CATSAT Structural Design

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ABSTRACT

CATSAT(Cooperative Astrophysical and Technology SATellite) is based upon an inexpensive, light, stiff and easily assembled structure. This paper details the overall design philosophy, manufacturing processes, and initial test results. The design utilizes flat aluminum panels that are screwed and bonded together, resulting in a stiff structure that costs less than $3000 and requires less than 40 hours to assemble. Honeycomb panels and rivets are not used in this structure making it very easy to manufacture, service and accommodate modifications.

The horizontal shelves in the structure are supported by vertical panels to transmit forces throughout the structure. By locating components over or adjacent to the vertical panels, acceleration forces are transmitted throughout the structure as compressive and shear forces.

Finite element analysis of the structure was performed to verify the strength of the panels and ensure that the resonant frequencies of the structure were met specification. Vibration testing has demonstrated that the axial frequency of vibration of the structure is 230 Hz.

A critical component of the CATSAT design is the cooperative effort of the three institutions involved. The overall structural design was accomplished as senior projects in the Department of Manufacturing and Mechanical Engineering Technology at Weber State University. The University of New Hampshire and Leicester University were responsible for integrating their individual components into the overall structure. The methodology and configuration control processes that resulted in a successful structural design are discussed.

PROJECT ORGANIZATION

The CATSAT project at WSU was organized as senior projects in the Manufacturing and Mechanical Engineering

Technology Department (MMFET). Students from both the MET and MFET programs were involved in the structural design under the direction of the same academic advisor. At WSU, senior projects are traditionally included in the fall, winter and spring quarters of the students senior year. The CATSAT design effort at WSU has been successful because the major portion of the work is scheduled for the summer quarter when students do not normally take ET classes. The students complete two quarters of capstone work during the summer, and finalize details and documentation during the fall quarter. This academic organizational philosophy has been very successful because the students work over the summer without conflicts from other courses and some students are willing to work full time on the project. Because the students still have their senior year to complete, unmotivated students can be removed from the project, and assigned to a project that they are more interested in fall quarter.

The project is also successful because it is a full time effort for the faculty advisor. The advisor is able to work alongside the students and constantly monitor and guide their progress. The students are very motivated when the faculty advisor is as involved in the project as they are, rather than acting as a peripheral advisor.

In any cooperative project involving multiple sites, system engineering is a difficult organization problem. Compounding the systems engineering problem, is the reluctance of students to document their work, and the difficulty of defining system requirements before a design is established. Because this is a first time effort, there is not a history of test programs to base specifications on, and a substantial effort needs to be devoted to developing an adequate environmental test specification. This situation has prompted a reorganization of the MET 432 Mechanical Instrumentation course at WSU to be oriented towards system engineering. The major laboratory exercise involved instrumenting the prototype CATSAT structure with strain gages and accelerometers, and measuring the structural transmissibility with a sine sweep input. The students were responsible for all aspects of the test, including: defining test specifications, installing the transducers, setting up the amplifiers and data acquisition system, and debugging the overall setup. Because the students were responsible for calibration and debugging, which is not normally the case in canned lab exercises, they learned the subtle details of instrumentation, and how different effects interact in a measurement system. Upon completion of data gathering, the students discussed and documented the data and structural impact of stiffening shelves, adding mass, and how changes affect the overall characteristics of the satellite. This course received very high rating as a result of this hands on application and the students were very enthusiastic about the overall exercise.

DESIGN PHILOSOPHY

CATSAT is 28” square and 30” tall with a target weight of 300 lb., and is designed to be structurally stiff and easily manufactured, assembled, and modified with low cost as the overall design constraint. The CATSAT design has been successful because weight is not a critical design constraint and structural components can be added as needed to stiffen various panels. However, this does not mean that the structure is unnecessarily heavy. At this point in the design the overall weight of the structure is less than 50 lb., including fasteners, angle brackets, shelves, and side panels, and there is approximately 40 LB of mass contingency.

The CATSAT structure is designed as an assembly of cubes that are assembled into the overall structure as shown in Figure 1. The panels are fastened together with 3/4” aluminum angle stock and 6-32 screws and with floating nuts that are nominally spaced 2” apart. The nuts float .015” in all directions from the centerline of the bolt, so that overall there is a .030” total true position tolerance on the fastener location. The advantage of these floating fasteners is ease of assembly due to increased positional tolerances, but the compromise is weight. Currently, over 8 LB of fasteners are used in the structure, which is more than double what rivets would have been. However, the use of floating nut inserts has made it possible to assemble and disassemble the structure due to many blind nut locations.

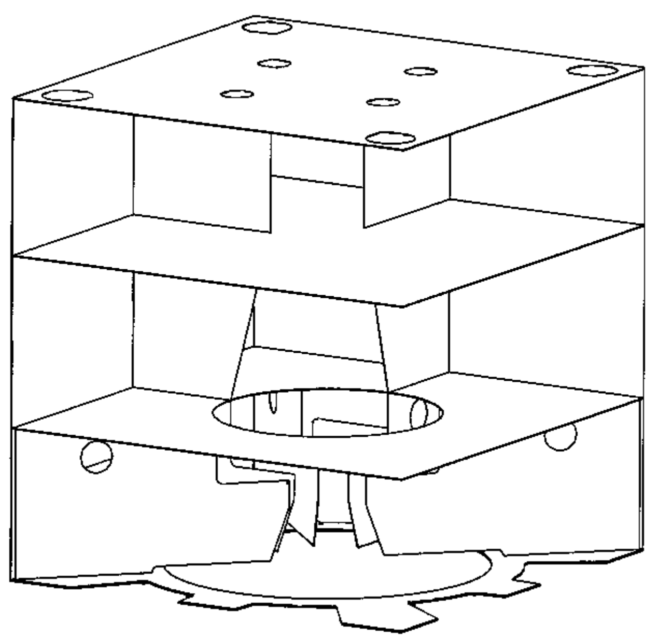

Figure 1.
Cutaway view of the CATSAT solid model showing how horizontal panels are separated with vertical panels resulting in an overall assembly of box sections.

The CATSAT structure is assembled with over 1400 fasteners and ensuring that all the holes and fasteners line up is a major design task. This problem was solved by using a flat pattern analysis in AutoCAD as shown in Figure 2. Each unique panel is laid next to its mating panel and the spacing is set to ensure a gap of .025” between the two panels. The hole pattern is laid out down the centerline of the angle stock and the fastener spacing is adjusted to give an even hole pattern. The hole pattern is then transferred to the panel and the corresponding .155” holes are then detailed on the panel print. By paying careful attention to the spacing between each flat panel during layout of the pattern, the proper panel spacing is ensured in the final assembly. It was found during assembly that it is very important to ensure that all of the panels are squared up before tightening the fasteners. All four of the side panels must be loosely attached to the frame and the complete assembly squared up before tightening the fasteners.

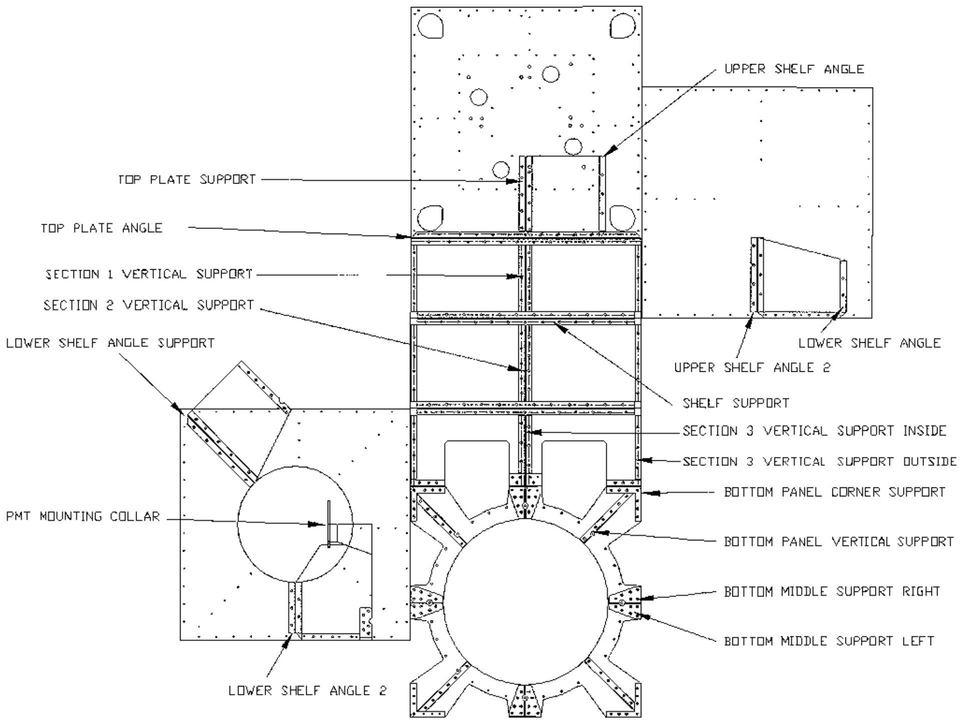

Figure 2
Flat pattern analysis that was used to track hole and bracket locations in the design of the CATSAT structure.

It can also be seen in Figure 2 that most of the panels are joined with 3/4” angle stock. The exception to this method is seen on the bottom shelf of the satellite. There are 12 brackets associated with the lower shelf and 8 bracket/rib pieces associated with the albedo detector mounting structure. These 20 pieces are the only machined bracket pieces in the structure, but do not require complex machining methods. By relying on a standard 3/4” angle, that is readily available locally, and easily machined brackets, the high costs traditionally associated with a satellite structure are eliminated.

The greatest cost savings in CATSAT comes from using flat aluminum sheet stock, rather than honeycomb, for all the panels. All panels were drawn in AutoCAD from the flat pattern analysis and the *.DWG files were transferred directly to a laser cutting shop. CNC machine code was generated directly from the *.DWG files and the flat panels were all laser cut with .002” tolerances. This means that all features including panel edges, holes, curves, and cutouts, were all within .002” of the basic dimensions. All panels were deburred by hand, cleaned, conversion coated, and assembled. Each panel cost approximately $50/each and the exceptional tolerance capability, combined with the computer controlled manufacturing process, resulted in a structure that went together the first time with no hole misalignments or hand repairs required.

There was some discussion as to the metallurgical effects of laser cutting on the 6061-T6 aluminum. The current development structure has experienced approximately 10 hours of vibration testing. No noticeable fatigue cracks have been observed and so it is felt that crack initiation at laser cut edges is not a concern. The biggest problem with the laser cut panels has been large burrs. The bottom edge of the cut generally has .010” burrs that must be removed. The burrs are softer than the base metal, and easily removed, but it is a labor intensive operation to deburr all the holes in CATSAT.

In summary, the use of a flat pattern analysis in AutoCAD, laser cutting, 3/4” angle stock, relatively simple machined brackets, and floating nuts, has resulted in a very inexpensive, easily assembled, and easily modified structure.

STRUCTURAL ANALYSIS

All finite element analysis on the CATSAT structure was accomplished using SDRC I-DEAS Master Series. Figure 3 shows the finite element model that was used to calculate the natural frequencies and mode shapes of the overall structure.

Initial FEA results show that the first axial natural frequency is greater than 200 Hz, and that the first lateral natural frequency is greater than 150 Hz. Even though this is a preliminary analysis and does not include the total mass of the satellite, which will increase as the design matures, it indicates that the structure is very stiff with a large design margin to accommodate increased mass.

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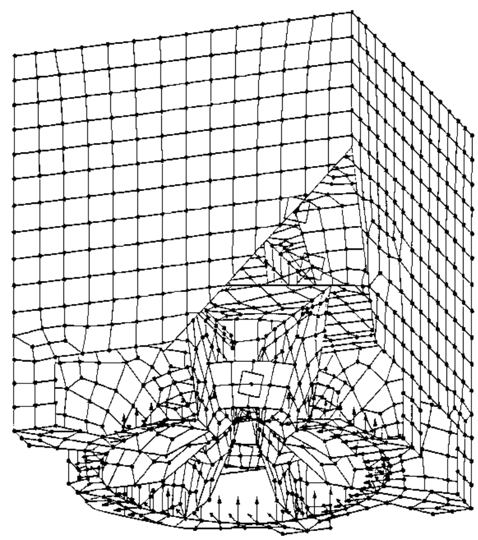

Figure 3.
Finite element analysis model of CATSAT structure. Model is constructed of thin shell elements, rigid links, and lumped mass elements and was used to calculate the first axial mode of vibration of the overall structure.

The real issue with this type of design is the stiffness of the interior shelves. These shelves are thin, loaded in bending, and the attached masses will cause extreme bending stresses under load. Even more critical will be the large Q factors associated with a thin, mass loaded shelf, without the structural damping normally associated with honeycomb panels. There are four shelves within the CATSAT structure: the bottom shelf which is the launch interface, and the lower, middle, and top shelves. The lower, middle, and top shelves are .050” thick flat panels, and the bottom is .100” thick with a large diameter hole in the center. There are 8 vertical panels 45° apart in the lower section and 4 vertical panels 90° apart in the center and top sections. The individual components in the midsection are placed directly over, or close to, the vertical panels as shown in Figure 4. By placing the components close to the vertical supports, the forces from them are reacted out as shear or buckling forces, rather than bending forces in the shelves.

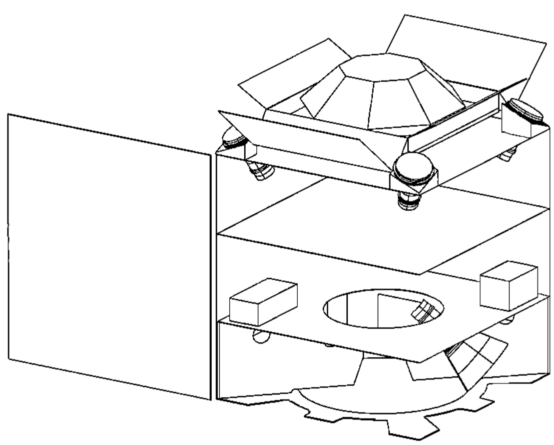

Figure 4
Cutaway view of the CATSAT structure showing how components in the middle section of the satellite are placed over vertical panels in the lower section.

The difficulty with interior vertical panels is that any change in shelf thickness requires a redesign of the complete structure because the spacing of the shelves will change. To eliminate expensive redesigns during the design cycle, a standard .050” thickness of the shelves has been specified. to accommodate stiffening and resonant frequency requirements, the individual satellite components are designed with large bases that are easily modified. The bases are larger than the footprint of the component, and serve to distribute vibration stresses across the shelf rather than concentrating them in one location. When the components are installed in the satellite, the bases are cleaned, coated with 3M 2216 B/A gray epoxy, and screwed to the shelves. It is important to not use base panels thicker than .100” so that there are not large stiffness gradients in the shelves. If more stiffening is required, stepped bases should be used to smooth out the transition from the stiff base to the flexible shelf.

At this point in the CATSAT development, the concept of epoxied on stiffeners has yet to be vibration tested. Preliminary FEA of the structure indicates that the bonded panels will be very effective at stiffening the shelves and damping their motion, but structural testing results will be reported in the future.

STRUCTURAL TEST VERIFICATION

All structural testing will be done at WSU using Ling Model 540 shakers. WSU has both vertical and horizontal shaker systems and a Vibration Research Corporation sine/random controller in a 486 PC machine. Data acquisition is based on a pentium PC with National Instruments AT-MIO-16X and AT-DSP2200 input boards running under LabVIEW.

At this point in the CATSAT development cycle, structural testing is just beginning, and the purpose is design verification. Qualification and flight testing will occur later in 1996 and early 1997. Two types of testing are currently being conducted, a low level (.005 g^2/Hz) random vibration that is level from 20 to 2000 Hz and a 1 g sine sweep from 20 to 2000 Hz. Structural transmissibility functions are measured from the low level random tests. Low vibration levels are used to avoid structural phenomena such as panel to panel impacts and panel motion in the bolted joints. The sine sweeps are used to isolate resonances and measure amplification ratios.

The CATSAT test structure is mounted to the shaker with a 1" thick aluminum annular ring fixture with an outside diameter of 26" and an inside diameter of 14.5". The purpose of using a ring rather than a solid plate is to isolate the satellite from the 900 Hz armature resonance of the shaker that manifests itself as an oil canning mode of the shaker top. There are two other shaker resonances at 1400 and 1500 Hz as shown in Figure 5. The controller can compensate for these resonances, but it is important to know the source of the resonances so that they are not misinterpreted as a satellite structural problem.

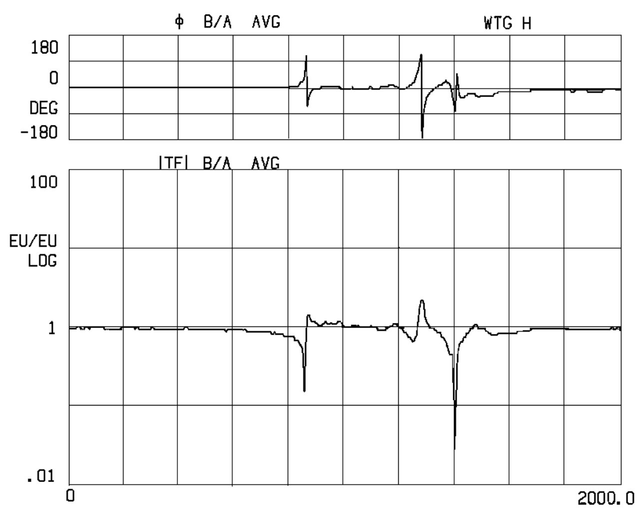

Figure 5.
Shaker resonances as measured on the CATSAT mounting ring.

The structural transmissibility function between the base and one of the upper corners is shown in Figure 6. It is seen that there are three strong resonances: 230 Hz, 450 Hz, and 1500 Hz. Figure 7 is a 0 to 500 Hz transmissibility function showing the 230 Hz resonance in more detail.

There are several important features of this data that need to be discussed. First, the axial resonance of the satellite is 230 Hz, which indicates that the overall structure is very stiff and will easily accommodate additional mass during the design cycle. The data also shows an amplification factor at 230 Hz of 10. Even though this is a high amplification factor, it is not a critical structural problem because the amplitude of vibration at this frequency is low. However, it is very important to know how the hard x-ray (HXR) detectors at the upper corners respond to the structural resonances. Using the Field Data Replicator in the Vibration Research controller it is possible to use the measured response at the HXR interface as an input function. Extensive testing will be performed in the future using the field data replicator to ensure the survivability of all the mounted components.

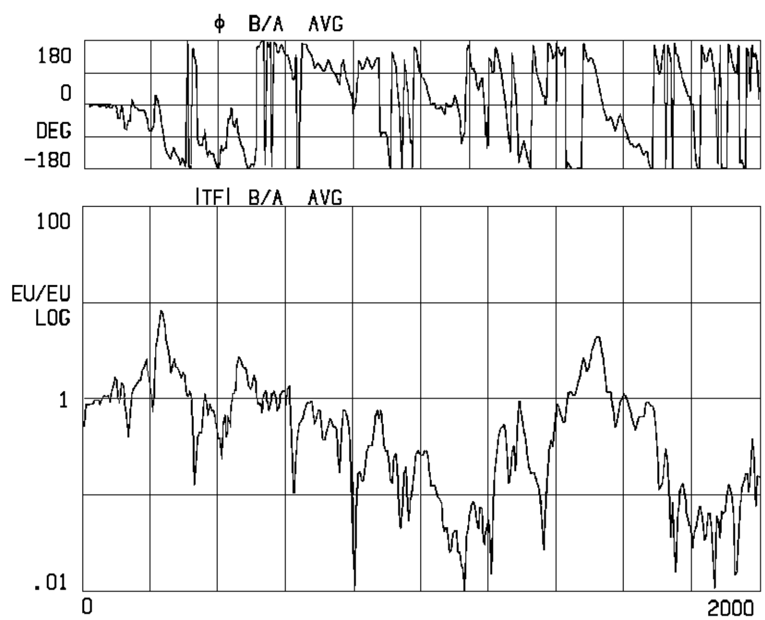

Figure 6.
Structural transmissibility of the CATSAT structure, as measured on the top plate, showing the 230 Hz axial resonance. Function was measured with a .001 g^2/Hz random signal.

Another important feature of the transmissibility functions is that they are not smooth and appear very ragged. This is due to rattling with the structure during the vibration test. Impulses in the time domain transform to impulses in the frequency domain, resulting in “noisy” spectrums. The conclusion of this is that it is very important that all panel edges be fixed in this type of a structure. Thin panels, with low damping ratios, can exhibit large displacements at resonance, and the motion of the panels must be controlled. The bolted joints used throughout the satellite will dissipate some energy due to friction, but the final configuration will be epoxied together. 3M 2216 epoxy is classed as flexible and some energy will be dissipated in the adhesive, but the best way to stiffen and control resonances in this structure is with the base stiffening plates and strategically placed stiffening ribs.

It is very important that all panels are adhesively bonded to their mounting brackets and that there is a gap between perpendicular panels. If this practice is not followed panels rub against adjacent panels creating aluminum filings that will disperse throughout the structure. Also the desired force transmission path is through the bolted joints, rather than through a non supported panel edge. CATSAT is designed with a nominal gap of .025” between all mating panels. The impact noise in the current structure is due to the incomplete albedo detector mounting structure. At this time there are free panel edges adjacent to each other that exhibit extreme buzzing during testing. This is not the final configuration, but the buzzing does affect the structure in this testing.

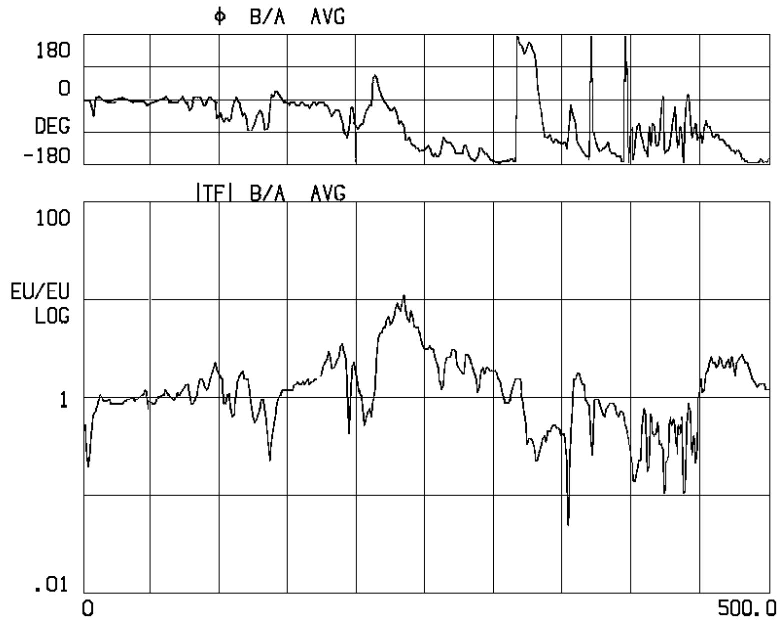

Figure 7.
Structural transmissibility of the CATSAT structure from 0 to 500 Hz showing the details of the 230 Hz axial resonance.

It is also important that free edges of highly loaded panels be reinforced. For example, the albedo detector mounting plates are fixed on three sides and free on the fourth. These panels show high resonance amplitudes which would be controlled with a fully constrained design. The final configuration will have a machined bracket/edge stiffening rib assembly.

SUMMARY AND RECOMMENDATIONS

1. The CATSAT structure has proven to be very inexpensive, easy to manufacture, and structurally robust.
2. The use of a flat pattern analysis in AutoCAD has proven to be an effective method to layout the panels and ensure their correct layout in final assembly.
3. The use of laser cutting has proven to greatly reduce the manufacturing costs of the panels and provides excellent tolerance control.
4. The modular construction concept of horizontal panels separated and supported with vertical panels has proven to be a robust design.
5. The first axial resonance of the CATSAT structure is 230 Hz.
6. The CATSAT structure is very stiff with a large design margin for additional mass during design development.

7. The use of 3/4” angle stock and easily machined brackets has contributed to a low cost structure.
8. It is recommended that panels be bonded to their mating brackets.
9. There must be a gap between adjacent edges of panels to ensure that forces are transmitted through the bolted joints and that the panels do not abrade each other.
10. All edges of loaded panels must be supported for the design to be structurally sound.
11. Components should be placed over, or adjacent to, vertical panels for support.