LIGO Laboratory / LIGO Scientific Collaboration

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Preliminary Frequency Analysis of the Mode Cleaner Structure

M. Barton, C. A. Cantley, L. Jones, R. Jones, J. Romie, **C. I. Torrie**

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This is an internal working note
of the LIGO Project.

California Institute of Technology
LIGO Project – MS 18-34
1200 E. California Blvd.
Pasadena, CA 91125
Phone (626) 395-2129
Fax (626) 304-9834
E-mail: info@ligo.caltech.edu

Massachusetts Institute of Technology
LIGO Project – NW17-161
175 Albany St
Cambridge, MA 02139
Phone (617) 253-4824
Fax (617) 253-7014
E-mail: info@ligo.mit.edu

LIGO Hanford Observatory
P.O. Box 1970
Mail Stop S9-02
Richland WA 99352
Phone 509-372-8106
Fax 509-372-8137

LIGO Livingston Observatory
P.O. Box 940
Livingston, LA 70754
Phone 225-686-3100
Fax 225-686-7189

http://www.ligo.caltech.edu/

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Revision 03: Review and additions from RAJ and JHR
Revision 05: For Review by JHR, RJ, CAC

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1. Introduction

The purpose of this document is to record the status of the frequency analysis performed on both the Mode Cleaner and Recycling Mirror structures as well as summarizing experimental data collected from the existing Mode Cleaner structures, as shown below in *figure (i)*. Furthermore, it will address possible stiffening designs for both of the HAM suspension structures.

It is the belief of the authors that by using the above work in conjunction with the report written by Dennis Coyne, LIGO-T03044, that an adequate structure for the end test mass quadruple pendulum suspension for advanced LIGO may be designed.

The author would like to point out that the work summarized here should be considered preliminary and that a lot of work still has to be done.

2. Summary

In order to give the reader an insight into structure analysis carried out for the LIGO I project the authors have included an extract from a previous report by Janeen Romie.

This report outlines a brief history of the existing mode cleaner structure design as well as a description of experiment and a detailed summary of all of the finite element analysis carried out on this structure.

The first set of results compares frequency analyses performed on three different configurations of the mode cleaner structure with experimental results. The second set of results compares modeled and experimental results of various methods of clamping and concepts for stiffening the structures. Also outlined are several concepts that could be used for an improved mode cleaner structure design as well as for a recycling mirror structure.

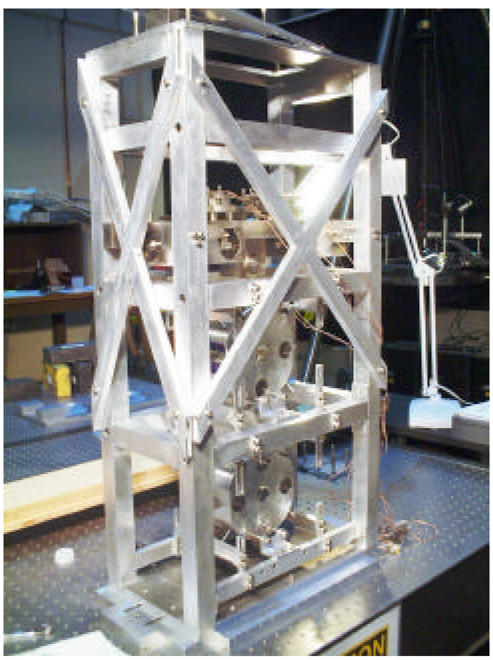


Figure (i): - Photograph of the assembled Mode Cleaner Suspension, D020700 in the laboratory

3. Structure design used in LIGO I

The following is an extract from a report by Janeen Romie that highlights structure analysis carried out for the LIGO I project: -

"Many iterations of the finite element model of the LIGO I large optic suspension (LOS) structure were made. The LOS structure, D960133, see *figure (i)*, has a similar footprint to the Advanced LIGO Mode Cleaner Structure, D020023.

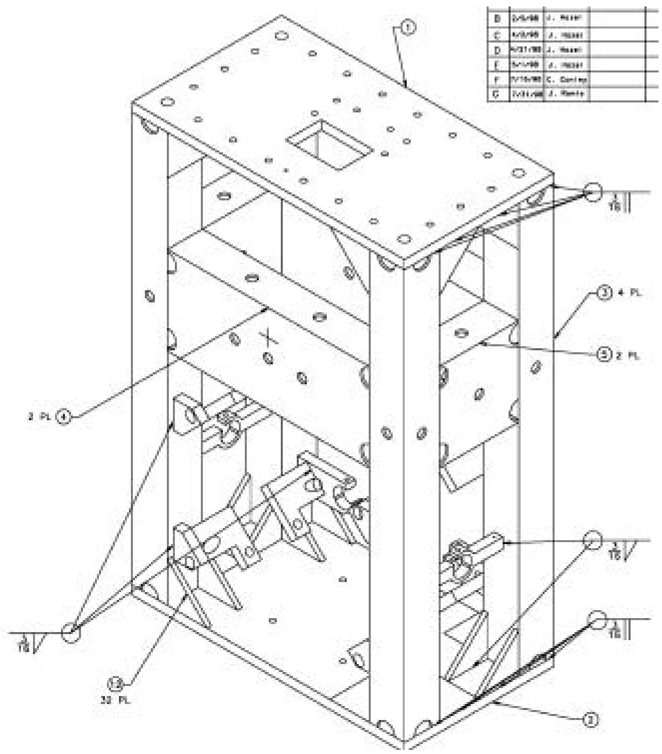


Figure (ii): - Initial LIGO I Test mass structure, D960133

The LOS structure is 216mm x 395mm x 616mm. Whereas the current mode cleaner footprint is 220mm x 400mm x 800mm. The LOS structure was made from 2" x 2" x .125" thick 300 series stainless structural members. The LOS structures utilized a set of welded-in stiffeners that are 2" x 5" x .125 thick structural members. They start about halfway up the structure. The structure also utilized 32 welded 2.25" x 2.25" x .125" thick gussets around the bottom and top of the legs to stiffen up the structure.

For the LIGO I LOS structure, early attempts to measure resonances gave systematically low values. The discrepancy was traced to the use of an optical table whose top surface was only loosely connected to the honeycomb body. When the tests were performed with the structure clamped to the milling bed in the Central Machine Shop, as shown in *figure (ii)*, satisfactory results were obtained. The milling bed is approx. 80 tons. For the LOS structure, the FEA was done in IDEAS with 3D brick elements. The theoretical results were 150 Hz, 166 Hz and 322 Hz, which compared favorably with the measured resonances of 170 Hz, 177 Hz and 311 Hz."

Figure (iii): - 80 ton Milling Machine in CES

4. Design Requirement

Quoting from LIGO-T030044[1], "The requirement is that the first natural frequency should be greater than 150 Hz, so that interaction of this structure or assembly with the seismic system does not destabilize the seismic control. For now the requirement to have no payload structural resonances close to the seismic upper unit gain point is taken as the requirement, i.e. > 150 Hz"

5. Existing Mode Cleaner Prototype Structure

5.1 Mode Cleaner Prototype Structure, D020023

As already mentioned the mode cleaner structure shown has a footprint of 220mm x 400mm x 800mm. It is made from 1.25? x 1.25? x 0.125? thick aluminium structural members welded together at the Central Engineering Services (CES) at California Institute of Technology. Aluminium was chosen in an attempt to reduce the overall weight of the system.

FEA of the mode cleaner structure carried out in early 2002 using the software package ALGOR provided a first resonance mode that appeared to meet the requirements. This has since been proven to be incorrect and as a result not only is ALGOR no longer used but also a new mode cleaner structure will have to be built to meet the 150 Hz requirement.

In order to learn more about stiffening and clamping techniques that will ultimately aid in the design of other structures it was decided to not only make use of the existing mode cleaner structure, outlined above, but to also to build a robust and reliable finite element model that utilized the capability of drawing 3-D ideas in a CAD package.

[1] LIGO-T030044-02-D Frequency Analysis of the Quadruple Pendulum Structure (D.Coyne)

5.2 The Experimental Set-up

The mode cleaner structures, D020023, are shown in *figure (vii)*. As already mentioned the mode cleaner assembly, D020700 can be seen in *figure (i)*.

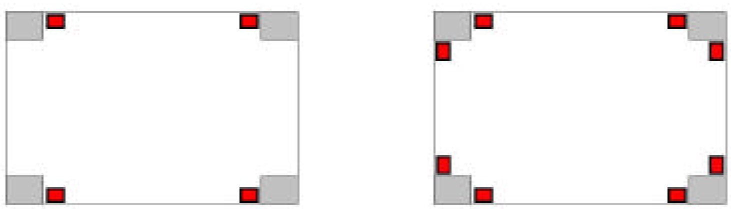
Throughout the course of the experiment various assembled states were considered, i.e. bare structure through to fully assembled structure. Pictures that clearly show these states can be viewed in *Appendix (A)* with reference to the two results tables.

The resonant frequencies of the mode cleaner structure were obtained by exciting the structure and measuring the response. The measured signal was amplified using a pre-amplifier, monitored on an oscilloscope and analyzed using a spectrum analyzer. The structure was excited using a externally driven shaker. The analyzer, in the swept sine mode (LIN SPEC 1 LOG MAG), drove the shaker over a frequency range 20 Hz to 500 Hz. An example of the output from the spectrum analyzer can be seen in *figure (viii)*. Structural resonances were checked using the FFT mode of the spectrum analyzer, a hammer and the accelerometer.

Because of information gained from LIGO I all of the experimental data was obtained on an 80-ton Milling table in CES. The table is shown in *figure (v)* below.

5.3 Method and type of Clamping

The number and type of clamps used to fix the structure to the table was varied during the course of the experiment.. *Figure (iv)* shows a plan view of the base of the structure and small squares representing the position of the clamps.



(a) *(b)*

Figure (iv): - Plan view of the base of the structure showing the two main positions used for the clamps. The clamps shown in sketch (a) 4 and (b) 8 are represented by small squares.

Two basic different types of clamps were used. Firstly, a large set of clamps, as shown in *figure (v)*, which are part of the hardware from the milling machine and secondly a set of clamps, similar to those used in LIGO I, as shown in *figure (vi)*. Due to its close relationship with this work, the authors have included a calculation by Larry Jones in Appendix B. In it Larry calculates the effective spring constant of a clamp and how many clamps would be needed to clamp a suspension to the assumed stiff seismic system of a BSC Chamber in advanced LIGO.

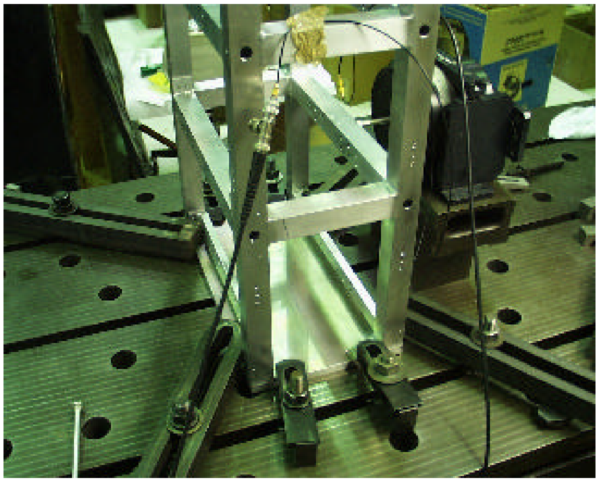


Figure (v): - Large Clamps

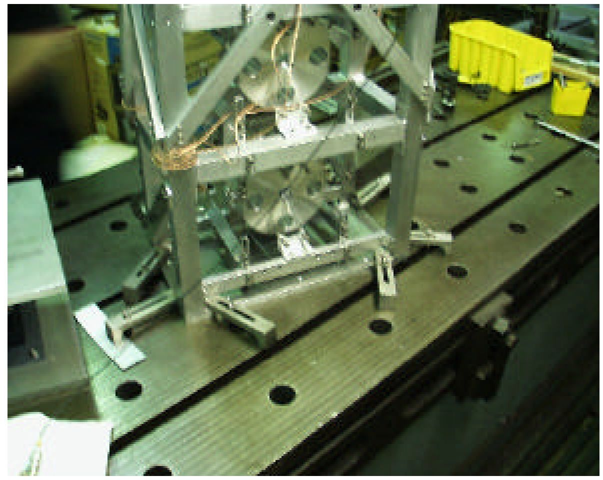


Figure (vi): - Small Clamps

5.4 Experimental data

For each set of data points, the first two resonances of the structure were measured. From both *figure (vii)* and *figure (ix)* it can be seen that the shaker was positioned at a central location on the structure with the tip of the pusher resting against one of the crossbars. The accelerometer, B&K type 709, was fixed to the structure, vertically above the position of the shaker, close to the top plate, using bees wax. Strain relief was provided for the accelerometer cable. All of the results were carried out in air.

Prior to measuring each set of experimental data, the response from accelerometer was checked. Before moving on to the next configuration each set of results were recorded and checked. In order to tighten each screw nut combination a 6-inch Alan key was used for the small clamps and a 12-inch Wrench for the large clamps. (Finger tight plus a half turn)
The experimental results measured from three main configurations of the structure were compared directly with the modeled data. Section 5.5.4 explains the experimental configurations in more detail. The overall goal was to develop a reliable finite element model.

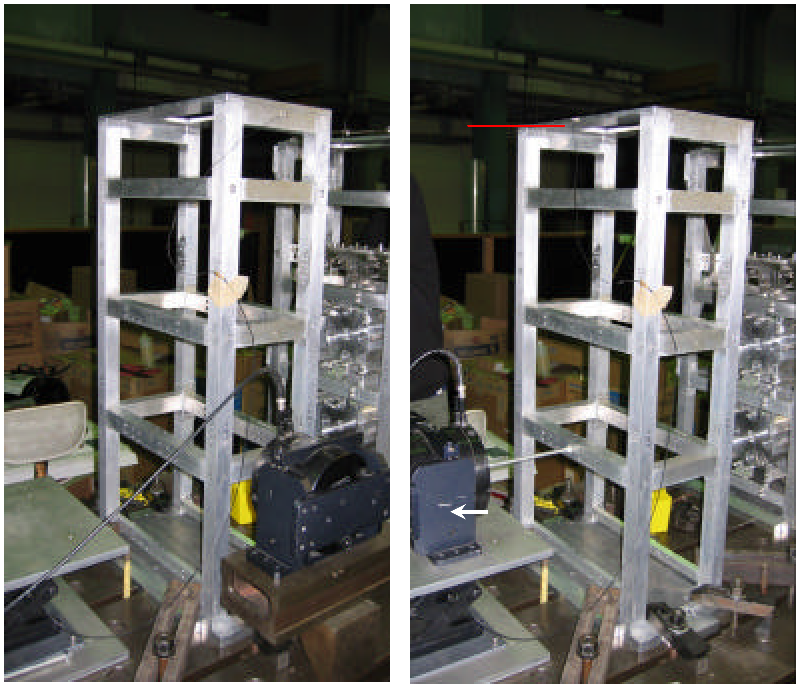


Figure (vii): - Mode Cleaner Structure, D020023, in the CES, on the Milling Machine

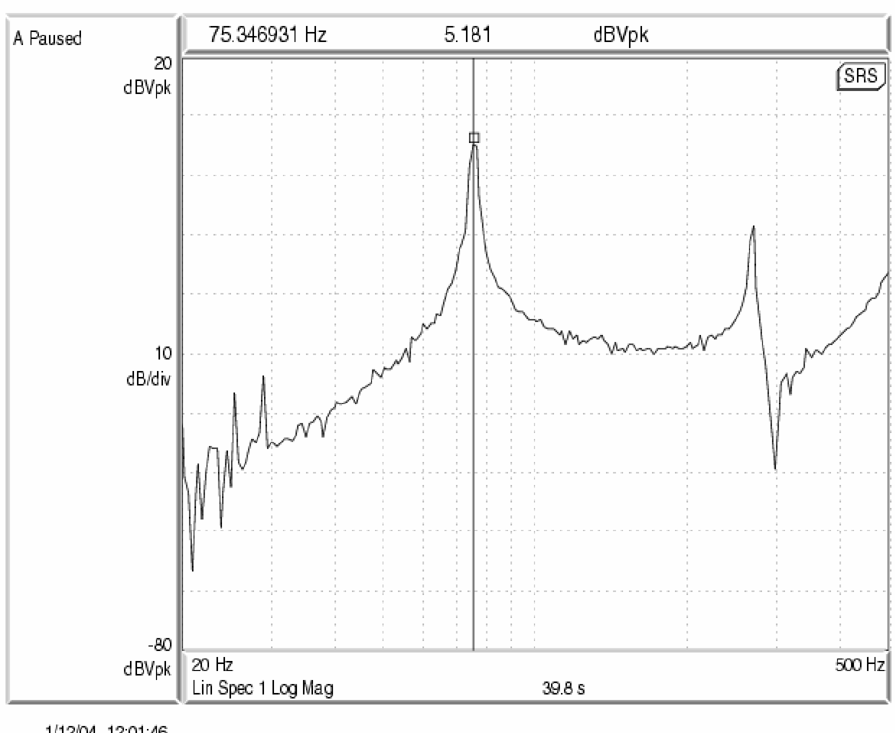


Figure (viii): - View of a trace from the spectrum analyzer

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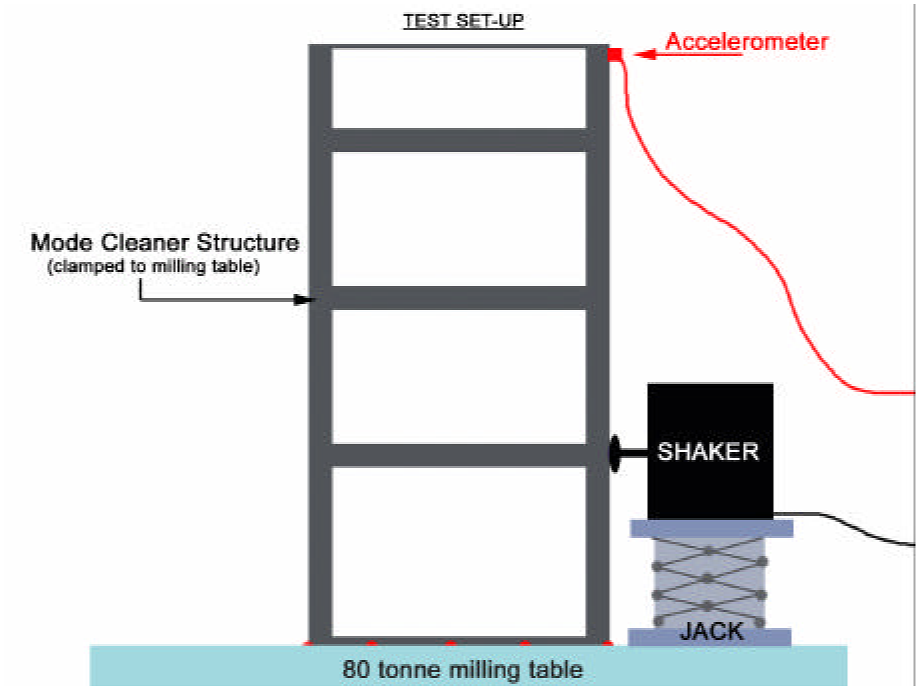

Figure (ix): -Sketch of the structure showing the position of the accelerometer and the shaker, measuring in the transverse mode

5.5 Finite Element modeling (ANSYS and I-DEAS)

5.5.1 Introduction

There has been a substantial effort recently to develop a reliable finite element model of the structure and assembly that produces comparable results to those obtained experimentally. As of December 2003, both groups at Glasgow and Caltech have the ability to use ANSYS version 7.0 University Advanced. A Research version with a specification for 512,000 mechanical nodes is now available from ANSYS re-sellers, an evaluation copy is currently being reviewed at Caltech.

5.5.2 Input Data

A .SAT (version 7) file was exported from SolidWorks 2001 Research edition for each variation of the mode cleaner structure. Experience gained by the author indicates that it is best to use meters when exporting from SolidWorks. Exported files to I-DEAS from SolidWorks made use of a STEP translator, AP214.

For the results obtained in ANSYS, the following input data was used.

Material:	Aluminium
Density:	2700 kg/m^3
Young's Modulus:	70 GPa
Poisson's ratio:	0.33
Element Type:	Solid 92
Mesh type:	Smart size 9
Clamping:	Fixed 3-D constraint

Analysis performed in IDEAS utilized a very similar data set.

5.5.3 Post Processing

At least six frequencies were processed for each modal analysis. Modal pictures of both the deformed and un-deformed shapes, see *figure (x)*, were analyzed in order to ensure that the results obtained matched those measured experimentally.

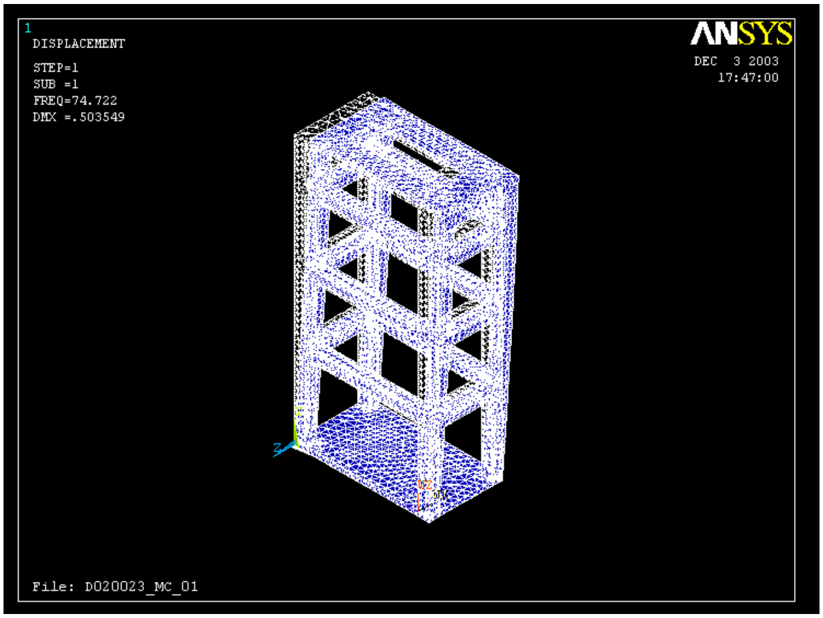

Figure (x): - Example of a screen shot from ANSYS example. (Table I, line 6, transverse)

It is important to note that the spacer plate, as shown in *figure (xi)* below, present for some of the experimental results was not included in any of the finite element models. It should be noted that the presence of this spacer is noted in both *table (I)* and *(II)* and its effect of this spacer is considered in section 5.5.3.

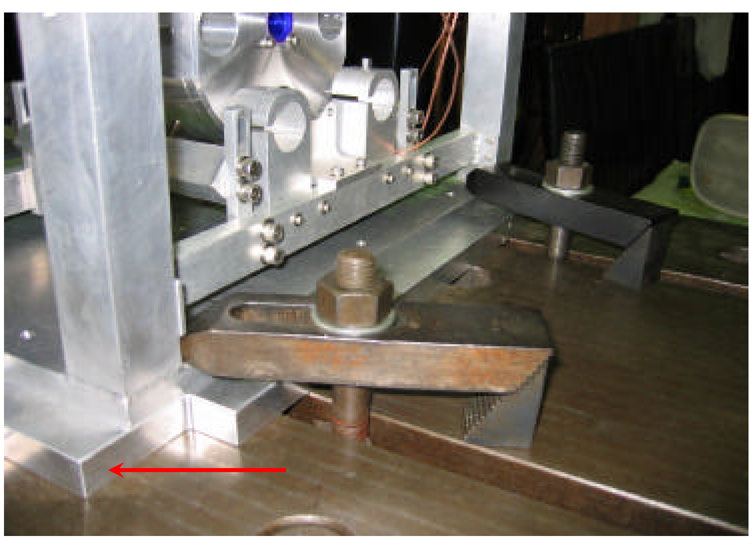

Figure (xi): - Mode Cleaner Spacer, D020479

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5.5.4 Configurations of the structure used in the modeling and experiment

There have been three main configurations of the structure at this point, with respect to building a dedicated comparison between FEA results and experimental data.

Analysis that considers both clamping and stiffening techniques are highlighted in *table (II)* and discussed in a later section.

The three configurations are as follows: -

- Bare MC structure
- Bare MC structure + 6kg
- MC structure with lumped mass*

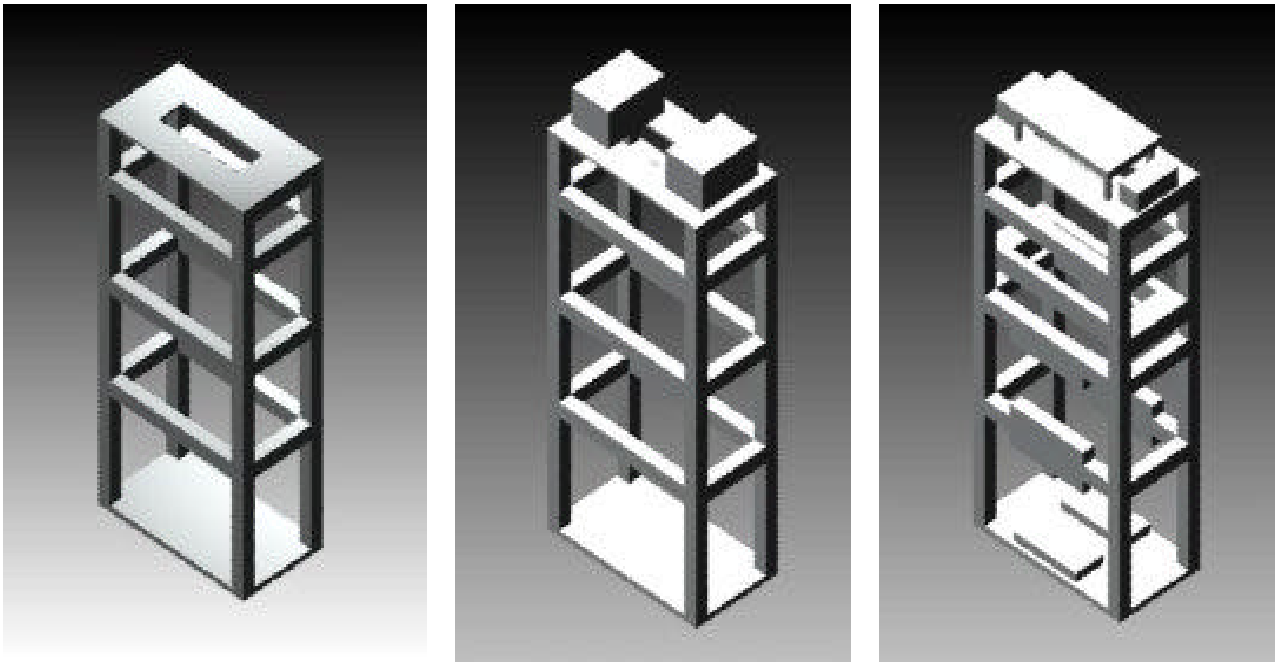
* For modeling purposes the non-suspended components associated with the assembly, D020700, shown in *figure (i)*, are represented by sections of lumped mass distributed around the structure.

Graphical representations of these configurations are shown in *figure (xii)*. A screen shot from ANSYS using a meshed structure with 3-D constraints in shown in *figure (xiii)*.

It should be noted that for the structure with the lumped mass that several revisions were considered. The reason for this was twofold. Firstly, as our understanding of the importance of the non-suspended mass developed, we improved the SolidWorks model representing it. Secondly, revisions were made in order to allow us to investigate the effect of small variations of mass (e.g. +/- 0.5 kg).

It is assumed that the suspended components i.e. the mode cleaner triple pendulum suspension with 3 stages each of ~ 3 kg will not effect the structural resonances.

Each file was created as single part in SolidWorks prior to exporting to the relevant FEA package. A feature of the export function is that if STEP is chosen it does not allow for the presence of suppressed features. This is not the case for files exported as .SAT files.



(a) (b) (c)

Figure (xii): - Graphical representation of the Mode cleaner structures prior to analysis in ANSYS. From the left: (a) bare structure;
(b) Bare + 6kg on top, used as an extra data point;
(c) MC structure plus lumped mass. The lumped mass represents the assembled mode cleaner suspension.

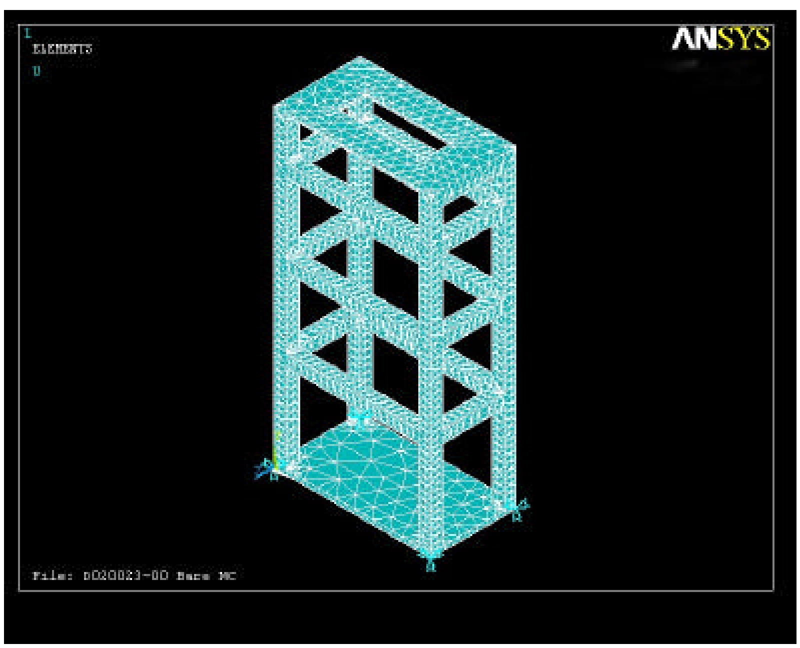


Figure (xiii): Screen shot from ANSYS of the meshed mode cleaner structure with the four corners of the base fixed with 3-D constraints.

5.5 Comparison of Results

5.5.1 Experimental vs. FEA (a key can be found at the top of page 14)

#	Description of clamping/contraints	Transverse y	Longitudinal x	by
	BARE MC STRUCTURE (D020023-00)			
	Experimental (80 tonne milling table)			
1	8 milling machine clamps	79	89	MB/RJ
2	8 milling machine clamps	79	89	CIT
3	8 milling machine clamps, spacer removed	77	85	CIT
4	8 small clamps	**76**	**85**	CIT
	MC STRUCTURE with Lumped Mass representing non suspended components			
	Experimental (80 tonne milling table)			
11	8 milling machine clamps with spacer	49	56	MB/RJ
	Estimated 8 milling clamps, spacer removed	?*	?*	
12	8 small clamps with spacer removed	46	53	CIT
13	8 small clamps, no spacer or suspension	**46**	**53**	CIT
	BARE MC STRUCTURE + 6kg (D020023-03)			
	Experimental (80 tonne milling table)			
19	8 milling machine clamps, spacer removed	47	53	CIT
20	8 small clamps	**46**	**53**	CIT

#	Description of clamping/contraints	Transverse y	Longitudinal x	by
	BARE MC STRUCTURE (D020023-00)			
	FEA (Ansys)			
5	8 fixed nodes (2 beside each upright on top of the baseplate)	74	78	CIT
6	...repeat of 5 (to check result)	75	79	RJ
7	Base fixed entirely	84	94	CIT (*RJ)
8	No displacement constraints whatsoever		174??	CIT
9	4 nodes fixed @ corners	**74**	**84**	CIT
10	...repeat of 9 (to check result)	**76**	**86**	RJ
	FEA (IDEAS)			
i	4 nodes fixed at corners (cf. #9 above)	**78**	**88**	JHR
	MC STRUCTURE with Lumped Mass representing non suspended components			
	FEA (Ansys)			
14	8 fixed nodes (2 beside each upright on top of	_57_	_55_	_CIT (*RJ)_
15	4 nodes fixed @ corners	58	61	CIT
16	4 nodes fixed @ corners (0.5kg extra lumped mass: recalculated values for blade guard and rotational adjuster)	56	59	CIT
17	4 nodes fixed @ corners (0.5kg extra lumped mass: more mass for OSEMS and table cloth brackets)	**55**	**58**	CIT (*RJ)
18	4 nodes fixed @ corners, but alternative blade guard configuration	_55_	_57_	_CIT (*RJ)_
	FEA (IDEAS)			
ii	4 nodes fixed @ corners, (cf. #17, above)	**56**	**60**	JHR
	BARE MC STRUCTURE + 6kg (D020023-03)			
	FEA (Ansys)			
21	8 fixed nodes (2 beside each upright on top of the baseplate)	_47_	_46_	_CIT (*RJ)_
22	4 nodes fixed @ corners	**48**	**53**	CIT (*RJ)
	FEA (IDEAS)			
iii	4 nodes fixed @ corners, (cf. # 22, above)	**49**	**54**	JHR

Table (I): - Comparing the experimental data directly with the modeled data.

5.5.2 Refinements of Mass, Stiffness and Clamping

Results were recorded as we investigated the effects of adding mass as well as features for stiffening, for example X-bars, single diagonal cross braces and Aluminium sheets bolted to the faces) the bare mode cleaner structure, D020023, before switching to an assembled mode cleaner assembly, D020700, and assuming a similar approach.

BARE STRUCTURE (MB, RJ, CIT) 20th-21st November 2003				
	Description of Setup	# of Clamps	**Transverse** y Hz	**Longitudinal** x Hz
	(Measurements 1-7 tainted by loose clamp)			
1	Completely bare structure, removable horizontal bar removed	4	64	80
2	4kg added at top, removable horizontal bar removed	4	44	52
3	Completely bare structure, removable horizontal bar ADDED!	4	69	78
4	As in 3, 4kg added at top	4	48	52
5	No added mass, side 'X' bars added	4	65	86
6	No added mass, WITH front & side 'X' bars	4	86	77
7	4kg added at top, WITH front & side 'X' bars	4	65	55
	Realisation of poor clamping! Therefore clamping corrected!			
8	Repeat of **3** above…bare structure, all horizontal bars.	4	79	89
9	Repeat of **6** above…bare structure with front & side 'X' bars	4	91	91
10	Repeat of **6** above…bare structure with front & side 'X' bars	4 moved in!	80	71
11	Repeat of **6** above…bare structure with front & side 'X' bars	8	101	96
12	Repeat of **6** above…bare structure with front & side 'X' bars	10	101	96
13	Repeat of **6** above…bare structure with front & side 'X' bars and addition of single diagonal cross braces to the sides	8	102	122
	Bolted on sheets, **TO DO!**			

TESTS ON ASSEMBLED "MC" STRUCTURE (MB, RJ, CIT) 20th-21st November 2003				
	Description of Setup	Clamping	**Transverse** y Hz	**Longitudinal** x Hz
14	**Present**: tablecloth, EQ stops, tombstones, rotational adjusters **Not Present**: 'X' bars, single diagonal cross braces, Local Control OSEMs, Global Control OSEMs, Blade guard (and assoc. parts)	8 pts.	56	65
15	As in 14 … Blade Guard (and assoc parts.) and 5 Local Control OSEMs added	8 pts.	49	56
16	As in 15 … Side Xbars added	8 pts.	48	68
17	As in 16 … Front Xbars added	8 pts.	70	65
18	As in 17 … Side Xbars removed	8 pts.	70.5	54.5
19	As in 18 … all stiffeners added (Front & Side Xbars + single diagonal cross braces)	8 pts.	69.5	84.4
20	As above, but with **spacer** removed	8 pts.	68	82
21	As above, but using **small clamps**	8 pts.	63	79

Table (II): - Analysis of various methods to stiffen the structures

KEY: -

*RJ means checked by Russell Jones, U. of Glasgow
CIT Calum Torrie
MB Mark Barton
JHR Janeen Hazel Romie
* if required needs to be estimated based on other results
57 frequencies in italics implies we observed mode coupling in the FEA

Key: - information related to table (I)

5.5.3 Conclusions

The following sets of results, of the two structural resonances, have been extracted from *table (I)*. As can be seen for all of these cases the theoretical model matches the experimental results within ~ 15 %.

CONFIGURATION		THEORETICAL (4 clamps at the corner)	EXPERIMENT (No spacer, 8 small clamps)
Bare	ANSYS	74 Hz and 84 Hz	76 Hz and 85 Hz
Bare + 6 kg	ANSYS	48 Hz and 53 Hz	46 Hz and 53 Hz *
Bare + lumped mass	ANSYS	55 Hz and 58 Hz	46 Hz and 53 Hz *
			* coincidence

It can be seen from these results how important it is to consider the non-suspended mass associated with the suspension.
The author believes that as a direct result of these comparisons that a robust and reliable model has been devised that can be utilized for further analysis. It should be noted that the ANSYS work was carried out by researchers at both Glasgow and Caltech.

5.5.4 Discussion points from the results tables

In comparing #20 and #21 *in table (II)*, for example, it can be seen that the difference between clamping with 8 small to 8 large clamps reduces the first two resonances by a couple of Hertz. However, in comparing # 3 and #4 in *table (I)* there is little or no effect. The effect of removing the spacer can be seen by comparing #19 and #20 in *table (II)* reduces the two resonances by a few Hertz.

For both of these effects the author believes that the amount by which each clamp is tightened is contributing to non-conclusive results? It should also be noted that the lighter the structure being considered then the lower the effects from the differences in clamping.

In *table (II)* several of the existing concepts for stiffening the structure are considered individually. The slight canceling effect of the existing “X” bar designs, picture #16 and #18 in appendix A, should also be emphasized. Designs are already being considered for improving these components. The diagonal bars, #19 in *table (II)* and picture #21 in appendix A, are extremely light in comparison to the X bars, but as can be seen are fairly effective.

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6.0 Stiffening Concepts

6.1 Advanced LIGO Stiffening Concepts

In a meeting with Dr. Caroline Cantley, from the University of Glasgow, in October, a series of stiffening concepts to try in FEA and experimentally to stiffen up the MC structure were detailed. Caroline suggested that the X stiffeners ((D020422 and D020425) should be moved down as far as possible and that more attachment points should be added. Caroline also suggested using flat thin plates as stiffeners. Caroline's third suggestion involves bolting on small rectangular stiffener plates to the vertical and horizontal tubes of the MC, with as many screws as possible.
Dr. Norna Robertson also sent a picture of the stiffening concepts used by the Stanford SEI group, see *figure (xiv)*, and suggested we try incorporating some of these concepts.

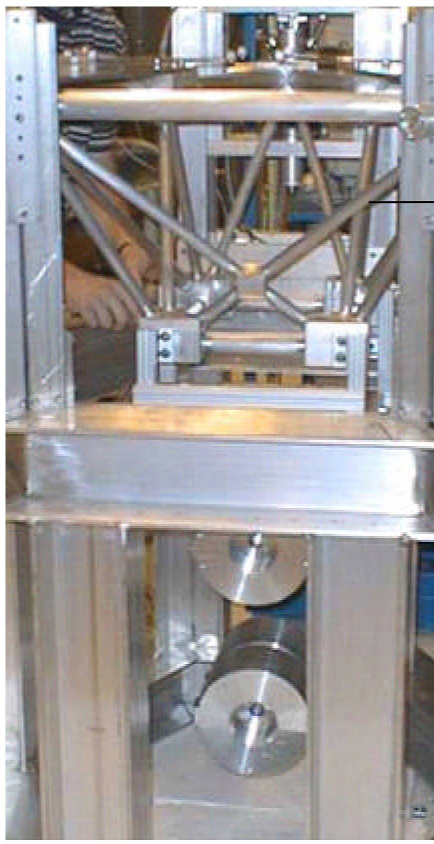


Figure (xiv): - Stiffening concepts used by the Stanford SEI Group, supplied by Dr. N. Robertson

In conversations with LIGO Chief Engineer, Dennis Coyne, emphasis was placed on providing attachments for the stiffening members that allow for screwing directly into female threads, as opposed to clamping the members in place with screws and nuts and using through holes in the structure's tubes. That means that with the current .125" wall thickness, the maximum screw size is 8-32. This makes the assumption that a 4-thread minimum engagement must be met. If a larger screw is wanted, or more thread engagement, either thicker tubes must be used or plates must be welded on where screw attachment is being utilized. Dennis also mentioned the possibility of using PEM-type self-clinching nuts and access holes in the tubes to provide strong threaded attachments.

Dennis, like Caroline suggested screwed on triangular plates at the junction of the horizontal and vertical tubes.

7.0 Structures for LASTI and advanced LIGO

7.1 Stiffening the Mode Cleaner (MC) Structure

The experimental and finite element analysis for stiffening up the MC is ongoing. So far, we have run a model that utilizes bigger structural members.

Bare Mode Cleaner structure (i.e. no lumped mass) modeled in IDEAS, using 2D shells and beams, 2" x 2" x .188" thick structural members, no lumped mass, 12 fixed nodes on bottom plate.

For file, L2_ModeCleaner, the first two resonances are 132 longitudinal, 139 Hz transverse.

At the time of writing CES is machining some .025" thick aluminium plates. These will be tested as soon as possible. This approach will also be analyzed using the finite element model. Other concepts are also being modeled that take into account not only the lumped mass but also several stiffening techniques.

7.2 Recycling Mirror (RM) Structure

At the time of writing the experimental and FEA work for stiffening up the RM structure has been put on hold. Selected preliminary FEA results can be found below.

Bare RM structure (i.e. no lumped mass) modeled in IDEAS, using 2D shells and beams, 2" x 2" x .188 thick structural members, 15 fixed nodes on bottom, structure is 1" too high.

For file, MarksTest4RM, the first two resonances are 108 Hz transverse, 114 Hz longitudinal.

Obviously, this model needs rework to reduce the error in height. Furthermore, Dennis Coyne suggested we consider triangular buttresses to stiffen the structure. The footprint for the RM is more forgiving with respect to the Advanced LIGO layout. The plan is to utilize the knowledge gained from the updated MC structure, outlined above.

7.3 End Test Mass (ETM) Structure

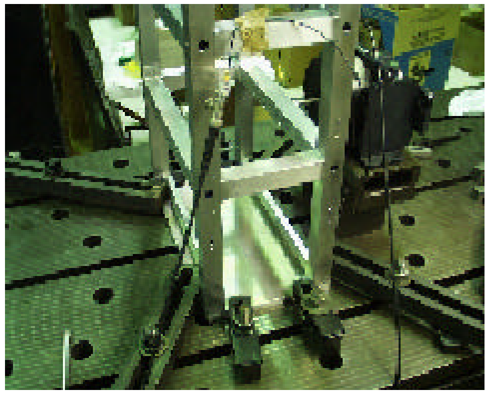
As already mentioned Dennis Coyne has summarized a section of work on a proposed structure for the ETM suspension, this can be found in T030044-02. Subsequent to this report various members of the suspension team have discussed several related concepts and ideas.

APPENDIX A (i of iv)

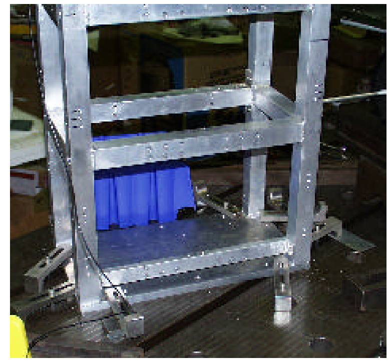
Photographs of each stage recorded in *table(I)* and *table (II)*.

Comparing examples in *table (I)* for the bare structure: -

1) 8 large clamps + spacer



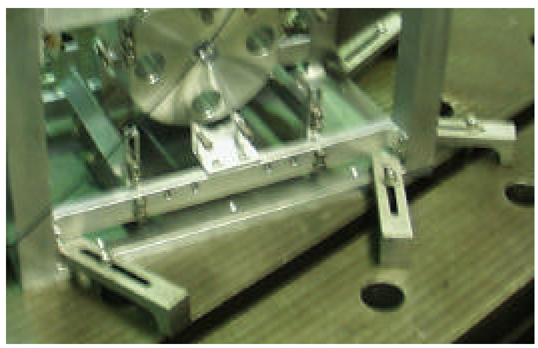
3) 8 large clamps, no spacer



4) 8 small clamps and no spacer

Comparing examples in *table (I)* for the structure plus lumped mass: -

11) 8 large clamps with spacer



12) 8 small clamps with spacer removed

Comparing examples in *table (I)* for the structure + 6 kg: -

19) 8 large clamps, no spacer

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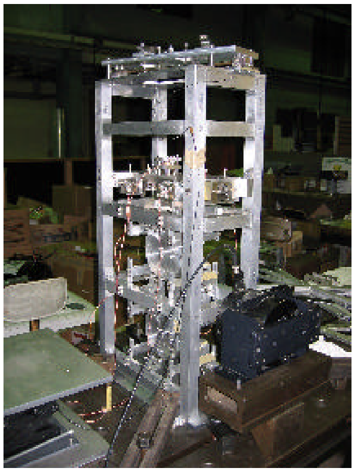
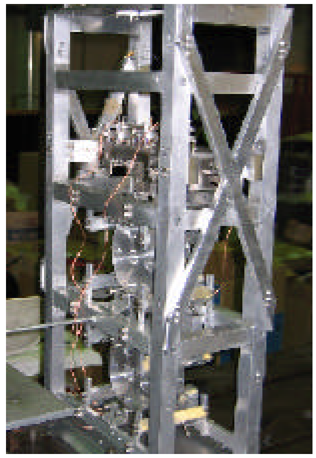
APPENDIX A **(ii of iv)**

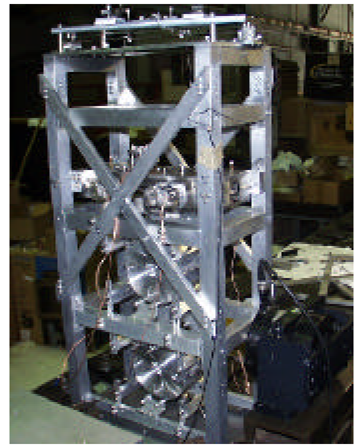
Comparing examples in Table (II) for the assembled structure: -



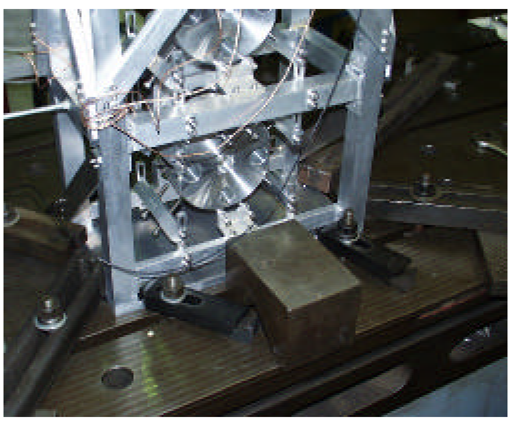
15) Spacer & 8 large clamps



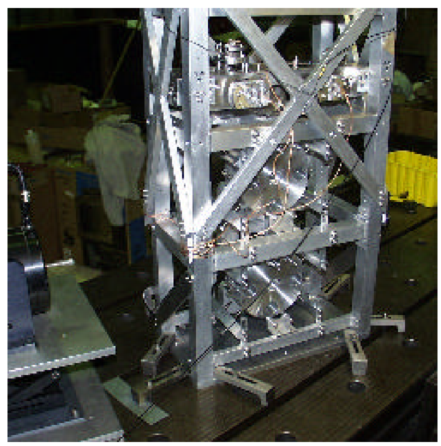
16) Spacer, 8 large clamps & side X bars



18) Spacer, 8 large clamps & front X bars



20) All Stiffeners added, 8 large clamps with spacer removed



21) All Stiffeners added, 8 small clamps with spacer removed

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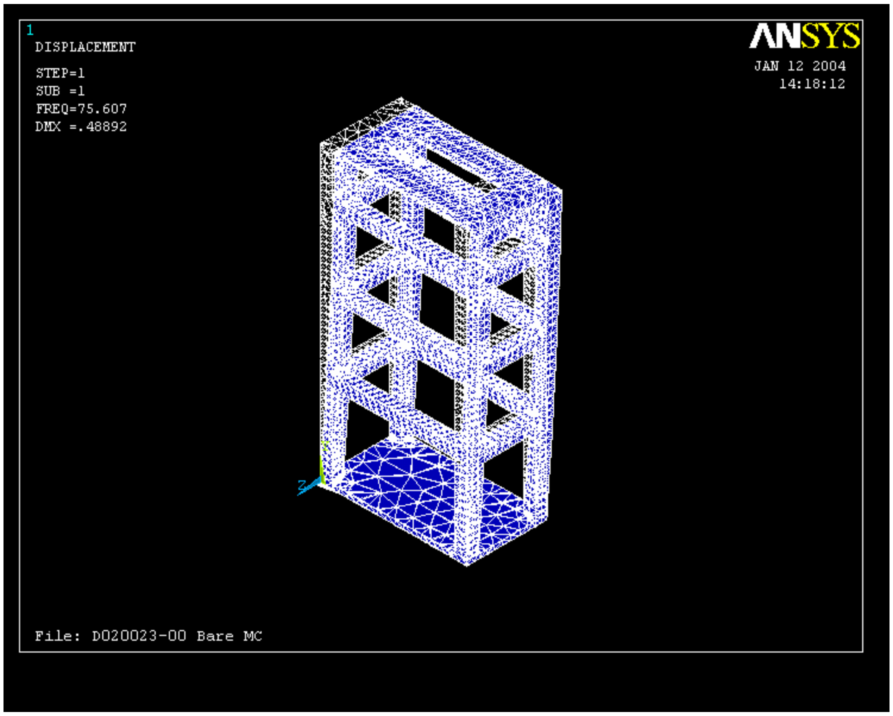
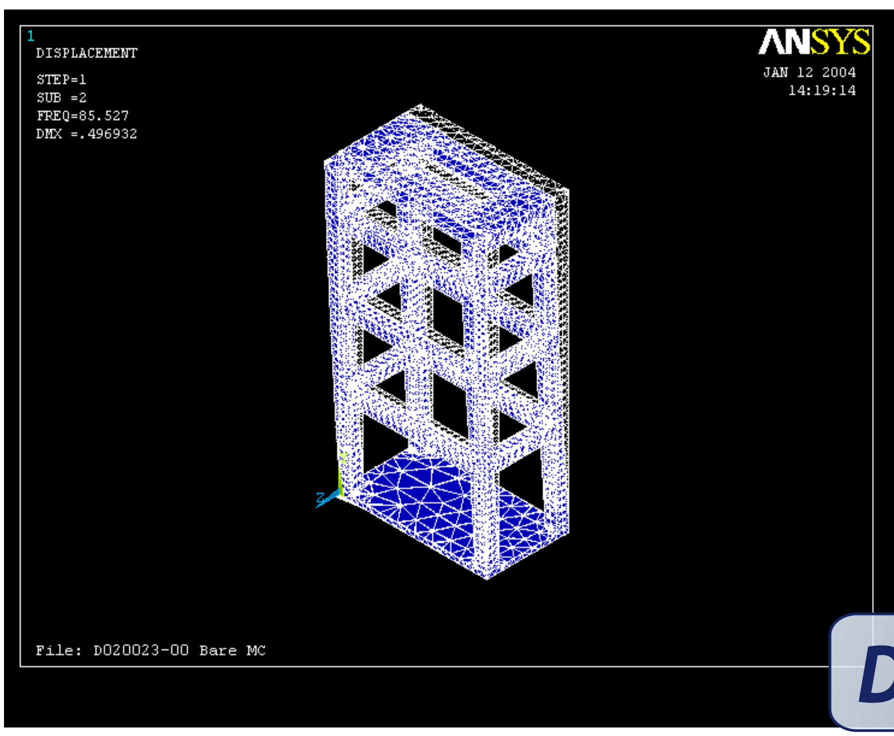
APPENDIX A (iii of iv)

Comparing results from FEA of the bare structure modeled in ANSYS: -



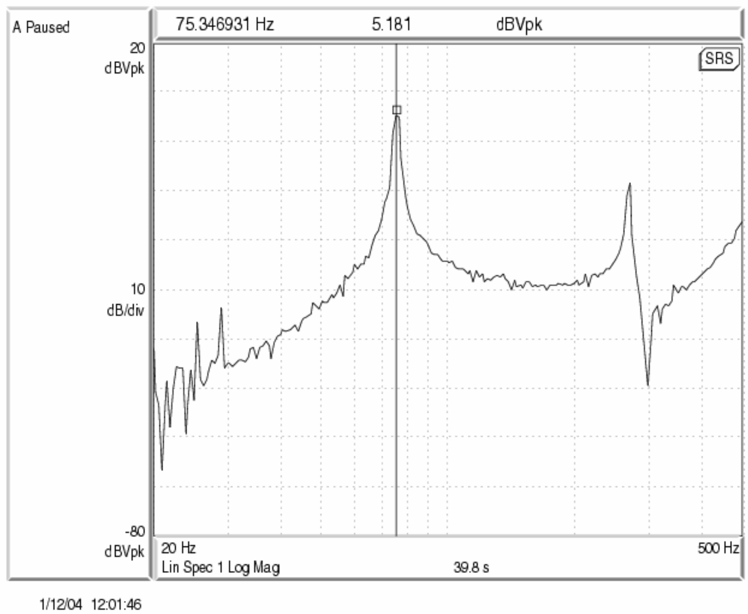
Example of Structural mode from ANSYS. Table (I) #10 transverse mode, 76Hz.



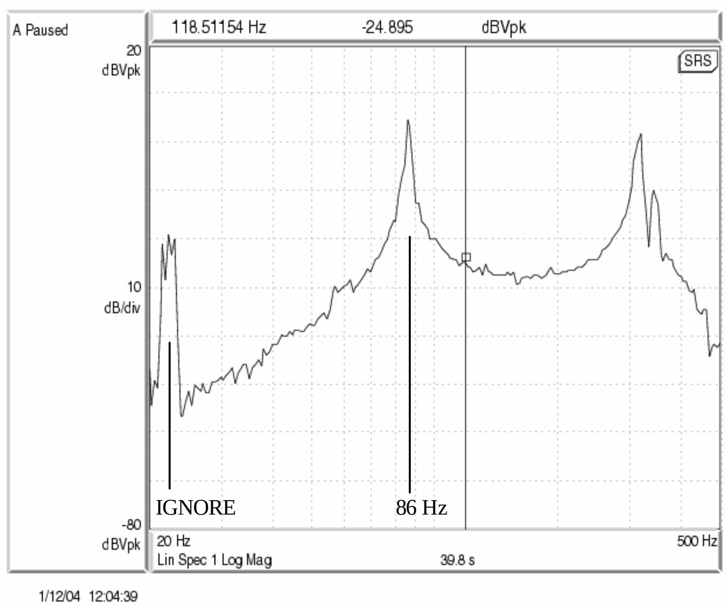
Example of Structural mode from ANSYS. Table (I) #10 longitudinal mode, 86Hz.

APPENDIX A (iii of iv)

Comparing results from the experiment for a bare structure: -



Example above is for a bare structure with 8 small clamps and no spacer measured in the transverse direction. The first mode is ~ 76 Hz. (Table (I) #4)



Example above is for a bare structure with 8 small clamps and no spacer measured in the longitudinal direction. The first mode is ~ 86 Hz. (Table (I) #4)

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APPENDIX B (i of ii)

1

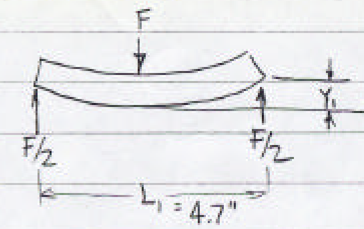
J. Romie 11/14/03

CALCULATION OF SPRING STIFFNESS OF DOG CLAMPS

- FIRST, CONSIDER THE CLAMP AS A SIMPLE BEAM IN BENDING:

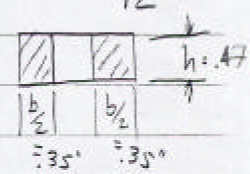
F = BOLT LOAD

F/2 = CLAMPING LOAD



$$Y_1 = \frac{F L_1^3}{48EI} \quad \text{WHERE } I = \frac{b h^3}{12}$$

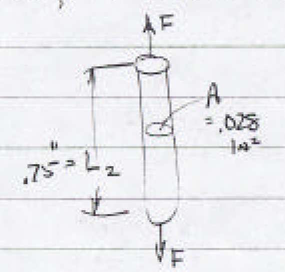
BEAM BENDING EQUATION



- SECOND, THE CLAMP BOLT IN TENSION:

$\Delta L_2 = Y_2$

$S = F/A$

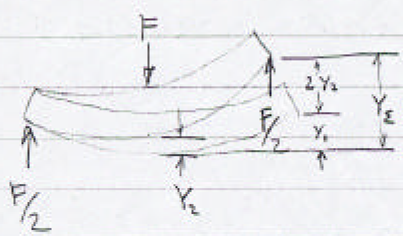


$$E = \frac{S}{\Delta L_2 / L_2} \qquad Y_2 = \frac{F/A}{E/L_2} = \frac{F L_2}{EA}$$

STRESS

STRAIN

- SUMMING THE EFFECTS (ASSUMING A CLAMP BOLT POSITION AT BEAM CENTER)



SUM

$$Y_\Sigma = Y_1 + 2Y_2 = \frac{F}{E}\left[\frac{L_1^3}{48I} + \frac{2L_2}{A}\right]$$

$$Y_\Sigma = \frac{F}{E}\left[\frac{4.7^3(12)}{48(.7)(.47)^3} + \frac{.75(2)}{.028}\right]$$

$$Y_\Sigma = \frac{F}{E}\left[357 + 54\right] = 411\, F/E$$

FROM BEAM BENDING — FROM BOLT STRETCHING

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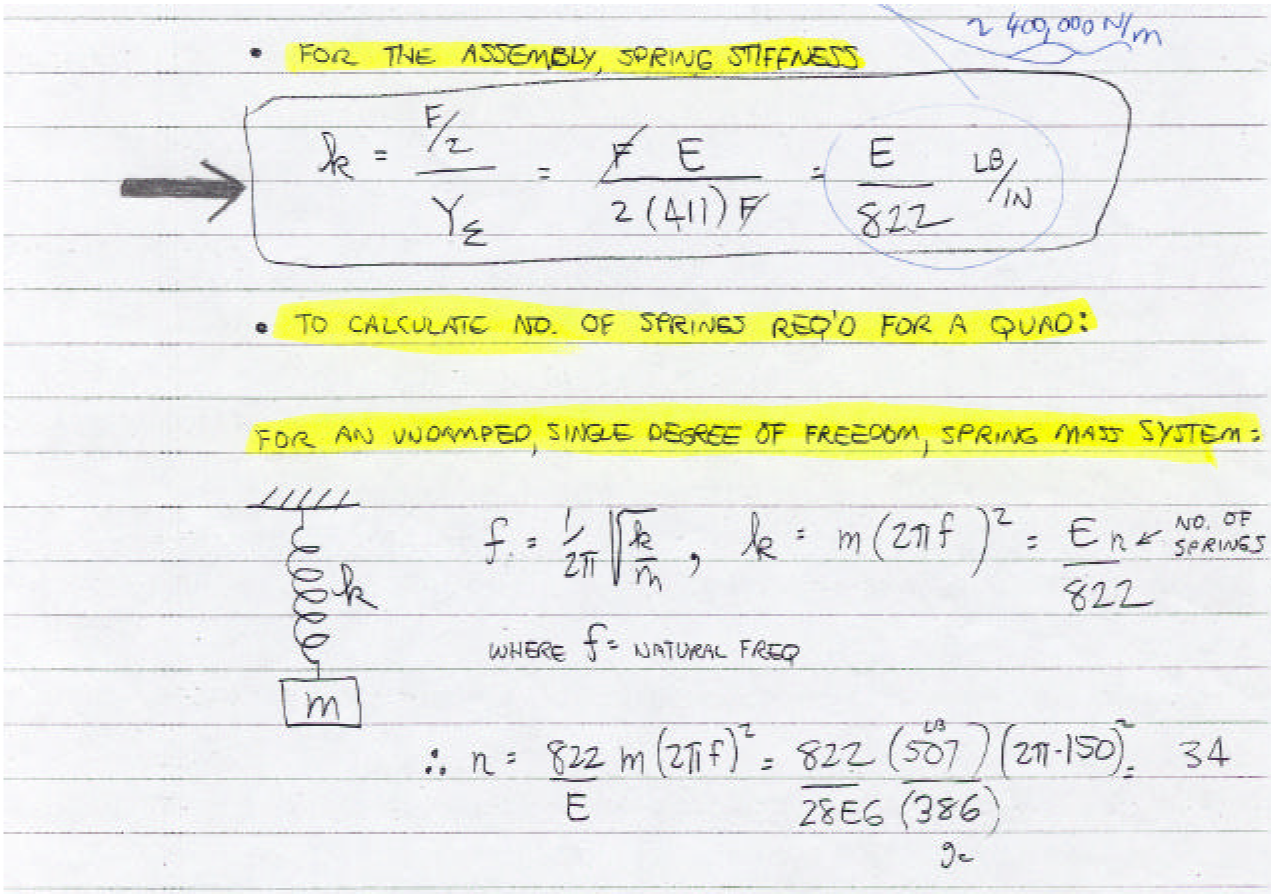
APPENDIX B (ii of ii)



- FOR THE ASSEMBLY, SPRING STIFFNESS

$$k = \frac{F/2}{Y_\Sigma} = \frac{F E}{2(411) F} = \frac{E}{822} \ \text{LB/IN}$$

~ 400,000 N/m

- TO CALCULATE NO. OF SPRINGS REQ'D FOR A QUAD:

FOR AN UNDAMPED, SINGLE DEGREE OF FREEDOM, SPRING MASS SYSTEM:

$$f = \frac{1}{2\pi}\sqrt{\frac{k}{m}}, \quad k = m(2\pi f)^2 = \frac{E n}{822} \leftarrow \text{NO. OF SPRINGS}$$

WHERE f = NATURAL FREQ

$$\therefore n = \frac{822}{E} m (2\pi f)^2 = \frac{822 (507 \text{ LB})}{28E6 (386)} (2\pi \cdot 150)^2 = 34$$

g_c

In the two scanned sections above Larry Jones has considered the effective spring constant of the combination of the clamp with a ¼-20 bolt. In the text Larry also considers how many “springs”, clamp / bolt combination, would be needed to fix a structure to the assumed stiff seismic system for advanced LIGO. Lastly, he considers the specific example of how many of a particular set of clamps would be needed to fix a quad structure of an assumed mass to the stiff seismic structure to obtain a frequency of 150 Hz.

It is clear from his analysis that the existing clamp, shown in *figure (vi)* could be improved upon in order to reduce the number of clamps required.

All of the tests outlined in the section 5 were conducted with the structure supported from beneath, as it is when mounted in a HAM chamber. Clamping differences would be expected to be greater when supported from above, as when mounted in a BSC chamber.

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8.0 The next steps

The following is taken from a list, compiled by Caroline Cantley updated by Calum Torrie and Janeen Romie that includes possible future subjects for consideration in analyzing the structures. The following list will be updated via an email "To do" list between Caroline Cantley, Calum Torrie, Janeen Romie and Russell Jones and it is this that should be referenced via the suspension weekly meeting notes on http://www.ligo.caltech.edu/SUS.html for the most up to date information.

Progression towards meeting the 150Hz requirement

- FEA
    - Design alterations
        - Existing MC – RJ / CIT
            - .SLDPRT and .SAT file to be created
        - Fat MC – JHR
            - .SLDPRT and .SAT file to be created
    - ETM cf. results by DC in T030044
        - with 512,00 node evaluation copy of ansys – CIT
        - in IDEAS – JHR and CIT
    - Modeling in more detail
        - Making better use of nodes available - EE
        - Brick elements and split volumes (introducing bias) – CAC?
        - Considering the stiffness of the table in the FEA – CAC?
- Experimental
    - Modal testing (Caroline…has been prompted but has had no time as yet)
    - BARE + 4 large clamps and no spacer – ?
    - BARE + 8 large clamps and no spacer – ?
    - BARE with 6kg + 8 large clamps and no spacer – ?
    - BARE + single transverse plates / sheets with 8 small clamps and no spacer – to do!
    - BARE + single longitudinal plates / sheets, 8 small clamps and no spacer – to do!
    - BARE + both sets of plates / sheets with 8 small clamps and no spacer – evaluating!
        - Applying cut outs to plates to represent reality – JHR
        - Adding more tapped holes to structure – JHR
- Report
    - With CAC, JHR and RJ for comment, in particular results the tables
- Web storage – CIT