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LIGO Laboratory / LIGO Scientific Collaboration

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Design development of the SUS ETM structures

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1 INTRODUCTION

This document traces the development of the SUS ETM structures through an iterative design process to meet the fundamental frequency requirements. It begins with the final design of the controls prototype and progresses through to the noise prototype design at the time of the preliminary design review. The document illustrates the lessons learnt from the controls prototype and how they formed the noise prototype design.

2 REQUIREMENTS

2.1 Performance requirements

The performance requirements for the noise prototype remain as they were for the controls prototype [Reference, LIGO E050159-00 section 1.1.4.3, Elastic mode frequencies, interface control document ICD]. Fundamental frequency limits, including structural and non structural mass, assuming a perfectly rigid support are:

- > 200Hz for the Upper structure.
- > 100Hz for the lower and sleeve structure combined
- > 100Hz combined upper, lower and sleeve structure.

Initial confirmation of the frequency is done by finite element analysis with a 15% contingency. Later the structures are to be made and qualified by modal testing.

3 CONTROLS STRUCTURE

3.1 Construction of the controls prototype

In March 2005 the SUS ETM structures for the controls prototype were as documented in LIGO-G050187-00-Z, structural design summary. Included in the document is a layout of the suspension, a mass budget, and a design study showing the development of the finite element analysis FEA. The ETM structures were designed in two parts an upper structure and a lower structure, this was to enable the “3 and 1” assembly procedure as documented in LIGO-T060039.

The upper structure houses the top stage and upper mass of the suspension; it has less functional demands than the lower structure and consequently has a simple design. The lower structure houses the upper intermediate, penultimate and test masses, as part of the “3 and 1” assembly it has to facilitate the welding of ribbons to glass masses making its design more complicated.

The upper structure is a simple truss frame predominantly welded together and the lower structure is made from piece parts bolted together, the combined structures are shown in figure 1.

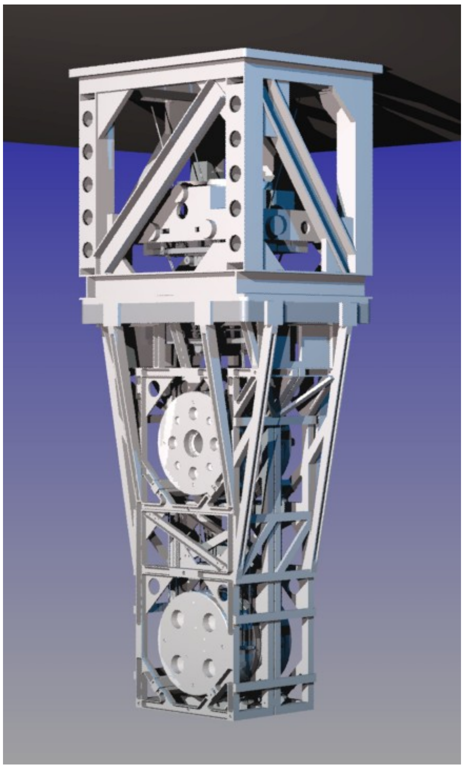

Figure 1. ETM controls prototype structure march 2005

3.2 Control structure frequency results

Having met the functional requirements the structures frequency performance was improved iteratively using FEA. After much iteration the best design for the structure was found to have a fundamental frequency of 85Hz, as shown in figure 2.

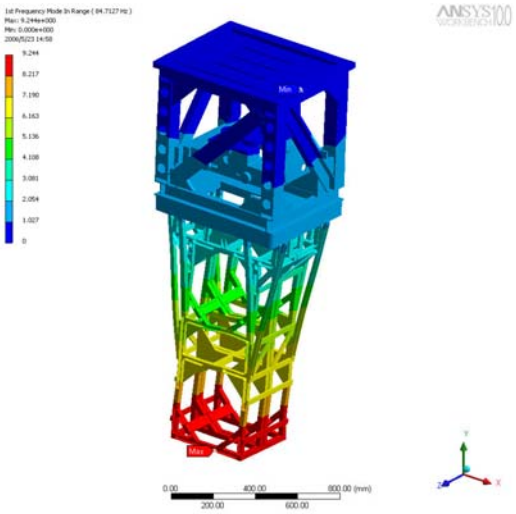

Figure 2. Controls structure with a first resonance of 85Hz.

3.3 Modal tests on the Controls structure

In July 2005 the controls prototype was built and a series of modal tests began at Caltech. The tests were done to compare the predicted finite element results with the measured frequencies. The document LIGO-T050237-03, Preliminary frequency analysis of the quadruple controls prototype (second) structure, records the frequency analysis of the controls structure as well as summarizing experimental data taken from a second structure tested at Stanford.

During the tests different configurations of the structures were tested, results were taken for the combined, upper and lower structures as well as some unique clamping and loading conditions.

Table 1. Summary of the control structures performance.

Controls Structure	Predicted Frequency [Hz]	Measured Frequency [Hz]	Discrepancy [%]
Combined	85	54	35
Upper	230	200	15
Lower	120	72	40

Table one summarizes the performance of the structures taken from the document, it demonstrates the discrepancy between the predicted and measured frequencies of the structures. The table shows that the combined structure has a large discrepancy of 35% between predicted and measured, by breaking down the structure into its component parts, it can be seen that the majority of this discrepancy is experienced by the lower structure. It was concluded that the upper structure discrepancy was small due to its simple welded construction and that the lower structure discrepancy was large due to its many bolted connections.

4. THE NOISE STRUCTURE

When using the finite element solver ANSYS workbench the models were imported directly from the Pro-Engineer CAD package. The CAD models were de-featured, such as suppressing holes, to simplify the mesh. ANSYS workbench uses a contact setting to determine how contacting bodies move relative to one another. The assembly models of the SUS structures were meshed with the default, bonded, configuration for contact regions. A bonded contact meant that no sliding or separation between faces or edges was allowed, this means that the contact regions could be thought of as of as glued or welded. Because the workbench solution treated the assembled structures as perfectly bonded together, it made no account of interface issues with the bolted connections. It was decided in order to model the structures more representatively we needed to adopt a method for modeling bolted joints. Being able to model the behavior of bolted joints would mean less discrepancy between predicted and measured results giving a more realistic way to design the structures.

Document LIGO T060059-00-K, Finite element analysis of advanced LIGO SUS ETM structures, records the majority of analyses work done on the structures beginning with simplified models of the bolted joint problem. An initial study of the bolted joint problem took a simple structure with a bolted flange and examined the way ANSYS workbench used contact elements and compared this to modeling actual bolts and screws (T060059, section 2, Bolted joints and contact stiffness). It was concluded that the FE results were only representative of the numbers you input for contact stiffness, or the modulus of the bolts, no real rationale could be derived that would give a universal solution to all structures.

Further analysis in this section (T060059, Analysis of complete structure) goes on to look at a new design for the implementation ring that reduces its mass and the number of bolts needed to connect the upper and lower structures together. Again modeling the interfaces with a bonded contact setting failed to pick up on the subtlety of the design.

A further study was done to investigate the behavior of the lower structure with particular attention to the connection between it and the implementation ring (T060059, Section 4, lower structure design). The aim of the study was to access whether the connection of the lower structure to the implementation ring could be made stiffer. It concluded that the dominant feature of the lower structure design in terms of frequency performance was the outriggers. This meant that design effort should focus on what could be done to optimize the outriggers.

A series of modal tests were done at Caltech recording the change in the lower structures integrity when removing component parts (T060059, Section 5, Structural integrity comparison between FE and modal results). In progressive steps the outriggers, side plates and one half of the structure were removed and the new frequencies measured, exactly the same thing was done with an FE model and comparisons made. Again it could be seen that the biggest contribution to the structures integrity was made by the outriggers, followed by the side plates. A very noticeable effect was that the side plates, necessary to stiffen the structure, had twice the impact in the FE model as they did in the actual structure. An explanation for this might be that the bolts in the real structure were moving. This again focused the design effort on the outriggers and threw more suspicion on the bolted joints.

A lower structure design developed exploiting new ideas for outriggers with “x” bracing. The new design made it possible for the outriggers, on each face of the lower structure, to contribute to the first two modes, longitudinal and traverse, and not just the mode shape they opposed. For maximum effect the outriggers connected to the hard or stiff points of the upper structure, those being the four corners. Unexpectedly this new structure did not improve on the frequency from previous designs. Possibly because the cross sections of the new outriggers exploiting “x” bracing were comparable to the sections of the monolithic frame, therefore adding mass and not increasing the stiffness (a full explanation is given in T060059, section 6, effective “x” bracing, by Dennis Coyne).

Attempts to model bolted joints had failed to highlight an insight into their behavior. Ideas for improving the design then turned towards more radical solutions such as reducing the mass and bracing the structure to the seismic table. It was found that by bracing the lower structure to the seismic table an idealized 50Hz improvement was achievable (T060059, section 7, supporting strut from the seismic table).

An idea for reducing the mass of the lower structure meant losing two of the four face plates (T060059, section 8, Reducing the lower structure mass). It could be seen that a saving of 10Hz could be made by this approach, although the disadvantage would be the associated problems with other systems.

Work by Brian Lantz showed that it was likely to be possible, but difficult, to control the SEI when loaded with the controls prototype structure with a minor infringement of science requirements. Brian measured the controls structure as having a natural frequency of ~61Hz (reference LIGO-G060007). This work also looked at the possibility of electronic and passive "constrained layer" damping. The conclusion from the work was that the design group should aim to improve the first mode of the structure by 10 to 20 Hz and that we may need to add passive damping, depending on the results of tests with the real noise prototype structure on the real seismic platform (reference LIGO-G060056).

A continuing frustration was the inability to develop a rationale to understand the behavior of the bolted joints. The lower structure had multiple bolted connections in different orientations making it difficult to see what exactly was contributing to the problem. In an attempt to understand the problem a simple structure was devised specifically for the purpose (LIGO-T060086-00-K, Finite element analysis of the bench test structure to examine the behavior of bolted joints). The plan was to make a structure that could be tested in two configurations, one with and one without its structural integrity reliant on bolted joints, this would provide two data points to compare with finite element predictions. The simple design of the structure made the interpretation of the results straightforward.

The work shows that the bolted joints behave very similar to the predicted results of the finite element model, concluding that a well designed bolted joint is as good as a weld.

Through all of the above it was clear we did not understand why our structure was not behaving as predicted by the finite element models. We knew that outriggers with "x" bracing could make a valuable contribution to increasing the frequency. Other attempts at improving the frequency would mean increased interaction with other systems or infringing on other systems space envelopes. To our advantage we had previously noted that the upper structure behaved close to the predicted results. Taking everything into consideration a new design, involving a third structure known as the sleeve, was developed.

The new sleeve design would bypass the bolted joints of the lower structure reducing their negative impact on the frequency, it would allow the lower structure to be light weighted reducing the effective mass, and it would offer a very integrated outrigger design having a similar construction to the upper structure, which we knew was performing as predicted, thus giving us confidence in the solution.

The new sleeve design was developed through simple beam analysis to understand the choice of section members, the nature of the "x" bracing and the effect of adding mass (reference, LIGO-T060087-00-K). Once the beam analysis had characterized the structure the frequency performance was further improved upon by light weighting the lower structure (reference, LIGO-T060088-K). The design of the noise prototype structure, upper, lower and sleeve are shown in figure 3. The new sleeve design has now been manufactured and is awaiting a series of modal tests to determine its frequency and that of the overall noise structure.

The FE predicted frequency of the overall noise structure is ~100Hz. Because of the introduction of a third welded structure, bypassing the bolted joint problem, we expect the measured frequency of the structure to be closer to the FE prediction bringing the actual frequency of the structure to ~75Hz.

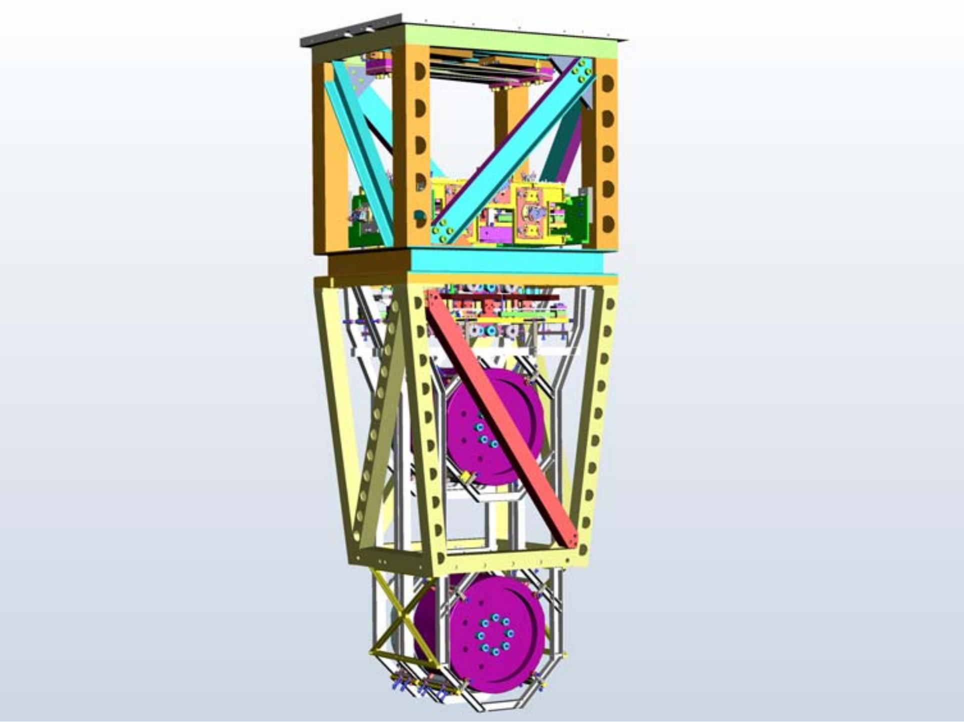

Figure 3. Noise prototype structure.