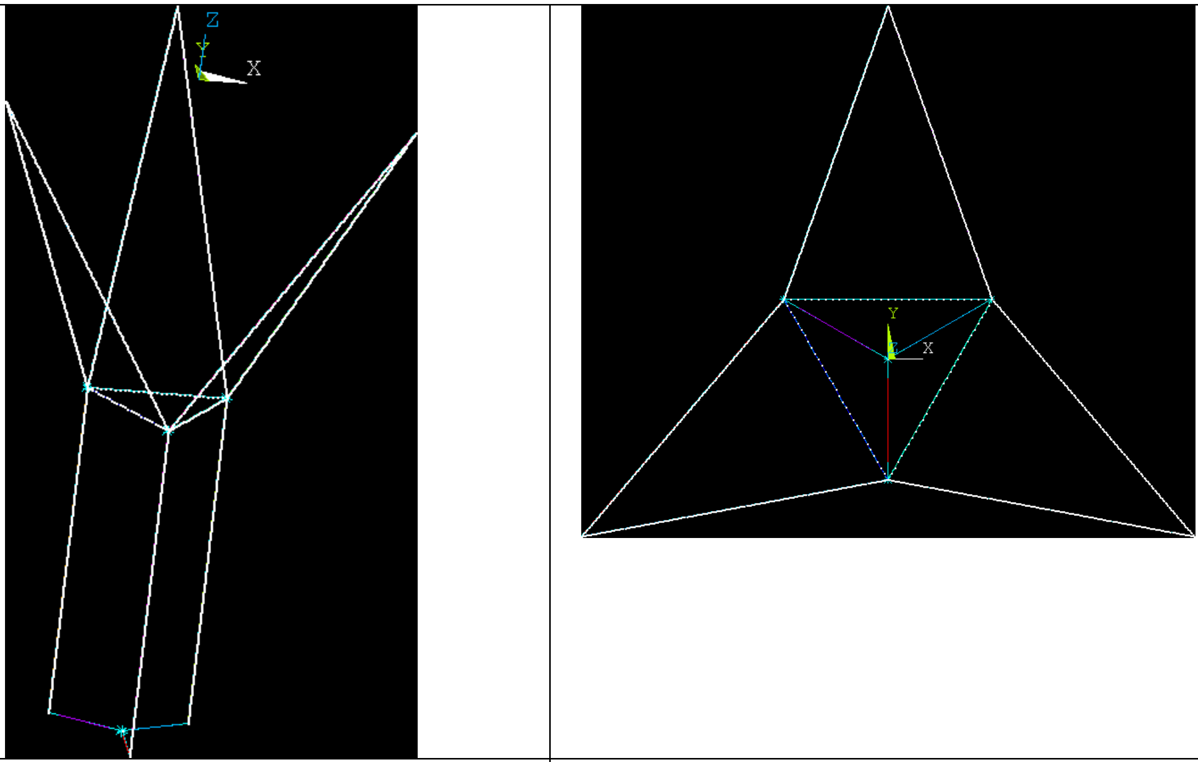
- an aluminum ring in the form of an equilateral triangle with a circumscribed radius of ~0.25 m. Each bar in the ring has an outer radius of ~15 mm and an inner radius of ~13 mm (hollow circular bar with ~2 mm wall thickness). The resulting mass is ~1.2 kg for the 3 bars total. (These are nominal ring dimensions – the dimensions were varied.)
- 0.1 to 1 kg mass was added at each of the 3 vertices of the ring to represent wire clamps & tube conections
- Two steel wires with ~1.5 mm radius support each of the 3 ring vertices. The wires connect to points on the optics table that are also the vertices of an equilateral triangle circumscribed by a radius of 0.5 m, but rotated 30 degrees from the ring.
- The ring was set to a distance of half (1742 -300) mm, or 721 mm, below the optics table
- At each of the three vertices of the ring, a vertical wire extends down to 1442 mm (the full magnet plate pendulum length). These vertical wires also have ~1.5 mm radius.
- The payload (the magnet plate) was represented as a point mass of 10 kg connected by rigid links (constraint equations) to the ends of the vertical wires. In order to

[1] Note that T060360-01, AOS: PO Mirror Assembly & Telescope, and OMMT Conceptual Design Requirements, is obsolete. The telescope is no longer refractive, the aperture is larger, the mass is likely much greater than 9.5 kg, and the ETM wedge angle is smaller (0.8 deg), so the distance is no longer 1744 mm.

effectively damp the main suspension, the magnet plate mass must be ~1/3 of the main suspension mass, which is guessed to be ~30 kg.

- The wires and ring were meshed as beam elements.

A depiction of the geometry is shown in Figure 2.



Isometric view	Top view

Figure 2: Simple ANSYS beam model of the reaction/damper suspension for the TransMon

The ANSYS script that generates the model and solves for the mode shapes and frequencies is listed in the appendix.

Frequencies

The modal frequencies were determined as some of the key parameters of the suspension were varied. The "nominal" case was for the ring circumscribed radius to be the same as the radius that circumscribes the points of attachment at the optics table, 0.25 m (i.e. vertical upper stage wires). The modal frequencies are listed in Table 1. The ring radius was then varied to determine an approximate optimum. At 0.17 m, the pendulum modes of the ring are greater than 150 Hz, but the upper wire violin modes decreased to 130 Hz. Note that due to highly coupled nature of the modes (it seems), the modal frequency variation is not very uniform (or perhaps the FEA is incorrect?).

Using a ring circumscribed radius of 0.17 m (with the optics table attachment point circumscribed radius still 0.25 m), the ring added vertex mass and wire radii were varied. For a ring added vertex mass of only 0.1 kg (unreasonable?), upper wire radii of 1.7 mm and lower radii of 1.3 mm, the frequencies (just barely) meet the stated frequency exclusion zone.

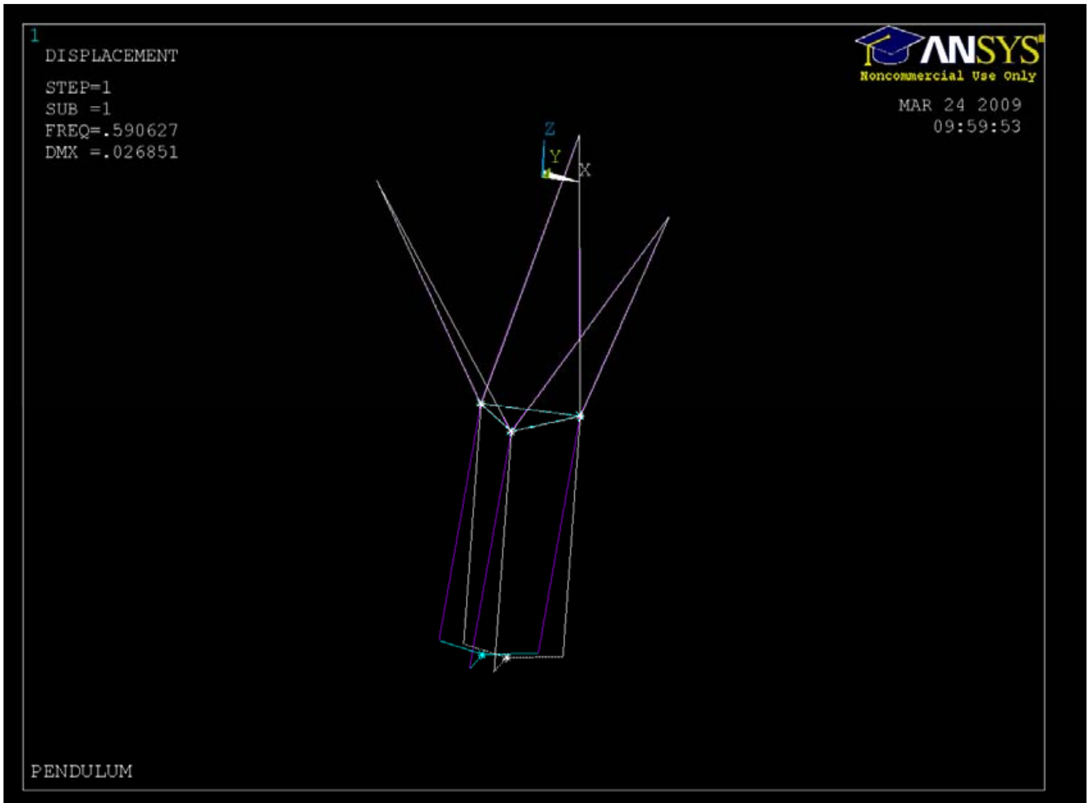
Note that the magnet plate roll & pitch frequencies can be lowered by making the circumscribed radius of the attachment points at the magnet plate smaller (while keeping the lower stage wires vertical). Note also that lower stage pitch mode is not modeled (no moments of inertia set for the magnet plate mass, or pitch offset distance for the wire attachment). Note also that there are a number of frequencies below 150 Hz in this particular design.

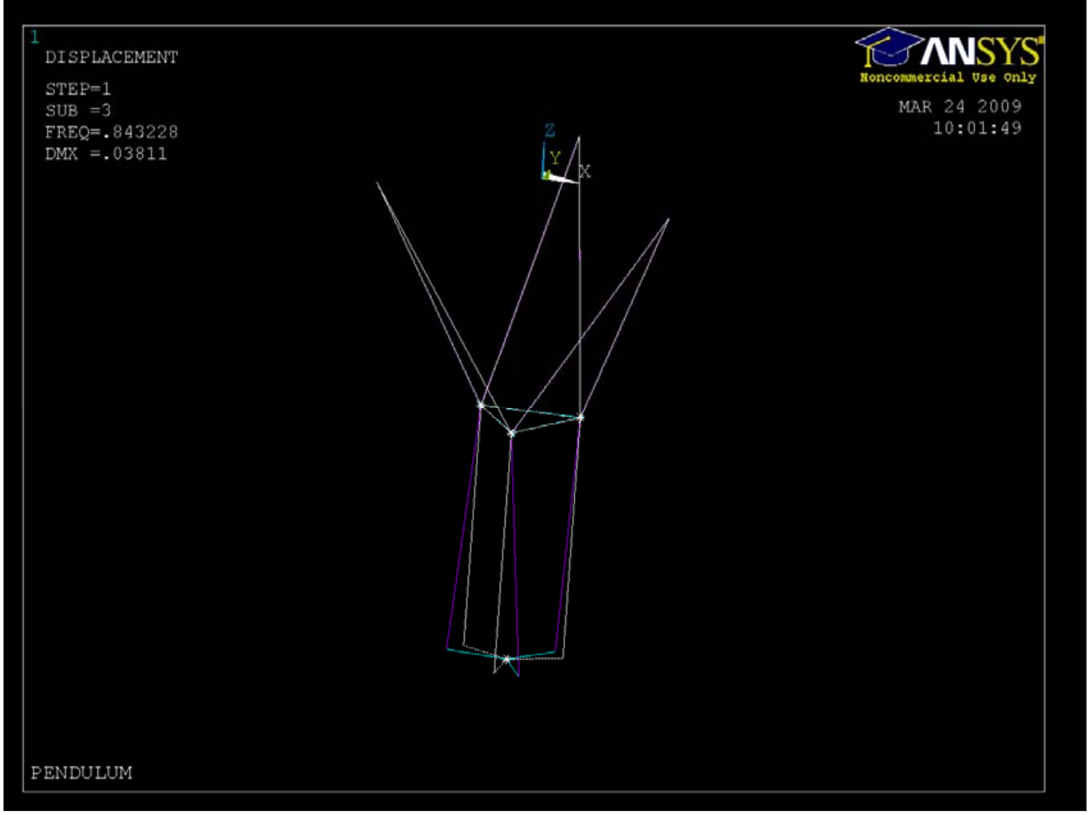
					(nominal)		
	ring circumscribed radius (m), r2 =	0.15	0.17	0.2	0.25	0.3	0.35
Mode No. (nominal)	**mode**	**freq (Hz)**	**freq (Hz)**	**freq (Hz)**	**freq (Hz)**	**freq (Hz)**	**freq (Hz)**
1, 2	magnet plate pendulum	0.6	0.6	0.6	0.6	0.6	0.6
3	magnet plate yaw	0.8	0.8	0.8	0.8	0.8	0.8
4	vertical bounce	8.2	7.7	7.1	6.4	5.8	5.4
5, 6	magnet plate pitch, roll	11.5	10.9	10.1	9.1	8.2	7.5
7, 8	ring pendulum	156	157	135	136	133	128
9 thru 20	upper wire 1st violin (161 - 170)	124	130	146	161	174	191
21	ring yaw	233	236	212	218	218	218
22 thru 27	lower wire 1st violin (249 - 258)	191	201	224	249	272	290
28 thru 39	upper wire 2nd violin (328 - 331)				328		384
40	ring common mode 1st bending				349	266	203
41, 42	ring differential mode 1st bending				439		260
43 thru 54	upper wire 3rd violin				496		

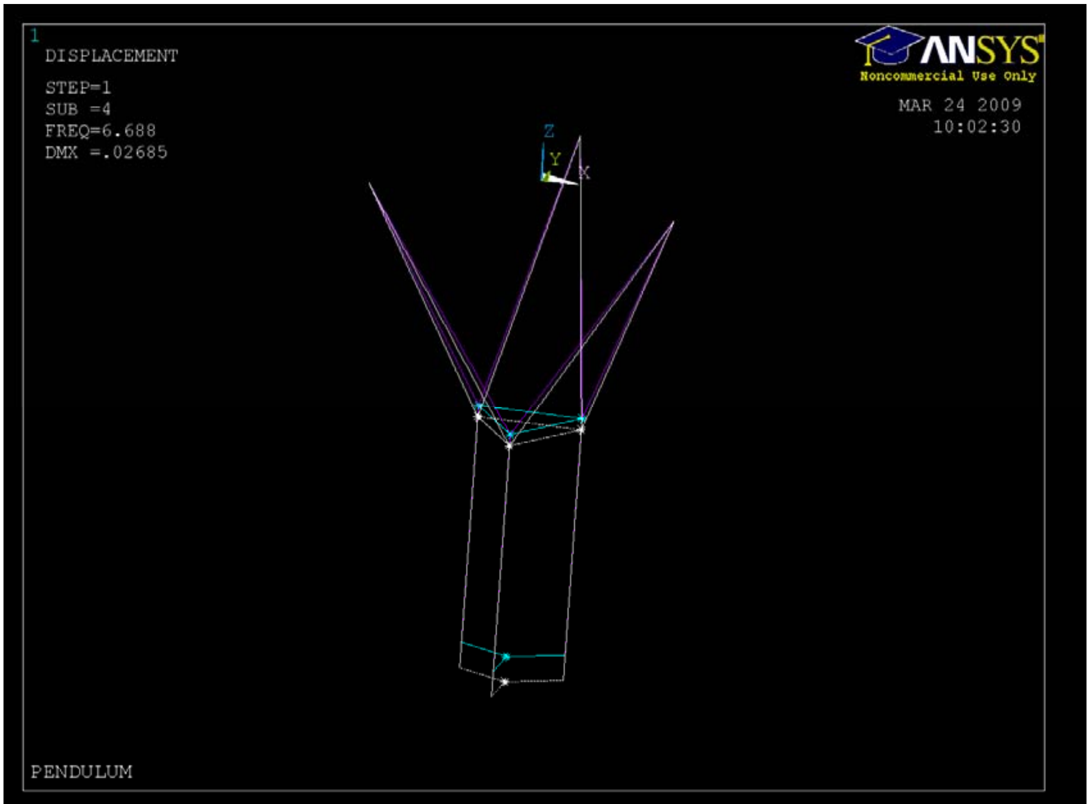
	ring vertex added mass (kg), m1 =	1	1	1	1	0.1	0.1
	ring circumscribed radius (m), r2 =	0.17	0.17	0.17	0.17	0.17	0.17
	upper stage wire radius (m), rw1 =	0.001	0.0015	0.0017	0.0017	0.0017	0.0016
	lower stage wire radius (m), rw2 =	0.001	0.0015	0.0017	0.0013	0.0013	0.0013
Mode No. (nominal)	**mode**	**freq (Hz)**	**freq (Hz)**	**freq (Hz)**	**freq (Hz)**	**freq (Hz)**	**freq (Hz)**
1, 2	magnet plate pendulum	0.6	0.6	0.6	0.6	0.6	0.6
3	magnet plate yaw	0.8	0.8	0.8	0.8	0.8	0.8
4	vertical bounce	5.1	7.7	8.7	6.7	6.7	6.7
5, 6	magnet plate pitch, roll	7.3	10.9	12.4	9.5	9.5	9.5
7, 8	ring pendulum	103	157	166	128	207	207
9 thru 20	upper wire 1st violin (161 - 170)	199	130	119	152	150	150
21	ring yaw	154	236	269	200	385	
22 thru 27	lower wire 1st violin (249 - 258)	304	201	183	237	233	
28 thru 39	upper wire 2nd violin (328 - 331)			240		306	
40	ring common mode 1st bending						
41, 42	ring differential mode 1st bending						
43 thru 54	upper wire 3rd violin						
	ring vertical bounce	313		166			

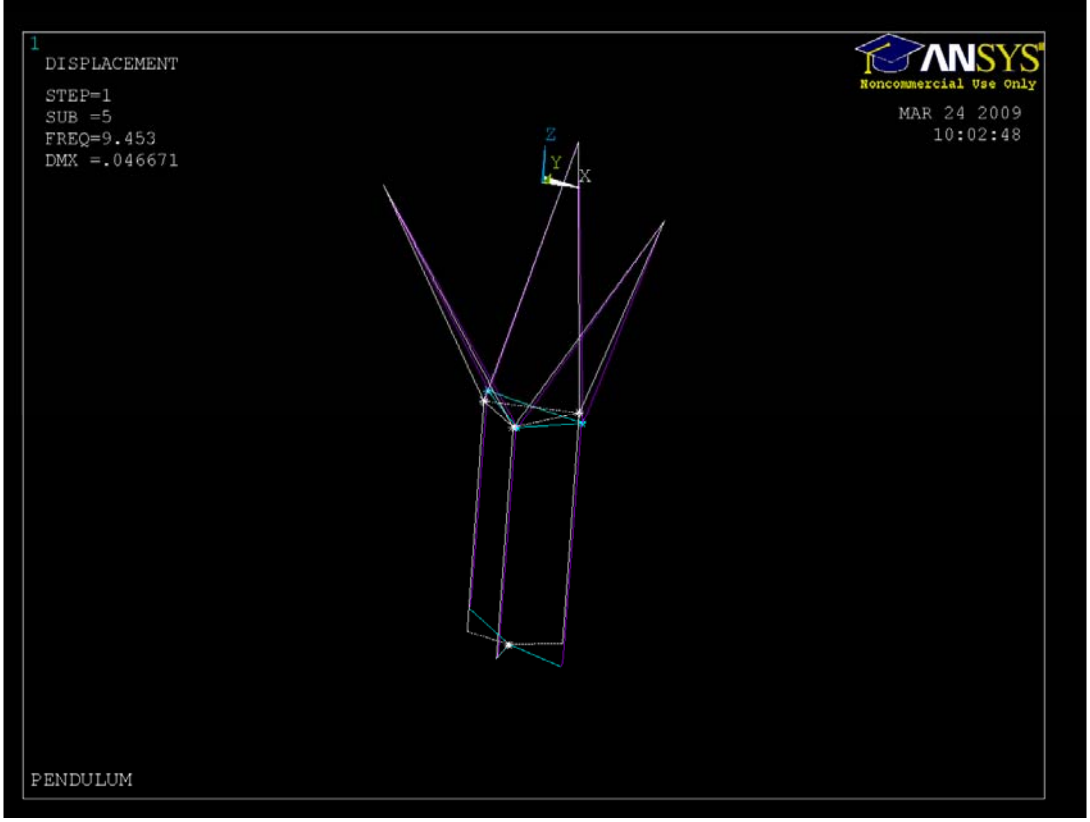
Table 1: Modal Frequency variation with suspension parameters

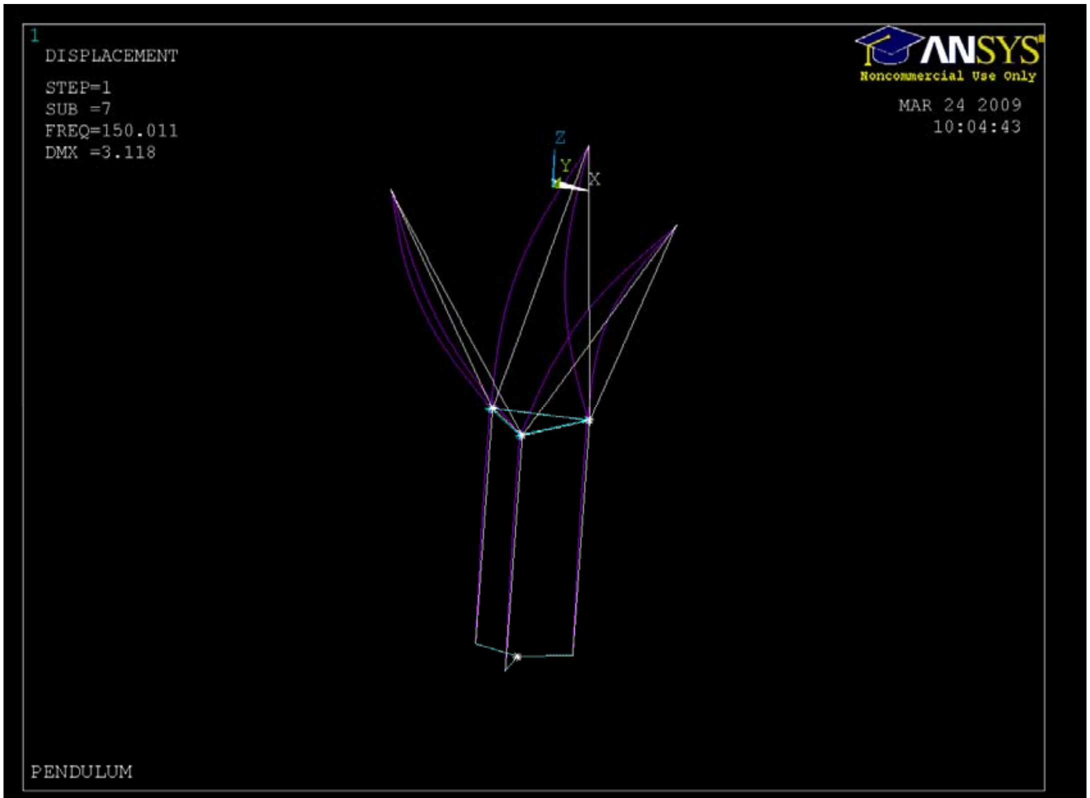
Selected mode shapes

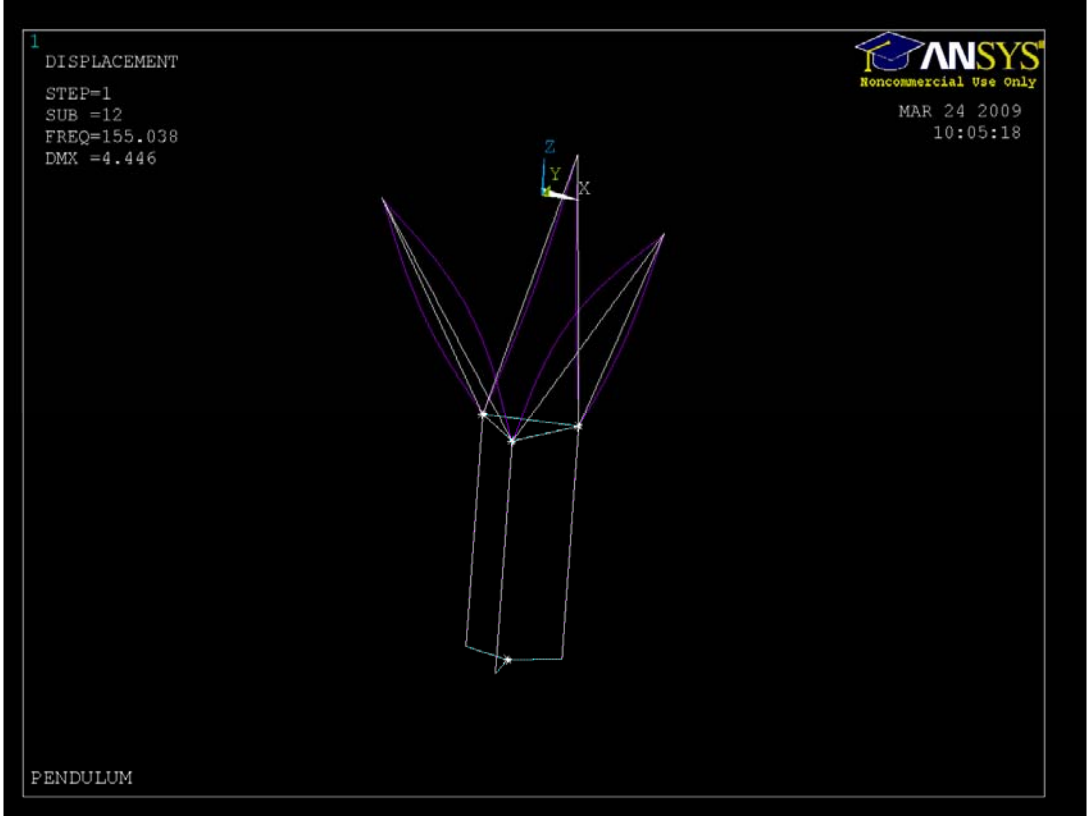


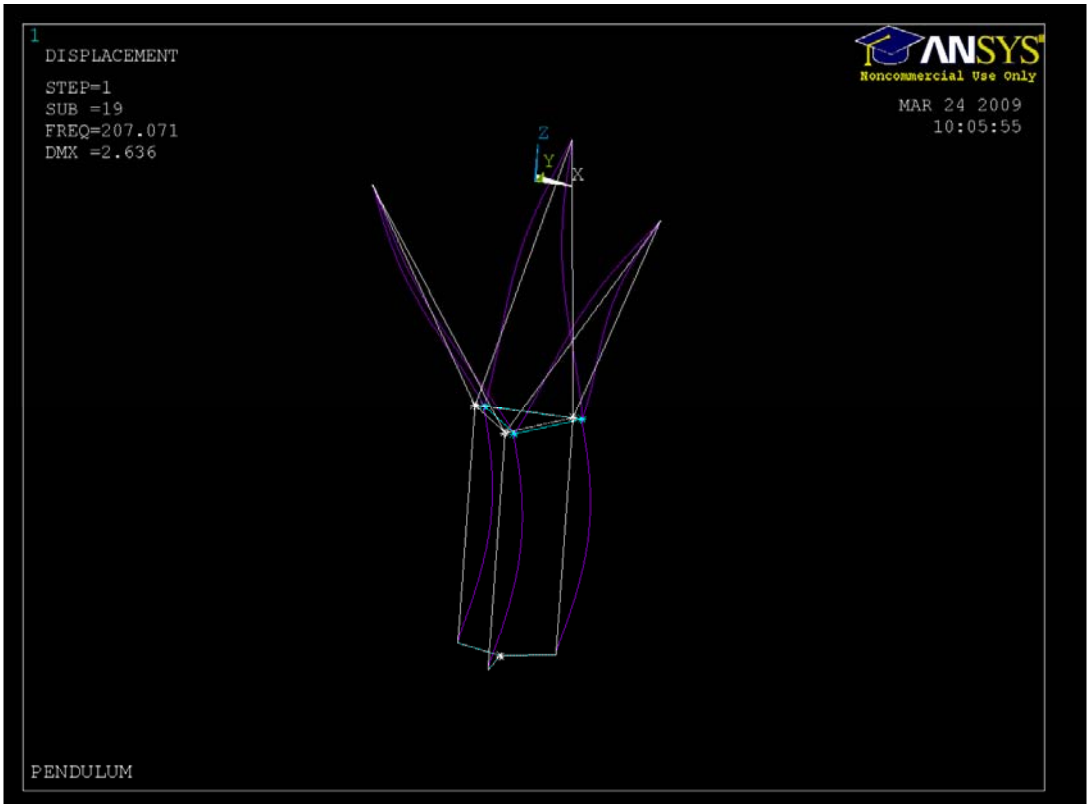


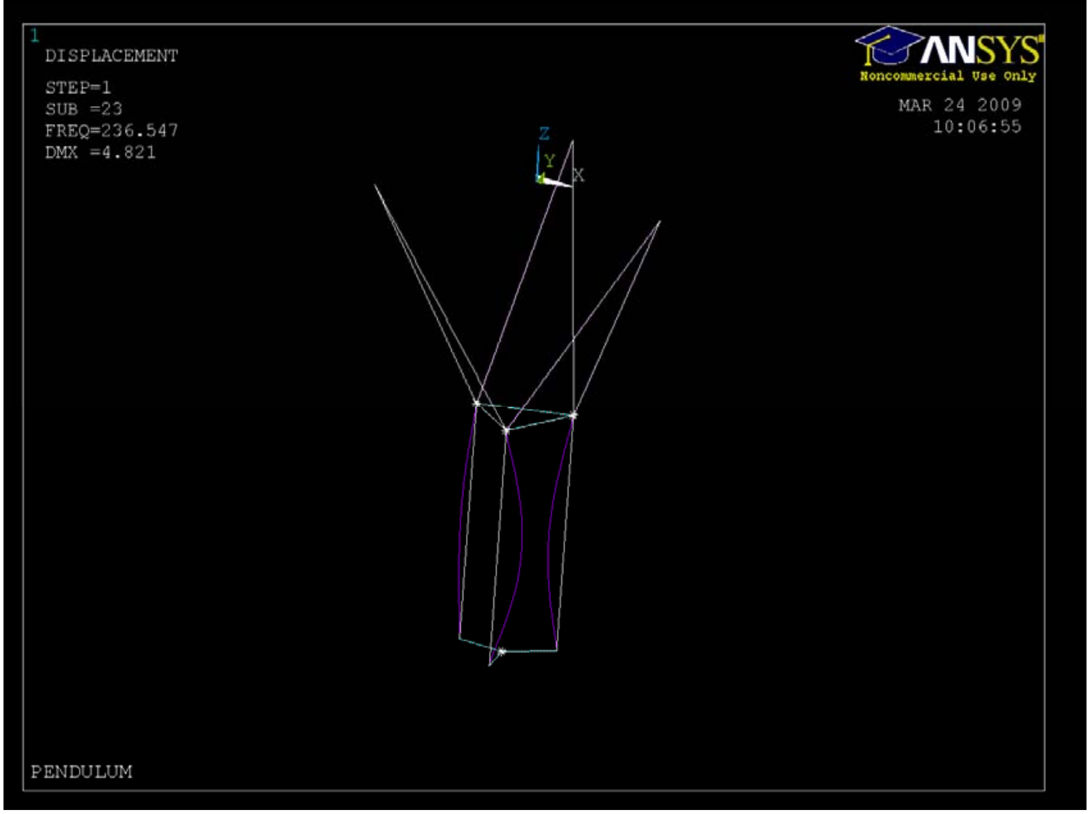

1
DISPLACEMENT
STEP=1
SUB =4
FREQ=6.688
DMX =.02685
ANSYS
Noncommercial Use Only
MAR 24 2009
10:02:30
Z
Y
X
PENDULUM

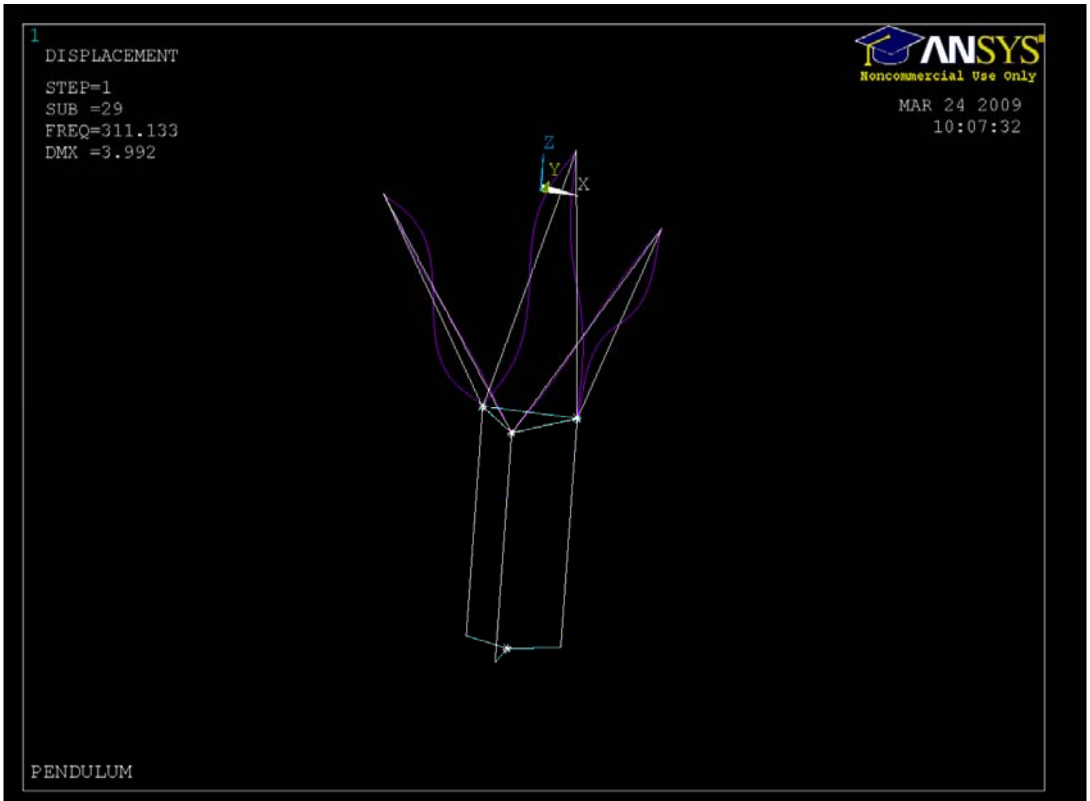

1
DISPLACEMENT
STEP=1
SUB =5
FREQ=9.453
DMX =.046671
ANSYS
Noncommercial Use Only
MAR 24 2009
10:02:48
Z
Y
X
PENDULUM

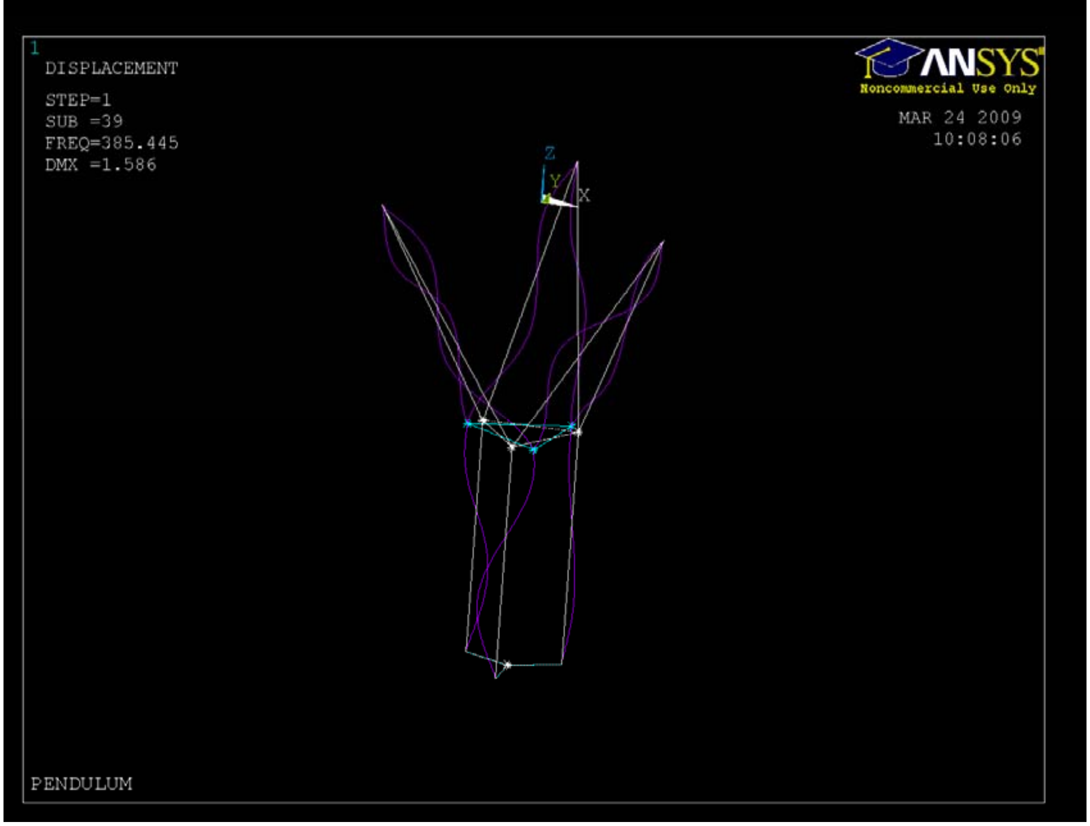

1
DISPLACEMENT
STEP=1
SUB =7
FREQ=150.011
DMX =3.118
ANSYS
Noncommercial Use Only
MAR 24 2009
10:04:43
Z
Y
X
PENDULUM


1
DISPLACEMENT
STEP=1
SUB =12
FREQ=155.038
DMX =4.446
ANSYS
Noncommercial Use Only
MAR 24 2009
10:05:18
Z
Y
X
PENDULUM


1
DISPLACEMENT
STEP=1
SUB =19
FREQ=207.071
DMX =2.636
ANSYS
Noncommercial Use Only
MAR 24 2009
10:05:55
Z
Y
X
PENDULUM


1
DISPLACEMENT
STEP=1
SUB =23
FREQ=236.547
DMX =4.821
ANSYS
Noncommercial Use Only
MAR 24 2009
10:06:55
Z
Y
X
PENDULUM


1
DISPLACEMENT
STEP=1
SUB =29
FREQ=311.133
DMX =3.992
ANSYS
Noncommercial Use Only
MAR 24 2009
10:07:32
Z
Y
X
PENDULUM


1
DISPLACEMENT
STEP=1
SUB =39
FREQ=385.445
DMX =1.586
ANSYS
Noncommercial Use Only
MAR 24 2009
10:08:06
Z
Y
X
PENDULUM

Appendix: ANSYS Macro Listing

```
!*************************************************************************
! pend4.mac
!*************************************************************************
! macro to analyse natural frequencies of a double pendulum suspension
! proposed for the reaction/damper suspension used on the TransMon assy
!
!Dennis Coyne 2009-03-23
!
finish
/CLEAR,START
/COM,ANSYS MODEL OF A SIMPLE PENDULUM
/PREP7
/TITLE,PENDULUM
PSTRES,ON
!*************************************************************************
!*     GEOMETRIC PARAMETERS
!*************************************************************************
! values of parameters
! SI units (m,N)

! r1 = radius of circle circumscribing equilateral triangle which forms
!       wire termination points at the optics table interface
! r2 = radius of circle circumscribing equilateral triangle ring of 1st stage
! r3 = radius of circle circumscribing equilateral triangle which forms
!       wire termination points at the magnet plate
! l1 = distance from optics table to ring
! l2 = distance from ring to magnet plate
! rw1 = radius of upper wires
! rw2 = radius of lower wires
! rro = outer radius of rods forming 1st stage triagular ring
! rri= inner radius of rods
! mr = added mass of the ring (added to the vertices)
! mmp = mass of the magnet plate
! Inx, Iny, Inz = mass moments of inertia for the magnet plate
pi=3.1416
r1=0.5
r2=0.17
r3=r2
l1=(1.742-0.300)/2
l2=l1
rw1=0.0017
rw2=0.0013
rro=0.015
rri=0.013

!*************************************************************************
!*     MASS PARAMETERS
!*************************************************************************

mmp=10
mr=0.1
Inx=0
Iny=0
```

```
Inz=0

!*********************************************************************
!*     MATERIAL PROPERTIES
!*********************************************************************
ringyoung=68.9e9
ringpoiss=0.33
ringdens=2700

wireyoung=2.0e11
wirepoiss=0.3
wiredens=7800

MP,EX,1,ringyoung
MP,EY,1,ringyoung
MP,EZ,1,ringyoung
MP,PRXY,1,ringpoiss
MP,DENS,1,ringdens

MP,EX,2,wireyoung
MP,EY,2,wireyoung
MP,EZ,2,wireyoung
MP,PRXY,2,wirepoiss
MP,DENS,2,wiredens

!*********************************************************************
!*     GENERATE GEOMETRY
!*********************************************************************

K,1,0,r1,0,
K,2,-r1*cos(pi/6),-r1*sin(pi/6),0
K,3, r1*cos(pi/6),-r1*sin(pi/6),0

K,4,-r2*cos(pi/6), r2*sin(pi/6),-l1
K,5,0,-r2,-l1
K,6, r2*cos(pi/6), r2*sin(pi/6),-l1

K,7,-r3*cos(pi/6), r3*sin(pi/6),-l1-l2
K,8,0,-r3,-l1-l2
K,9, r3*cos(pi/6), r3*sin(pi/6),-l1-l2

K,10,0,0,-l1-l2

!**********************************
!*          Wires
!**********************************

LSTR,1,4     ! line 1
LSTR,1,6     ! line 2
LSTR,2,4     ! line 3
LSTR,2,5     ! line 4
LSTR,3,5     ! line 5
LSTR,3,6     ! line 6

LSTR,4,7     ! line 7
```

```
LSTR,5,8     ! line 8
LSTR,6,9     ! line 9

!**********************************
!*          Ring
!**********************************

LSTR,4,5     ! line 10
LSTR,5,6     ! line 11
LSTR,6,4     ! line 12

!**********************************
!*          Rigid links
!**********************************

LSTR,10,7    ! line 13
LSTR,10,8    ! line 14
LSTR,10,9    ! line 15

!*********************************************************************
!*     MESH GEOMETRY
!*********************************************************************

!**********************************
!           Suspension Masses
!**********************************
ET,2,MASS21,0,0,0
TYPE,2     ! discrete mass elements
!     Ring Mass
R,4,mr/3,mr/3,mr/3,0,0,0
REAL,4
KMESH,4,6,1
!     Magnet Plate Mass
R,5,mmp,mmp,mmp,Inx,Iny,Inz
REAL,5
KMESH,10

!**********************************
!           Wires
!**********************************
ET,3,BEAM4,,0,,,,0
TYPE,3     ! beam elements
MAT,2

wAn=3.14159*rw1**2
wIn=(3.14159*rw1**4)/4
wJn=(3.14159*rw1**4)/2
R,9,wAn,wIn,wIn,2*rw1,2*rw1,0
RMORE,0,wJn
REAL,9
ESIZE,0.005
LMESH,1,6

wAn=3.14159*rw2**2
wIn=(3.14159*rw2**4)/4
wJn=(3.14159*rw2**4)/2
```

```
R,9,wAn,wIn,wIn,2*rw2,2*rw2,0
RMORE,0,wJn
REAL,9
ESIZE,0.005
LMESH,7,9


!***********************************
!           Ring
!***********************************
ET,3,BEAM4,,0,,,,0
TYPE,3     ! beam elements
MAT,1

wAn=3.14159*(rro**2-rri**2)
wIn=(3.14159*(rro**4-rri**4))/4
wJn=(3.14159*(rro**4-rri**4))/2
R,10,wAn,wIn,wIn,2*rro,2*rro,0
RMORE,0,wJn
REAL,10
ESIZE,0.01
LMESH,10,12

!***********************************
!           Rigid Links
!***********************************
ET,4,MPC184,1,0
TYPE,4      ! rigid body constraint elements
ESIZE,,1
LMESH,13,15

!***********************************************************************
!*     BOUNDARY CONDITIONS
!***********************************************************************

DK, 1,ALL,0
DK, 2,ALL,0
DK, 3,ALL,0

EPLOT

FINISH

!***********************************************************************
!   Static Preload Analysis
!***********************************************************************
/SOL
ANTYPE,STATIC
PSTRES,ON
G=9.84
ACEL,0,0,G
SOLVE
FINISH

!***********************************************************************
```

```
!   Eigenvalue Analysis
!***********************************************************************
/SOL
ANTYPE,MODAL
nmodes=50
initialshiftfreq=0
MODOPT,LANB,nmodes
LUMPM,OFF
PSTRES,ON
SOLVE
FINISH
```