Flexure Based Mounts for Sensitive Payloads: A Management and Engineering Study

by

Daniel K. Moon

Submitted to the Department of
Mechanical Engineering in Partial
Fulfillment of the Requirements for the
Degrees of

Bachelor of Science and Master of Science

at the

Massachusetts Institute of Technology

June 2001

Signature of Author ....
Department of Mechanical Engineering
June 6, 2001

Certified by ....
Alexander H. Slocum
Professor of Mechanical Engineering, MacVicar Faculty Fellow, MIT
Thesis Supervisor

Accepted by ....
Ain A. Sonin
Chairman, Department Committee on Graduate Students

Flexure Based Mounts for Sensitive Payloads: A Management and Engineering Study

by

Daniel K. Moon

Submitted to the Department of Mechanical Engineering
on June 6, 2001 in Partial Fulfillment of the Requirements for the
Degrees of Bachelor of Science and Master of Science in
Mechanical Engineering

ABSTRACT

With the cooperation of the Los Alamos National Laboratory and the Massachusetts Institute of Technology, an investigative and design study was performed to examine the history of the W80-0 Area Aft Mount, understand its performance, and explore potential new designs. Simultaneously, professional and technical enhancement of the author was achieved.

The historical organization of LANL influences the design space for this project, and understanding those relationships provides insight into concept generation and selection. In addition, the current organizational structure within the laboratory as well as with its customers provides additional constraints that must be managed technically.

The new design concepts attempt to simulate the nonlinear load vs. displacement characteristics of the previously employed B3223 cellular silicone Pad Mount. New concepts separate the spring and damping characteristics of the cellular silicone into separate component parts. This uncoupled method should allow the new designs increased variability and control with respect to matching original Aft Area Mount performance in shock mitigation and deflection limiting.

Thesis Supervisor: Alexander H. Slocum
Title: Professor of Mechanical Engineering, Macvicar Fellow

Contents

Chapter 1: Project Definition

Chapter 2: Understanding the Original Design

Chapter 3: Functional Requirements

Chapter 4: Future Paths

Figures

Chapter 1: Project Definition

Identifying the Key Players: Thesis

The first phase of my thesis was to find a 'suitable' topic, where 'suitability' depended upon the topics potential success in meeting the needs of the key players, Los Alamos National Laboratory, MIT, and myself. In the past, MIT's involvement had been limited to logistical forms and checkups. However, for the graduate phase, I needed a faculty thesis advisor to officially represent MIT and to eventually approve my work for the Master's degree. Many MIT students find a topic by first finding a professor they want to work with. The criteria for this search are the student's field of interest, the quality and reputation of the professor's work, and funding availability. The student and professor then select and agree upon a thesis topic that meets their needs.

My thesis topic search was unique in that the Los Alamos National Laboratory (LANL) was the primary party whose 'needs' had to be met by my thesis work. LANL not only determined the technical problem I would work on, but also provided the funding for my work and tuition. Hence, my thesis topic search became the inverse of the typical student's problem. Instead of finding a professor whose work matched my interests, I needed to match my LANL project with a professor interested in acting as advisor.

Indeed, before returning to LANL for the summer, I had tried to 'plan ahead' by locating a professor willing to act as an advisor. Upon arriving at LANL and searching through available project topics, we had a difficult time isolating aspects of these technical problems that matched the specific research area of this professor. I discovered that the project definition power lay within LANL because their technical needs and issues were predetermined. The cumulative research conducted by the MIT Department of Mechanical Engineering is well developed and spans many disciplines and technical areas, yet any individual professor has a much narrower field of interest. Consequently, I realized it was wiser to hold available projects as constant and vary potential professors to choose from. While the specific professor who would represent MIT was undetermined, I continued with the project definition process, confident that an MIT advisor could be found within the ranks of MIT's Department of Mechanical Engineering later on.

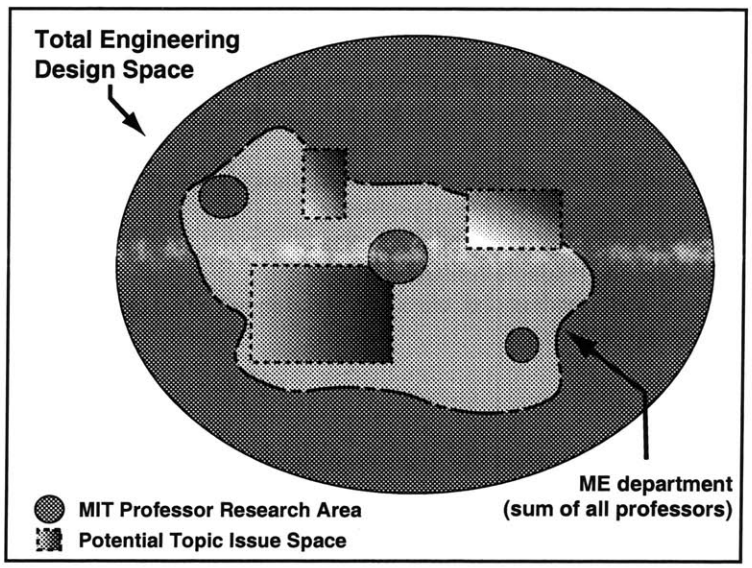


Figure 1. Engineering Design Space Divided by Topic, Professor, and Department Areas.

Defining Key Needs and Corresponding Goals

With Los Alamos National Laboratory and I defined as the key players, I tried to identify the essential requirements which my work must fulfill in order to be called a success. My single requirement was to complete work acceptable for partial fulfillment of the requirements for the Master of Science degree from MIT. The official metric for this need was obtaining the signature and approval of an MIT thesis advisor. LANL did not have such binary pass-fail requirements for me. Instead, my group only required that my work be unclassified so that it could be publicly available.

Although the needs were very broad, all parties involved had important goals that shaped the topic choice.

My objective to gain real world engineering experience carried over from my past internships with LANL. I had a strong desire for my work to serve as a means of enhancing my technical knowledge without immersing me too deeply within a niche discipline. Finally, I wanted my work to visibly contribute to LANL's mission of stockpile stewardship.

The main goal of my LANL mentors was that I succeed in obtaining my thesis, and I appreciated this support. They realized that if I successfully graduated, it would improve the likelihood of me returning to Los Alamos as a full-time employee. They hoped that my thesis work would help train and indoctrinate me into their mission for the long term. Finally, technical excellence of the thesis work was always used as a goal and was expected of me. With quality expected but no hard set LANL deliverables required, I was given a good deal of freedom while being motivated to produce usable work.

Finding the Technical Topic

Finding the technical topic required discussion with my supervisors regarding ongoing and available projects. After investigating options, we selected one that met the requirements with the most potential to attain the goals. This approach enabled my supervisors to make the difficult decision to offer me a project with a weapon system and mentor that I had never worked with during my previous two years at LANL. Though I had spent over two years working with projects related to the B61, a project with the W80-0 system had the greatest potential to achieve the goals set forth. I had built a solid relationship with my mentor over the previous two years and a continued working relationship had been the natural and assumed course of action. However, my mentor's understanding of the long-term goals enabled him to take me off his team and transfer me to a separate team and system under someone else. Although it was in his individual interest to keep me working on his system, he acted professionally and led me to the most appropriate project. Despite my transfer to another team, my mentor continued to advise me throughout my graduate phase and served as a valuable resource.

All the available projects had the technical potential required, but design project for the W80 Area Aft Mount had the most unclassified content, which made it the most attractive.

Criteria for Topic Selection

During the selection process, potential projects were evaluated based on a first-cut level understanding of the issues involved. A deeper investigation was required before committing to the project. The keys to understanding this problem were:

Familiarity with the background and context of the technical problem
Understanding the specific technical problem
Identifying the involved parties and their roles
Identify the time and resource constraints

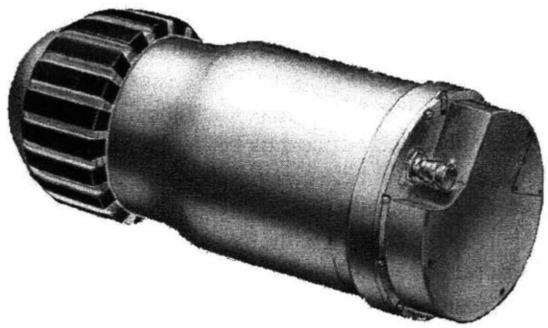
After these factors were better understood, we could make an informed decision to move forward with the W80 project or to go back to the project search.

Format of Thesis

The graduate phase of the EIP program was educational in the traditional academic sense; I gained technical experience and skills. However, a major component of the graduate phase was managing the non-technical project issues. Indeed, the decisions made about how to direct the technical work were arguably as important educationally as the technical information itself. Without direction, a technical problem can spiral down into increasingly fruitless detail. In addition, while I may not be able to utilize all the technical experience at my next job, the problem management skills gained from this project are directly transferable to future endeavors.

In light of my dual educational experience, my adviser and I decided to create a new thesis format to represent both sides of a technical project. For the rest of the thesis, the left column of the page will be devoted to the project management issues while the right column will be devoted to the more intensely technical issues. A reader interested in the general organizational and resource issues can read the left column, receive enough technical context to understand the project, and not be inundated with pages of technical detail he or she is not truly interested in or familiar with. For readers who are interested in the technical progress and logic underlying my work, the right column of each page should flesh out the engineering issues in more detail. For those who want to see a case study of how a real world engineering endeavor is a combination of project management and technical analysis, the left and right columns can be read together by section. This thesis has been laid out such that the topic at any given point in a column should be related through the management⇔technical gateway to the contents of the neighboring column.

Although this thesis is a first attempt at such a presentation, we believe that this format has great potential for presenting technical efforts and results to laymen or managerial audiences without sacrificing technical context for those readers who appreciate it.



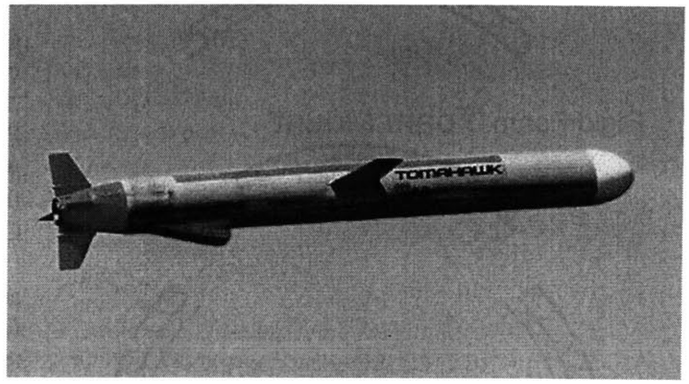


Figure 2. W80-0 with Area Mount (left) and Tomahawk missile (right)

Background and Context *(details right)*

The W80-0 is a warhead developed by Los Alamos National Laboratory in the 1970's and 1980's. The Tomahawk Land Attack Missile Nuclear (TLAM-N) is a submarine torpedo tube launched cruise missile, which delivers the W80-0 to target. The Area Aft Mount is a mechanical interface part between the W80-0 and the Warhead Can (a Tomahawk part).

Further background information was collected, and an understanding of the weapon's development history enabled me to keep my work progressing in directions relevant to the overall system. In addition, the background research helped me better understand the technical issues and the key parties' roles.

W80 Background

The W80-0 is positioned within the Tomahawk Warhead Can, a part of the missile's payload section. The W80-0, which can be modeled as a cylinder with a spherical end, is physically secured by two mounts to the Warhead Can, which can be modeled as a cylindrical open vessel with rounded bottom. The W80-0 and Warhead can are essentially concentric.

The current forward mount is a bolted interface between the W80 and the Warhead Can consisting of a spacer and a flanged ring, which clamps a step on the W80-0 against a ledge on the Warhead Can. The forward mount fixes the nominal alignment of the warhead and essentially cantilevers the body within the Warhead Can.

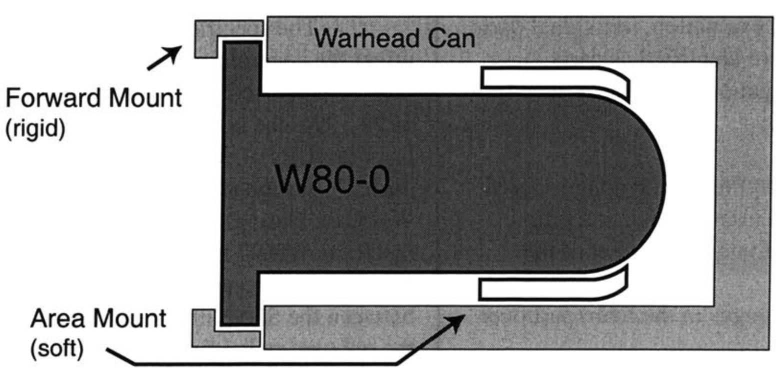


Figure 3. Rough Cross Section Sketch of W80-0 Cantilevered in Warhead Can with Forward and Aft Mounts.

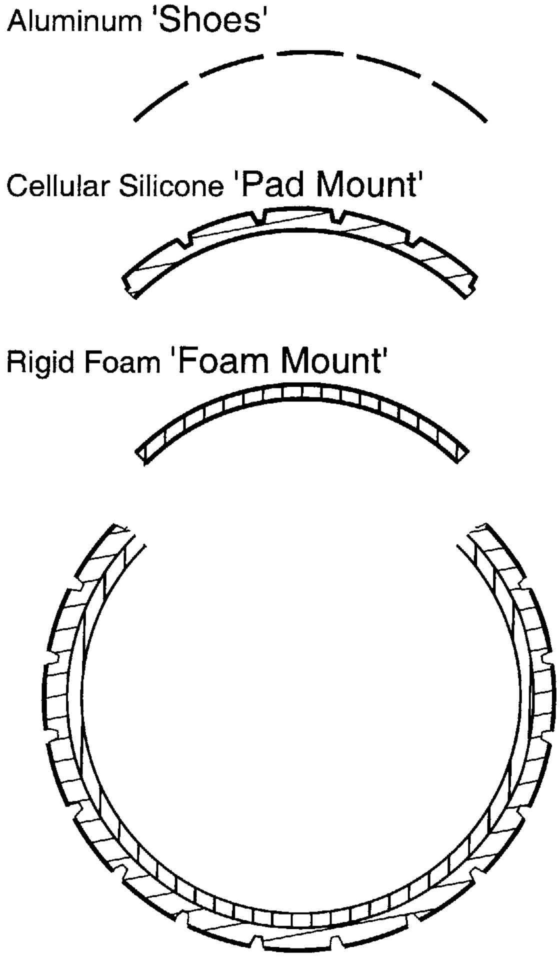


Figure 4. Cross Section Cutaway of Aft Area Mount Parts.

Technical Issues Summary *(details right)*

The W80-0 was nearing its 20 year original life cycle expectancy. As part of a Stockpile Life Extension Program (SLEP) evaluation, individual parts like the Area Aft Mount were identified as parts needing service and investigation. The issues specific to the Area Aft Mount were:

1. High forces required and damage caused during W80-0 insertion and extraction
2. Cracks in the foam component of the mount
3. Dimension changes in the foam part over time

The current aft mount is located at the junction of the spherical and cylindrical sections of the W80 aft area. The mount is composed of three different types of parts. The first part is a rigid polyurethane hoop, which covers a section of the W80's outer contour. The hoop, or Foam Mount, has radial symmetry and is roughly 5.77mm thick. The second part is called the Pad Mount and is composed of molded cellular silicone foam with a smooth inner surface and five raised trapezoidal 'fingers on its outer surface. Each of the molded cellular silicone parts covers a quarter of the cylindrical circumference. There are twenty aluminum slats called 'Shoes' that are each bonded to a raised surfaces on the Pad Mount. The outer surface of each shoe is covered with the dry lubricant Lube-Lok 99-A, decreasing the frictional coefficient between the Shoe and the Warhead Can, which are both aluminum.

During its service, the W80-0 can be removed and reinserted into the Tomahawk missile many times for service and inspection. When inserting the W80-0, the warhead is placed on a strongback (a metal frame on wheels), which attaches to the forward end of the W80 and cantilevers the warhead. The Tomahawk nose is detached and folded back to reveal the Tomahawk Warhead Can (WH Can) cavity. The W80-0 is lined up axially with the Warhead Can and then pushed into the can. There is an interference fit between the Pad Mount and the Warhead Can such that the Pad Mount finger areas are compressed underneath the shoes. The Shoes protect the cellular silicone from the rough finish of the Warhead Can.

The basic purposes of the Area Aft Mount are:

1. Mitigate shock and vibration
2. Limit lateral deflection
3. Have a lifetime expectancy of 20 years

Technical Issues: Insertion Problems

The specific technical issues and how they affect the general function of the Area Aft Mount can now be presented in light of the background. From 1990-1996, the Navy filed over 70 Unsatisfactory Reports (UR) of damage to the Area Aft Mount caused during insertion and extraction of the W80-0 from the WH Can. During installation, the force required to insert the W80-0 is monitored to be less than 4000 pounds. The resistance force is generated by friction between the Shoes and WH Can in combination with the outward radial force caused by the compressed cellular silicone.

When the Area Aft Mount was designed, 50-

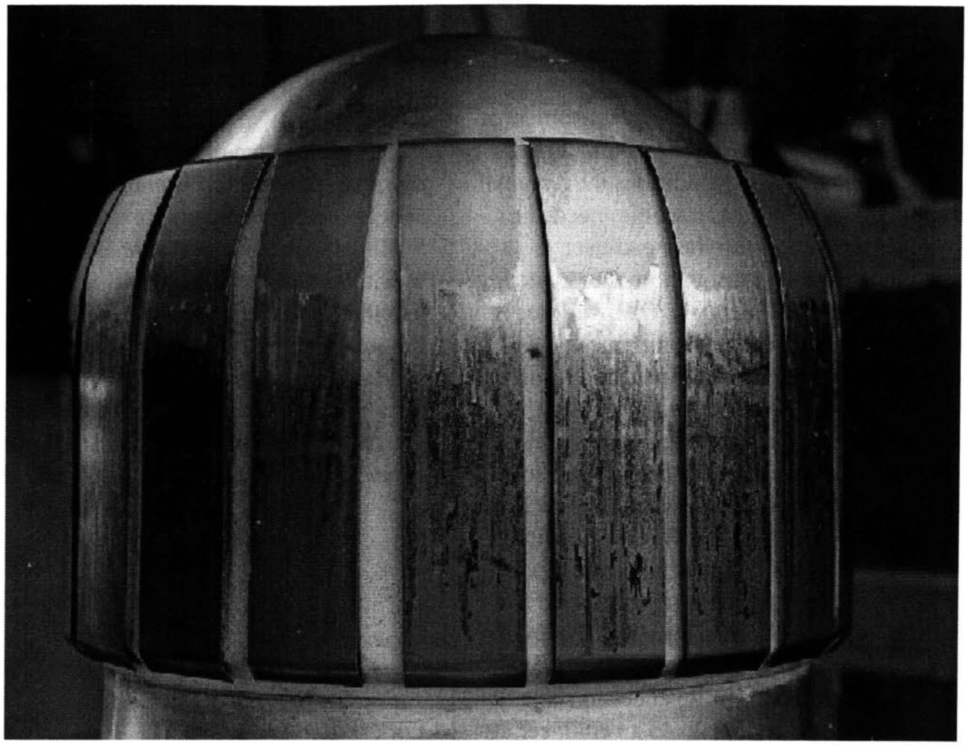


Figure 5. Wear on Aluminum Shoes after Multiple Insertions and Extractions.

Identifying Key Parties: Company External

The main parties involved with the W80 Area Mount redesign project were the Los Alamos National Laboratory, General Dynamics, the Navy, and the Department of Energy. The Los Alamos National Laboratory (located in New Mexico) and the Lawrence Livermore National Laboratory (located in California) are the key design agencies with regards to the United States nuclear stockpile. The W80 was primarily developed at LANL, who retained key design ownership. Other agencies such as Sandia National Laboratories designed other components of the W80 system and maintained design responsibility for them. In addition, other government agencies provided raw materials or manufactured the production systems. The LANL W80 systems engineer coordinated the engineering activity and was the lead on most W80 stockpile life extension program (SLEP) actions as well. He would serve as my company supervisor for the Area Aft Mount work.

General Dynamics was the manufacturer of the Tomahawk cruise missile, which carried the W80-0. The Aft Mount interfaced with one of General Dynamics' parts, the Warhead Can (WH Can), which was out of the purview of LANL's design responsibilities. Consequently, I could not consider changes to the Warhead Can as part of my design, although General

1200 pounds was the originally expected range of force required to install the W80-0, assuming low friction and no galling. [1] However, the actual force required during initial testing in 1981 averaged around 2156 pounds. [2] In service the insertion force is permitted to reach 4000 pounds. Such an increase was required because after multiple insertions/extractions, the required force increases substantially. This is due to increased friction and galling resulting from the dry lubricant wearing off the Shoes. The inner surface of the WH Can has a rough, as-cast finish that increases friction and accelerates lubricant wear.

After the lubricant wears away, the aluminum surfaces of the Shoes and WH Can come into compressed contact, encouraging galling. In addition, the Aluminum on Aluminum sliding friction coefficient (1.4) is greater than the static friction coefficient (1.05). [3] The combination of these factors explains the substantial increase in required force for insertion/extraction after multiple cycles. The only way to remedy these high forces is to reapply lubricant to the Shoes in the field, which is a troublesome annoyance.

The high insertion/extraction forces appear to have directly led to damage of the area aft mount. Of the seventy-two 1990-1996 Navy UR's, fifty cases were caused by the cellular silicone Pad Mount tearing apart during insertion or extraction. As frictional forces and

Dynamics would surely need to be informed and consulted about any significant Area Mount design changes.

The Navy was the 'customer' or 'consumer' of LANL's W80 'product'. Their service and target needs determined how and under what conditions the Area Aft Mount (and ultimately the W80 as a whole) needed to perform. It was important to keep their end-user perspective and needs in mind throughout the project.

The Department of Energy (DOE) was the government agency managing the overall nuclear weapons program. They determined funds and resource allocation to all the design, production, and testing agencies. In addition, they provide oversight of their sub-agencies' programs. The significance of their role in my project increased significantly when the DOE decided to transfer much of LANL's W80 responsibilities to Lawrence Livermore National Laboratory. A large majority of the nation's remaining stockpiled weapons are originally Los Alamos designs. The DOE decided to redistribute W80 work in the midst of my thesis project. The consequence of this decision was that I would likely transfer my results to an engineer at another laboratory instead of one of my LANL colleagues. This would require additional coordination and effort to ensure that information was passed on smoothly.

Identifying Time and Resource Constraints

The graduate phase of my internship at LANL was only six months long. When asked about the typical length of a project like the W80-0 Area Mount redesign, my team leader estimated that it might take a 'full engineer' three years to complete. While LANL had a long term responsibility to solve the technical problems, my short term responsibility was to make as much progress as possible. If I kept an understandable record of my work, some of my work would hopefully be usable by successors. Since there was no critical deliverable deadline within LANL, the MIT thesis deadline was the prevailing cutoff date.

A specific funding cap was not set for the project, but the anticipated scope of the work implied that the expenditures would be relatively small when compared with other technical efforts. My project was new, and I was the only engineer fully assigned to the task. This combination meant that much of my time would be spent gathering information and building technical understanding. This research and early-stage development tasks were not expected to require large amounts of spending when compared with the costs of full prototyping, testing, and manufacturing. It was expected that I do some preliminary design work which galling increase, a Shoe might become stuck. As the W80-0 continues to be pulled out, the cellular silicone beneath the stuck shoe is stretched and eventually tears or shears.

Nineteen of the 1990-1996 UR's were caused by separation of the aluminum Shoes from the Pad Mount (cellular silicone) or separation between the W80-0 and the Foam Mount. These cases were caused by a failure of the epoxy used to bond these surfaces together. There are two main reasons for the epoxy failure. First, the inner profile geometry of the WH Can suddenly compresses the Pad Mount and Shoe with a step-like profile that deforms the Shoe. After multiple insertions/extractions, the repeated deformation acts to strain harden the Shoe and to increase the required

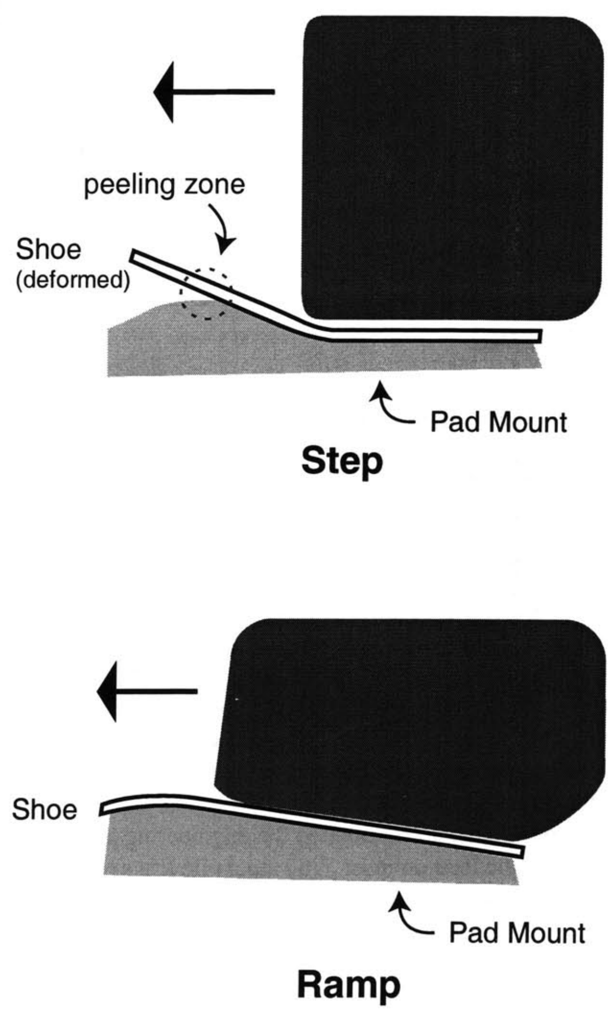


Figure 6. Step and Ramp Contact Profile.

would require some minor basic tooling and manufacturing resources. I received commitment from the W80-0 managers that as long as my efforts remained within this expected scope, all funding needs would be aptly met.

Ample knowledge resources were critical to this project's success. I would require access to historical archives, technical experts, and analysis tools. With the appropriate security clearance and training, access to historical archives would be readily provided. As I conducted preliminary interviews, I found that the LANL working culture encouraged knowledge exchange and cooperation. It was easy to schedule meetings with all individuals, from technical staff members to division manager. Although access to information was not a hurdle, I was concerned about what information was left to recover. Since the original W80-0 development decades ago, many of the original designers had left the laboratory or had passed away. Still, it was impossible to accurately judge what knowledge was or was not available until the project was actually pursued. Finally, I predicted that I would need access to some computing capability and help, and the W80-0 supervisor felt that these things were already available or could be purchased with little difficulty.

Confirming the Decision to Move Forward

By now I had found an MIT professor willing to serve as my thesis advisor. His added goals were that I make headway into the design work and conduct some physical experiments. He would continue to act as a catalyst throughout the thesis, both for technical ideas and for professional development. When technical difficulties arose, he would provide recommendations that got the ball rolling again. When I struggled with prioritization of tasks, he provided insight as to how I should correct my working habits and inefficiencies. Having selected the final 'player' in the thesis, I was prepared to finally approve moving forward on this project.

Given the above, I decided that the project was definitely a good one to pursue. Another look around showed that there were no other projects as interesting or with as much unclassified content. This project had broad, promising technical potential and should any particular thrusts of work run into unanticipated obstacles, I would be able to pursue other avenues relevant to the overall project. There was little reason to believe that the resources for the project would dry up, insertion force. [4]

It is thought that the deformation and friction forces combine and create high peeling stresses on the epoxy bonds. Adhesives are generally expected to perform best in shear, and peeling stress is the most difficult stress for the epoxy to resist.

In addition, the cellular silicone does not adhere to the epoxy well. During Aft Mount assembly, the surfaces to be bonded must be plasma treated to promote epoxy adhesion. [5] During Aft Mount development, an open-cell silicone was originally intended for the Pad Mount material. However, this material adhered so poorly to the Shoes that it was replaced by the current cellular silicone, which bonds better but still exhibits poor adhesion. [1]

When the epoxy fails, the Area Mount parts can fully or partially separate from each other. If the parts cleanly delaminate, epoxy is sometimes reapplied, and the part is reaffixed. Other times, one of the parts may be damaged and require replacement. In either case, part separation has been a continuing annoyance for in-service personnel, but it is not known whether Area Aft Mount performance affected by successfully reaffixed parts.

Technical Issues: Cracks

During the Stockpile Life Extension Program assessment, cracks were discovered in the Pad Mount cellular silicone part. The cracks were caused by a stress concentration located at the base corners of the raised areas on the Pad Mount. It is not known how these cracks affect Aft Area Mount function; however, the presence of such cracks certainly decreases the confidence in the Pad Mount design. [5]

Technical Issues: Compressive Set

At and above its glass transition temperature, a polymer will experience slow, permanent, and time dependent deformations termed 'creep'. 'Compressive set' is another term for creep exhibited in foam materials. When a load applied to closed-cell foam is sustained, individual cell walls will eventually buckle permanently. For example, suppose a coupon of polymeric foam is compressed and held at 20% deflection, and the reaction force is recorded. If we returned after a lengthy period of time and measured the reaction force being provided at 20% deflection, we would find that the new reaction force would be less than the originally measured force. [6]

Long term load retention tests performed by and the problem itself was interesting to me. The foreseeable risk seemed small, so I continued with the project and planned the next stages of the thesis:

1. Understanding the Original Design
2. Establishing New Design Functional Requirements
3. Concept Generation
4. Concept Development

the cellular silicone manufacturer have shown that after 2 years at the nominal compression in the Aft Area Mount, the cellular silicone retains 70% of the original compressed load. A 1996 analysis concluded that this compressive relaxation resulted in the radial pressure (and, therefore, force) falling below the minimum threshold set by the original designers. Unfortunately, there is not much documentation pertaining to the proper load to be supplied by the cellular silicone. In 1993, the B3223 cellular silicone was replaced in production by a similar cellular silicone M9747. This replacement cellular silicone was shown to have a load retention of 83% after 1.75 years. While the M9747 has superior performance, the retained load still falls below the same specified design criteria failed by the B3223 after 2 years. [5]

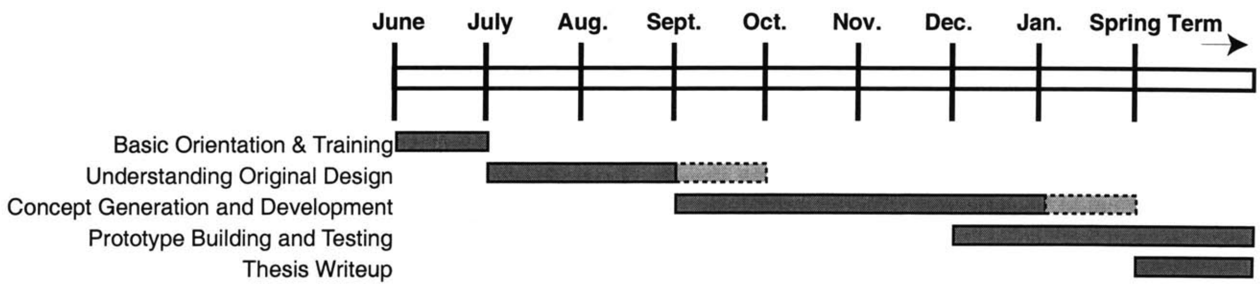


Figure 7. Thesis Project Timeframe.

Chapter 2: Understanding the Original Design

Timeframe

Before I started a full scale information and technical investigation of the W80-0 and Area Mount, I set some basic timeline milestones. I decided to spend approximately two months solely devoted to 'Understanding the original design' phase. While I might write down random concept ideas and recommendations, I wanted to spend at least two month investigating design intent and function without bias from new design ideas. Of course, I was working with a limited schedule, and if I wasn't 'finished' understanding the original Area Mount, I planned on continuing research while beginning new design work.

Using the Past to Help the Future

Suppose someone hands you a drill and asks you to redesign it because it has a few problems. There are several levels on which your improvement efforts

Technical Study

It became clear while investigating the technical problem that a more detailed independent study of the Aft Mount's purpose and function was necessary. The original design knowledge was not collected in any one place or individual, and most recent investigations of the Area Mount were rough or did not provide enough background information about the aft mount's function and performance criteria.

Parts and Assembly Study : Geometry

A natural starting point for investigation was the geometry of the individual parts and assembly composing the Area Mount. Understanding the parts' spatial relationships and constraints required a historical parts drawings search. Each of the three parts had gone must work. On the technical side, you must know what is actually 'wrong' with the drill. Is the motor breaking? Is it slipping out of people's hands? Is it requiring too much time to drill a big hole? Next, you might seek out the technical design data such as part dimensions and material performance data to help you design a technical solution to the problem. While the quantitative data is obviously necessary to solve the problem, what about the design intent of the drill, 'making holes'? Without a 'big picture' design purpose in mind, the redesigned part may solve the technical problems only to worsen the actual performance of the device. Therefore, I reasoned that a good redesign project must pursue a greater understanding of original purpose as much as technical detail.

There are other benefits to understanding the development history of a part to be redesigned. While researching the design history, the new designer may come across alternative designs considered during original development. Recognizing why these ideas were previously judged inferior can save the new designer from unwittingly pursuing similar ideas and 'reinventing' the broken wheel. On the other hand, these alternatives may have been less attractive because the required technology was infeasible at the time due to cost, availability, etc. However, as technology and knowledge improved over the years, those original obstacles may no longer exist, and in a redesign project, the alternative ideas might supplant the initially selected design concept.

Background Research

Multiple avenues were pursued for both the technical and design purpose searches. For written and hard copy documents, I carried out archive searches in our group vault, requested searches within other group vaults, asked the library search its own archives, and even made requests of external government contractors for information regarding their Area Mount involvement. I read through general W80 reports like a weapon development report for the W80, interface control documents (ICD) for the Tomahawk and installation equipment, stockpile life extension program documents, and the Stockpile-to-Target Sequence document. From these sources, I gathered Area Mount drawings, development records, material behavior data, test results, photographs, and other related material.

It was also important to develop personal contacts and carry out interviews with engineers who had experience with the Area Mount or whose expertise would be useful for the redesign effort. While general focus was maintained during interviews and meetings, some important facts were revealed through serendipitous digressions. Since the original design and testing through at least ten drawing revisions over the years and it was not readily apparent which drawings truly represented the parts in stockpile. The most recent revision was dated 1994, but the initial design and production of the W80-0 had taken place many years earlier. Fortunately, the most recent revisions apparently had been made in order to comply with new drawing standards and notation, while the actual part remained essentially unchanged. Unfortunately, the LANL drawing archive group was unable to locate copies of many of the earliest revisions. Although the drawing record remains incomplete, it seems that the key dimensions remained unchanged, i.e. the thickness dimensions and material callouts reflect what is actually in stockpile.

After verifying that the most recent drawings reflected dimensions of in-service parts, a tolerance study was conducted to discover the maximum and minimum material conditions for the Area Aft Mount Assembly. Unlike rectangular and right-angle based assemblies (like a standard desk), the Area Aft Mount surrounds the axisymmetric W80-0 external profile and must therefore have cylindrical parts with key dimensions expressed as radii and angles (instead of three orthogonal lengths). An ideal assembly without tolerances would have all the key radii defined at the same center. Yet, because each part radius has its own tolerance, it is likely that, once assembled, the centers of all the points would be offset. While examining the true interference fit, part thickness was used and added to the base radius determined by the external shape of the W80-0.

The results of the independent study using the Foam Mount dimensions as the base radius, showed an interference fit of 3.451 ± 0.645 mm between the cylindrical areas of the Area Mount and the WH Can. The corresponding cylindrical compression in the Pad Mount was $39 \pm 6\%$, assuming that the Pad Mount is the only part that compresses through its thickness. This nominal compression was 6 percentage points higher than the result of the 1996 analysis, although the maximum compression value was only 1 percentage point higher than the previously calculated maximum.

At first glance, one might assume that the entire shoe surface is compressed uniformly. However, at nominal conditions, only a small section of the spherical section of the Pad Mount is actually compressed by the WH Can. Nominally, only the cylindrical area of the WH Can actually contacts the Shoe. Using Matlab, the partial compression of the Shoe spherical section was calculated as a function of axial length.

of the Area Mount had occurred decades ago, most people needed some memory pointers or had to talk for a while before they remembered additional pieces of pertinent information. For example, I would let some people talk for a bit about the original designer personally, hoping that they might be reminded of professional comments or perspectives the original designer had regarding the Area Mount. Also, while listening to interviewee stories, I would often pick up the names of other potential contacts at the laboratory who I had not known previously.

Original Design Technical Issues *(see right)*

Examples of technical information needed to understand the Area mount were its parts' dimensions, materials' behavior, and operating performance. Familiarity with the part and assembly geometry would lead to an appreciation for the geometric constraints of the problem and how they affected function. The distance the Area Mount was compressed when inserted into the WH Can was an important value determined by the geometry study. In addition, a tolerance study gave the range of these deflections.

The Area Mount was essentially a shock absorber, and understanding the individual material(s) responsible for the damping and spring behavior was key to understanding the assembly's dynamic and static behavior. The cellular silicone Pad Mount part was the material most responsible for the function of the Area Mount. As it was compressed, it both provided an outwards spring force and dissipated energy. Any redesign would center on replacing this component since it provided most of the function, but also contained the most problems (cracking, compression set,

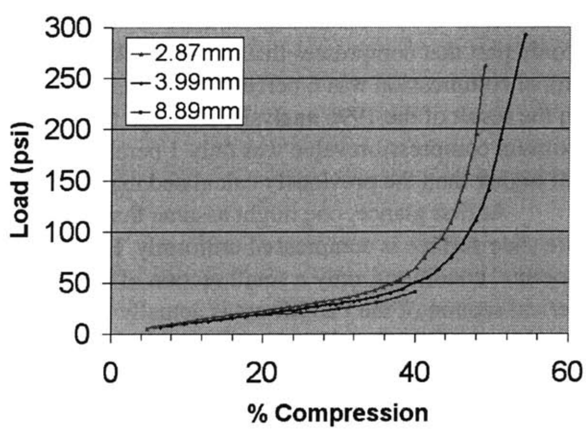


Figure 8. Load vs. % Deflection of B3223 Cellular Silicone of Varying Thickness.

Parts and Assembly Study : Mass and Materials

A few key points need to be made about the materials and manufacturing processes used in the Area Mount and WH Can. The Foam Mount is molded from rigid polyurethane foam 20 lb/ft^3 and has a total weight of 0.259 kg. Its rigidity provides the base structure for joining the Area Mount's four flexible Pad Mounts. The Foam Mount has a mass of 0.26 kg.

The Shoes are primarily made from 6061 aluminum with 2024 aluminum as an alternate material. The solid lubricant Lube-lok 99A contains graphite and molybdenum disulfide as the active lubricating solids. Since the shoes are each only 0.5 mm thick, they are not very stiff. Instead, their main purpose is to serve as Area Mount contact surfaces that handle sliding motion and abrasion caused by the WH Can inner surface. The total mass of the twenty shoes is less than 0.2 kg.

As discussed earlier, the Pad Mount was originally made of B3223 cellular silicone, which was supplied by Bendix. The nominal thickness of the finger section (where the part is compressed) is 8.89 mm (0.35 in). As a hyperfoam, this material has a nonlinear load vs. % deflection curve. In addition, the load vs. % deflection behavior varies depending on the nominal thickness of the sample. In Figure 8we observe three load vs. deflection curves for B3223 coupons of different thickness. For the nominal thickness 8.89mm, the data only cover the range of 20-40%, which does not include the upper limit compression value from the tolerance study. As the thickness increases, the load/deflection curve moves down, i.e. the stiffness of the material decreases.

Notice that the load begins to increase exponentially after the 50% deflection for the two thinner sections. The slope of the 3.39mm curve is not quite as steep as the 2.87mm curve in the exponential regions. More importantly, the 3.39mm loads begin to exponentially increase at a larger deflection than the 2.87mm curve. While the 8.89mm exponential region is not in the data, one could expect with good reason that its load vs. % deflection curve would begin to increase at a larger % deflection than the 3.39mm and have a slightly less steep slope.

As mentioned before, M9747 had replaced B3223 as the cellular silicone for production use beginning in 1993. M9747 was made by the same supplier as the B3223 and had similar properties. The switch to M9747 had been made because the silicone gum used in B3223 production had become unavailable. [5] But 1993 was long after the initial development and production, and I was unable to figure out how many units in the field were actually using M9747 and poor epoxy adhesion).

The W80-0 and Area Mount could potentially be exposed to many dynamic shock and vibration environments. More than the other environments, the maximum shock levels experienced during a 'near miss' depth charge explosion seem to have been key determinants in the Area Mount's final design. When the original environments were specified, the Area Mount was supposed to snub the shock such that the W80-0 would still function after this extreme disturbance.

Search for Design Intent and Historical Details

The Area Mount redesign project required that technical details be explored alongside the design intent and qualitative aspects of the design. For a successful redesign, the reasons for the current design being the way it is must be understood as much as what the current design is. As part of a complicated system, the Area Mount's purpose was complex and not entirely intuitive, so a concerted research effort was necessary to build an understanding of the original design intent and development 'story'. Historical evidence would help me to reliably build the basic assumptions and context for future design decisions.

The Designers: Then and Now

The Los Alamos National Laboratory has a functional organization where groups are organized by technical expertise more than by specific projects. The hierarchy of the organization moves from division, to group, to teams. Within the Engineering Science and Application (ESA) division, many of the groups are the condensed remnants of former divisions. These former divisions seem to have been functionally divided more by components than by strict discipline. Over time, as political treaties led to a moratorium on new designs, the large divisions shrank down and transformed into more and more specialized groups.

I needed to identify the former organizational bodies involved in the original design and understand who their modern organizational descendants are. These present day groups are the stewards of the surviving technical data pertaining to the Area Mount, and some of the individuals possess experiential and technical expertise, which may not have been written down. Once these modern groups were identified, I needed to develop contacts in the groups and arrange interviews to collect information and leads to further contacts or information.

I located individuals having Area Mount-related experiences in the Weapon Engineering (ESA-WE), Engineering Analysis (ESA-EA), Weapon Materials and Manufacturing (ESA-WMM), and Pad Mounts. Since Area Mounts were not procedurally replaced during service life unless they were damaged, the large majority of Area Mounts in service were probably using B3223 cellular silicone as opposed to the M9747.

Performance of Area Mount: Dynamic

Though the technical problem investigation unveiled some of the Area Mount function, understanding the overall performance of the Area Mount requires a focused look at how the earlier stated purposes are attained.

Shock Environments

According to a 1984 letter from the W80 Project Manager, the chief purposes of the Area Mount are to mitigate shock and vibration delivered to the sensitive payload (W80-0) from its local environment (Tomahawk missile) and to limit lateral deflection. [4] The shock and vibration environments experienced by the W80-0 are found in the Stockpile-to-Target Sequence (STS) document. [7]

The largest STS shock environment is the "near miss depth charge encounter", a near-miss explosion near the torpedo tube containing the Tomahawk and W80-0. This environment was originally considered 'Normal', meaning "the functional survival" of the W80-0 "after exposure to this environment is expected" [8]. The 'Barge Shock' test was created to simulate the "near miss depth charge" environment. In this test, instrumented W80 & Tomahawk payload mockups were placed on a barge in a body of water. An explosion was set off outside the barge, and the resulting shock waves would strike the barge and instrumented assemblies laterally (versus axially). See Figure 9 for diagram explanation

Prior to the actual water testing the barge shock itself was simulated at the HiG facility at the Sandia National Laboratory in Albuquerque, NM. The HiG facility was essentially a sled and track facility where a sled was accelerated down the track towards a target. A shock programmer assembly determined the input shockwave shape. On the HiG, both lateral and vertical shocks were applied to and tested on an instrumented W80-0 mockup with the Aft Mount.

Of all the shock spectra in the STS, the barge shock response spectra contain the highest acceleration values up to 400 g's. While the Area Mount was designed with these high shock levels in mind, it is a mistake to assume that the barge shock is the only reason for the Area Mount's existence. Additional 'Normal' environments such as sudden drops, forklift carry, and in-air boost also generate potential shocks

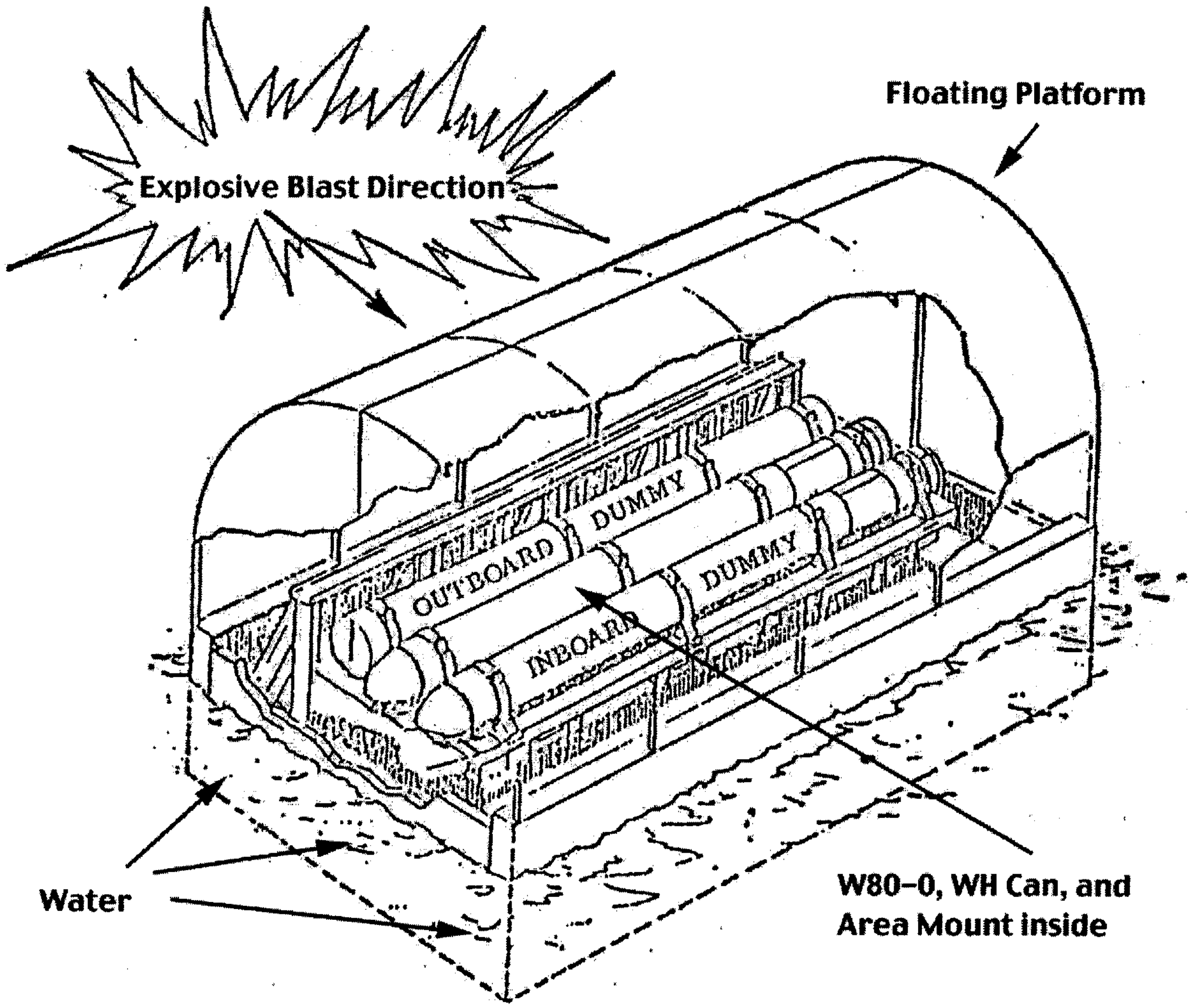


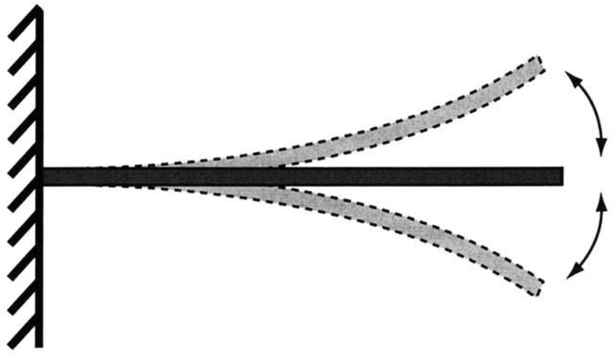
Figure 9. Barge Shock Test Setup.

Measurement Technology (ESA-MT) groups. Within the ESA-WE Weapon Systems team (my team), I spoke with my supervisor and team leader about their experiences with the W80-0 and the Area Mount. My supervisor had a good deal of knowledge about the problem and acted as a central hub to discuss collected information with. In general, many ESA-WE engineers had a good understanding of the relationships between LANL and outside production agencies, supply agencies, other contractors, and the customer.

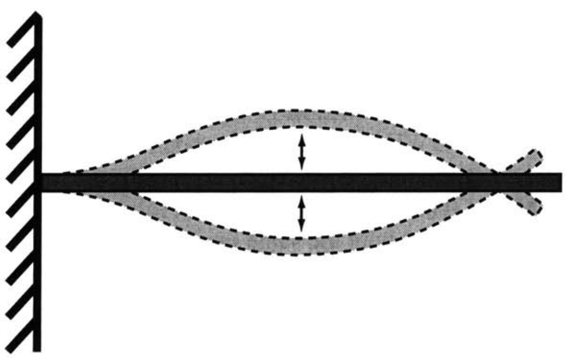
I found that a couple individuals in ESA-EA had the largest quantity of Aft Mount design experience of anyone I spoke with. These individuals had been at the lab for many years and had worked with the original designers of the Aft Mount (who were now deceased or retired). In general, the ESA-EA engineers had tremendous collective experience modeling and analyzing assemblies. In addition, their familiarity with complex that must be mitigated by the Area Mount. These environments generate accelerations up to 100 g's at some frequencies, which makes them significant albeit several times smaller than the barge shock maximum.

The nonlinear load-deflection behavior of the B3223 and M9747 cellular silicone was considered the fundamental design feature of the Area Mount that mitigated large forces generated by the barge shock. A sudden large force applied by the WH Can to the Area Mount would encounter exponentially increasing resistance as the force deflected the cellular silicone past its nominal position. This "self-snubbing characteristic is desirable to limit WH side motion under transient High-G conditions." [4]

In 1990, the near miss depth charge environment was changed to an "Abnormal" environment. [9] This meant that the W80 no longer had to functionally survive after exposure to the near miss depth charge



1st Mode of Vibration



2nd Mode of Vibration

Figure 10. Cantilevered Beam Vibration Modes.

technical issues made them excellent instructors for topics I was unfamiliar with.

In 1996, an ESA-WMM engineer carried out the most in-depth analysis about the Area Mount problem that I have seen so far. In addition, in the year prior to my graduate phase, two other ESA-WMM engineers looked at the redesign issue and had some of their own ideas about what types of materials could be used for redesigned parts. The ESA-WMM engineers had collected the essential data on cellular silicone load versus deflection. However, it seemed that their direct experience was less focused upon the Area Mount performance criteria than on pure material behavior.

ESA-MT engineers had a large amount of experience with testing and instrumentation, and they provided assistance with design for manufacturing and experiment design. While my ESA-MT contact did not have specific Area Mount experience, his technical expertise enabled him to suggest appropriate setups after hearing basic problem descriptions.

environment. As a result, it might be reasonable to relax the shock requirements for a new Area Mount from the barge shock levels to those of the remaining shock environments' levels. However, changes in mount performance capability may affect overall system dynamics, which may in turn affect and exacerbate conditions for other components. Until the effects of such changes are well understood, it seems prudent to match the new mount design with the original Area Mount performance levels.

Vibration Environments

Most of the vibration environments presented in the STS are related to transportation and carriage of the W80-0 in trucks, helicopters, aircraft, and submarines. The last vibration environment is the in-flight vibration experienced by the W80-0 in the Tomahawk. In general, the largest spectral density found among the envelopes is not much larger than 10^{-2} g^2/Hz. [7]

A 1979 vibration test of the W80-0 and payload section showed that the W80-0 in the WH Can has two major modes of vibration in the lateral direction. The W80-0 is cantilevered within the WH Can part, and its first mode of vibration is similar to the free-end vibration of a cantilevered beam. Likewise, the second mode is probably similar to the oscillation of a beam with fixed nodes. (Figure 10)

Figure 12 shows some data collected from an accelerometer on the end of the W80-0 body. The same test data show that the first mode of vibration is found at approximately 75Hz while the second mode is approximately at 260Hz. At higher frequencies, no more distinct resonance frequencies are observed in the data. [10]

One of the interviewees in ESA-EA recalled that in a vibration test done with the W80 and WH Can on a shaker table, the Area Mount seemed to have no effect on the resonant modes of vibration. That is, a first vibration test was conducted of the payload assembly without the Area Mount in place. Then, a test of the same assembly with the Area Mount in place was conducted. The results of the two tests apparently matched each other, implying that the Area Mount made little impact on the vibration response of the assembly at quarter-g levels. One possible explanation for this behavior is the relative 'softness' of the Area Mount due to its compressibility.

W80 Model Development

The previously mentioned tests of the Area Mount were done two decades ago on physical mockups. At the time, design verification was mostly done empirically. Large equipment, detailed mockups, and extensive instrumentation were required by these

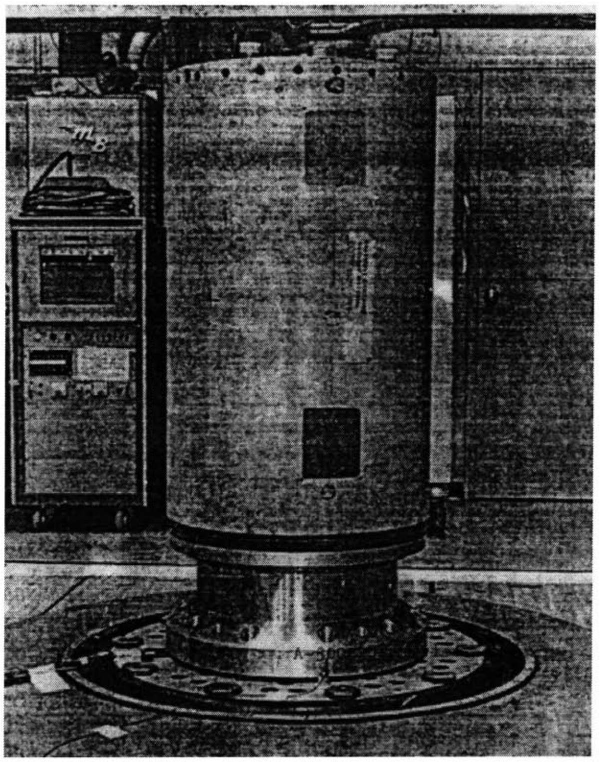


Figure 11. Vibration Test Setup for W80-0 Lateral Excitation.

tests verifying the original Area Mount's ability to mitigate shock and vibration. (Figure 11) While it would be ideal to have similar experiments at our disposal to compare and physically test new Area Mount concepts, these experiments required time and resources beyond those available to my project efforts. Nevertheless, some method for comparatively testing a totally new concept design would eventually be needed.

Instead of a physical test assembly, a finite element computer model was investigated as an alternative method of determining the output shock and vibration response of the W80-0 & Area Mount assembly. The first stage would be to build a reasonable dynamic model of the W80-0 fixed within the WH Can without the Area Mount. The second stage would be to build an accurate model of the Aft Mount, to add it to the W80-0/WH Can assembly model, and then to apply the input shock spectra. If the model was built reliably, the output shock response should accurately reflect the design intent shock limits. Most importantly, with a reliable W80-0/WH Can assembly model, New Area Mount designs could be modeled and substituted for the Area Mount. The new design could be evaluated by running the model with the same input shocks and comparing its performance with the original Area The FEA model of the W80 was built using the program ABAQUS, a code preferred by many individuals in

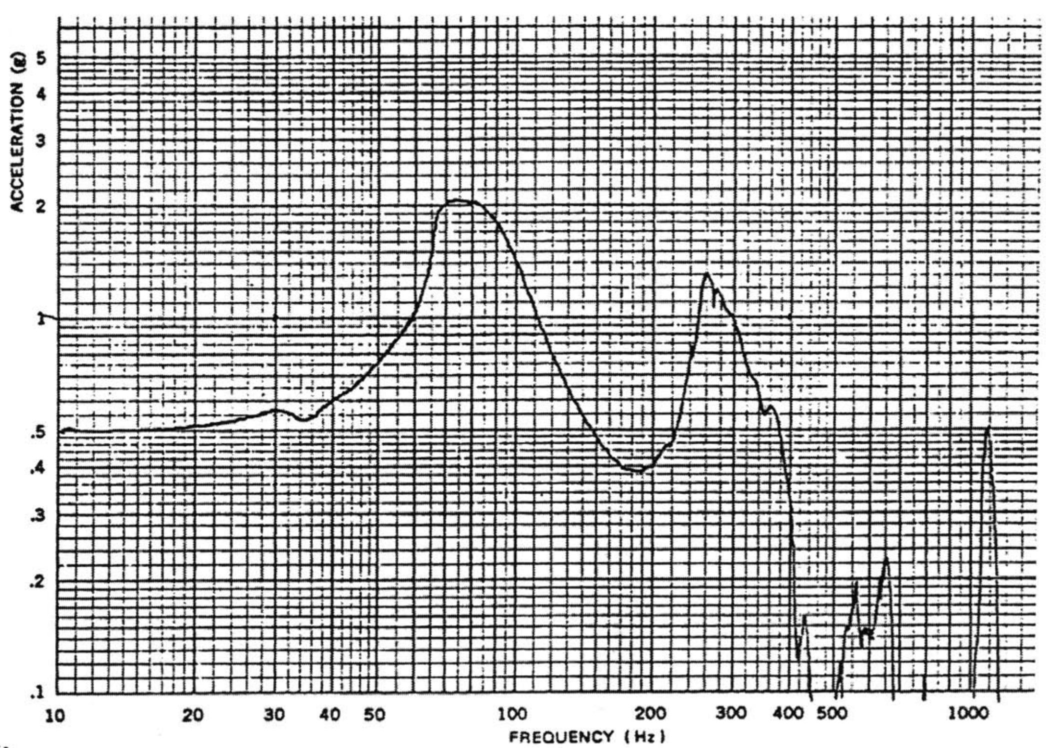


Figure 12. Acceleration vs. Frequency Response Curve obtained from Accelerometer on W80-0 Aft End during Vibration Test.

Initial Results of Searching

After conducting the initial archival searches and personal interviews, I had accumulated a modest collection of information. However, there were still many unanswered questions, especially regarding the Aft Mount performance criteria and the development history. In some cases, specific drawings could not be found or some of the requested information needed more time to arrive from the outside sources. Other times, I simply could not locate written evidence for specific design intent issues fully considered *and* addressed by the original designers.

Many LANL documents and information were created well before significant computing power was available for archiving tasks. While some groups have digitally scanned in information, much information is still stored in hard copy form, making searches somewhat difficult. Over the years since the original Aft Mount development, some outdated documents may have been destroyed or moved in order to make room. For example, I was unable to locate the original drawing revisions for the Area Mount parts. Due to the functional reorganization that had developed over the years, the information I was gathering had been

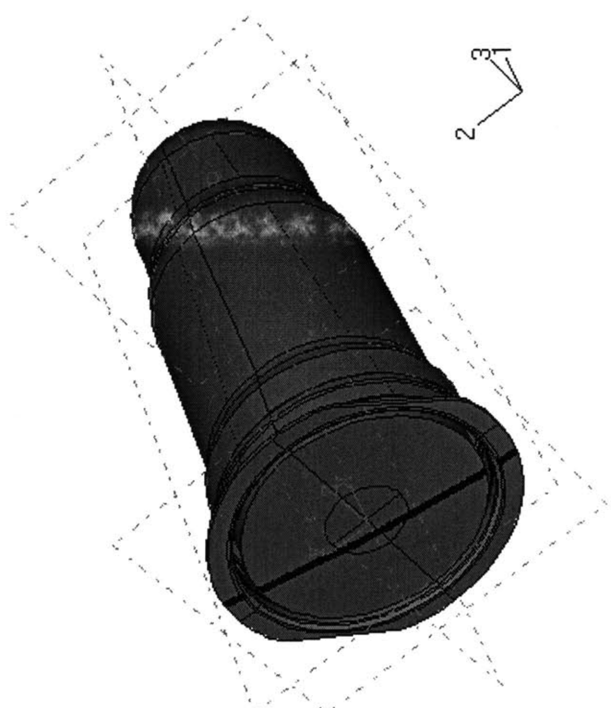


Figure 13. W80-0 and Forward Mount ABAQUS Assembly (WH Can left out).

ESA-EA. I would need training since I did not have much experience with the program, but the engineers in ESA-EA were lead users of the program and were willing to help me learn. I spent a week in Rhode Island taking a course in ABAQUS basics, and then began creating the model.

Assembly Geometry

Part geometry was done in ABAQUS/CAE, and nominal dimensions were used for all the parts. The Forward Mount cantilevers the W80-0 within the WH Can such that the largest relative displacements between the W80-0 and WH Can take place at the less stiff 'free' end, surrounded by the Area Mount. Therefore, the WH Can and the Forward Mount parts could be modeled as rigid bodies while the W80-0 and Area Mount parts were modeled as deformable 3D bodies. Modeling the WH Can and Forward Mounts as rigid bodies decreased model complexity, thereby saving computation time required by the model.

In order to keep my work unclassified, I could not model any specific parts within the W80-0 itself. The external profile of the W80 is unclassified, so I was able to revolve the profile and create the W80 'Blob' part, a uniform-density, deformable 3D body with the same shape as the true shape of the W80 but none of the inner parts.

Cellular Silicone Material Definition

After creating the assembly geometry, I needed to input material data into ABAQUS and assign materials to their corresponding parts. For the Shoe, all that was required was to find material values for Aluminum alloys in reference books and input them into ABAQUS. Modeling the B3223 cellular silicone required more judgement. The load vs. deflection information I had received from ESA-WMM showed that the thickness of the sample changed the shape of the curve. A 3.99mm coupon was the thickest sample for which there was complete data, i.e. load values from at least 0-50% deflection. Unfortunately, the data was limited to the 20-40% deflection range for the 8.89mm B3223, which was the thickness of the Pad Mount. Although this range included the nominal % deflection, larger deflections would be experienced if the model were to be dynamically excited by shocks.

In ABAQUS, the 3.99mm compression data was curve-fit to obtain the hyperfoam input coefficients required by the materials manager. As illustrated before, the 8.89mm B3223 was not as stiff as the 3.99 mm, so I was worried about using the 3.39mm behavior for the Area Mount model. The difference between the curves was smaller in the nominal and lower % deflections, but for large % deflections the loads might vary significantly. While the 8.89mm B3223 data was incomplete at the time, compression data for 8.89mm M9747 cellular silicone was available. This cellular silicone had replaced B3223 for production use beginning in 1993. Figures 14a and 14b show the M9747 data combined and compared with the B3223 data.

While I wanted to model the Area Mount with its original materials, which were still in service, the 8.89mm M9747 data was probably closer to the 8.89mm B3223 data than the 3.99mm B3223 data in the exponential range. A good compromise for a better material would be to curve-fit the 8.89mm B3223 data and fill in the missing ranges of deflection with 8.89mm M9747 load data.

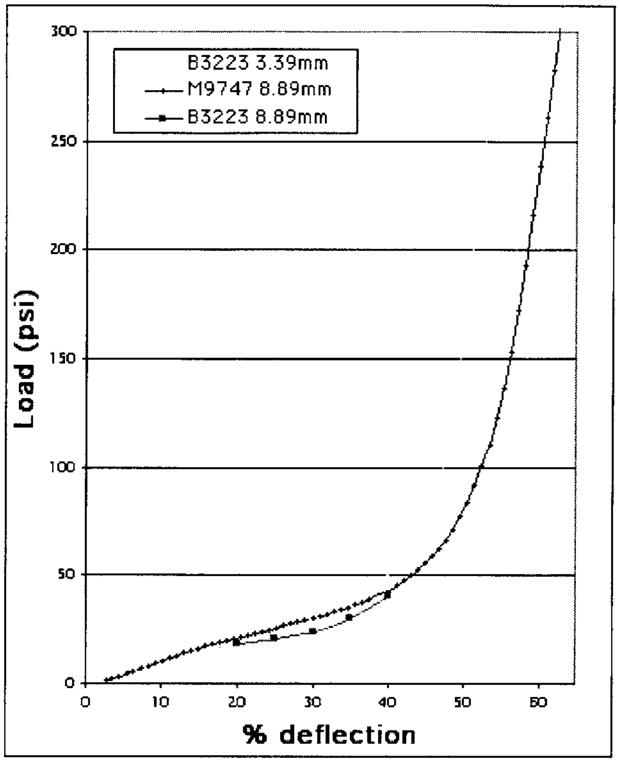


Figure 14(a). M9747 and B3223 Cellular Silicone Load vs. % Deflection.

W80 'Blob' Issues

Determining the material properties for the W80 'Blob' was really a dynamics modeling issue. Initially, the 'Blob' was created as a uniform density body in order to keep the model unclassified. Yet, even though total mass and external geometry were identical, a uniform density 'blob' cannot inherently exhibit the same dynamic behavior as a complicated assembly of many parts of different density. If all the subcomponents of the W80-0 were properly modeled and dynamically tested, the results should reflect the vibration and shock test data collected years ago. However, modeling or even describing the inner parts of the W80-0 is not permissible in an unclassified setting such as this thesis.

At Los Alamos, my Department of Energy clearance allowed me to conduct my work in a restricted area approved for classified work. If the work remained within secure Los Alamos facilities, I could have pursued a full W80-0 model. However, two significant obstacles lay on this path to a dynamically representative model. First, including accurate models

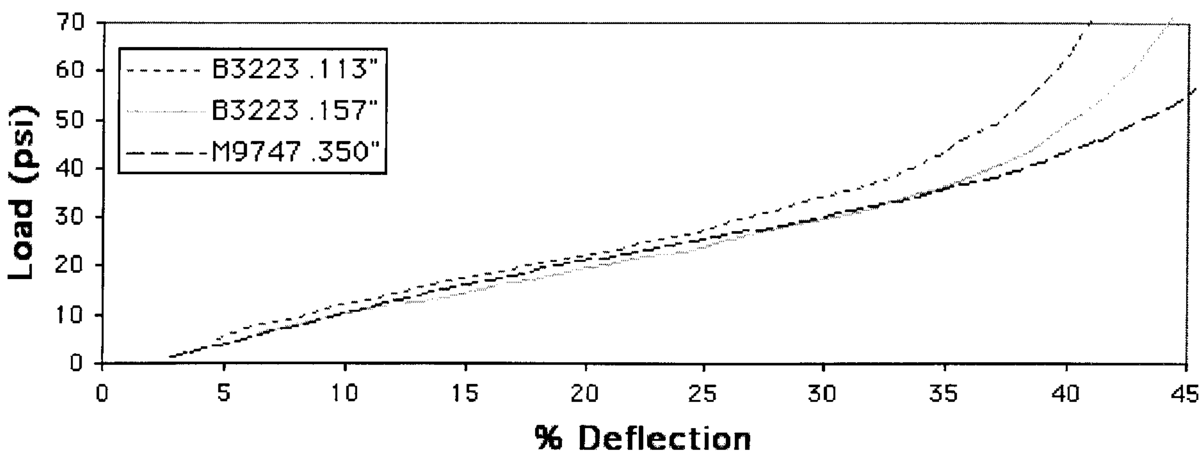


Figure 14(b). M9747 and B3223 Cellular Silicone Load vs. % Deflection.

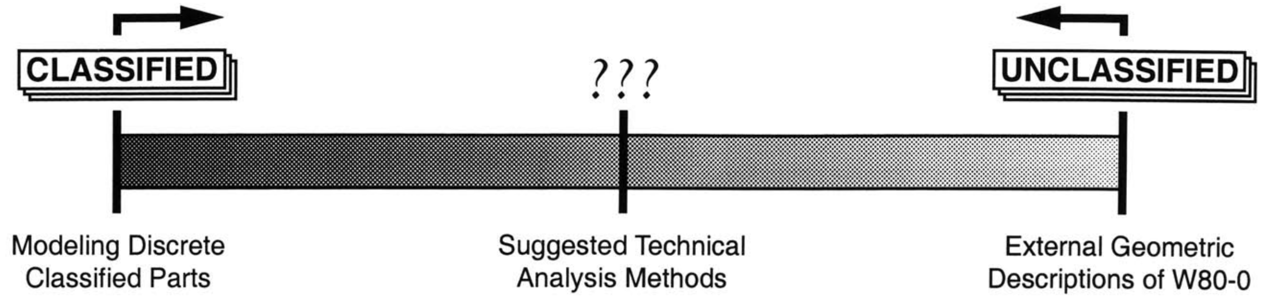


Figure 15. Technical Methods with Unknown Location on the LANL Classification Spectrum.

distributed over may groups and many individuals. There was no central place containing all the records and information I needed. Although most individuals were willing to help, contacting outside groups for information was time-consuming, and some materials could not be sent until later.

Anecdotal, historical, and technical context was gathered from the interviews, but I still depended heavily on the same brief references, which lacked detailed explanation. Some interviewees commented on technical performance characteristics of the Area Mount, but without test data from another government laboratory, this information still had to be treated more as speculation than fact. Nevertheless, I was sporadically referred to individuals or sources who might have more information about the Area Mount's original development or its current issues.

Evaluation of Search

At the end of the time I had set for this phase, there were gaps in the historical information I had gathered. Not all the technical questions had been answered, and I was waiting for data to be sent to me from outside sources. At this point, I had to make a decision; I either needed to spend more time accumulating data, or I needed to make some assumptions and forge ahead at the risk of not fully understanding the issues.

I felt that I had collected enough information to move forward with new design work as long as I did not rely too heavily on incomplete areas of Area Mount understanding. By the time a new and complete design would be approved, the function of the original Area Mount would have to be fully understood. But since my project was in the initial design stages, I could focus upon specific components of the new design without having to necessarily perfect a total design, although component design must be done with the total design concept in mind. As I moved on, I would continue collecting data, but not full-time. Indeed, additional information would continue to come in which would shed light on more aspects of Area Mount performance.

for the many parts of a complex assembly exponentially increases the time and work necessary for the overall model. Second, even if I managed to complete the full assembly model within ABAQUS, the model (and perhaps some of the results) would be classified and unsuitable for a publicly available thesis.

Figure 15 graphically represents the classification problem. Any dynamic model constructed from detailed part components would clearly be classified. On the other side of the spectrum, the uniform density W80-0 'Blob' with the W80-0 external geometry was definitely unclassified. Perhaps, there was a way to refine the W80-0 'Blob' model such that its dynamic behavior matched the test results but the model was still unclassified.

CG Relocation Method

The vibration testing had indicated that a good dynamic model must represent the first two modes of vibration well. For the first mode of vibration, the location of the W80-0 'Blob's center of gravity (CG) needed to match the location of the actual W80-0 CG. Fortunately, the W80-0 CG location was unclassified. The W80-0 'Blob' CG location was calculated, and Figure 16(a) shows that as a uniform density body, the W80-0 'Blob's natural CG was located 76mm forward of the true CG position. Figure 16(b) shows one strategy for matching CG's; take an arbitrary section at the free end of the W80-0 'Blob' and increase its density. At the same time, the density of an arbitrary section at the forward clamped end is reduced such that the overall mass of the W80-0 is kept constant.

We believed that this strategy was unclassified because the subdivisions we would make within the W80-0 blob were arbitrary and would not reveal any particular information about the W80-0 contents since the CG location was unclassified. While this mostly homogenous body might be able to simulate first mode dynamics, it was much more unlikely to match the second mode behavior using this technique.

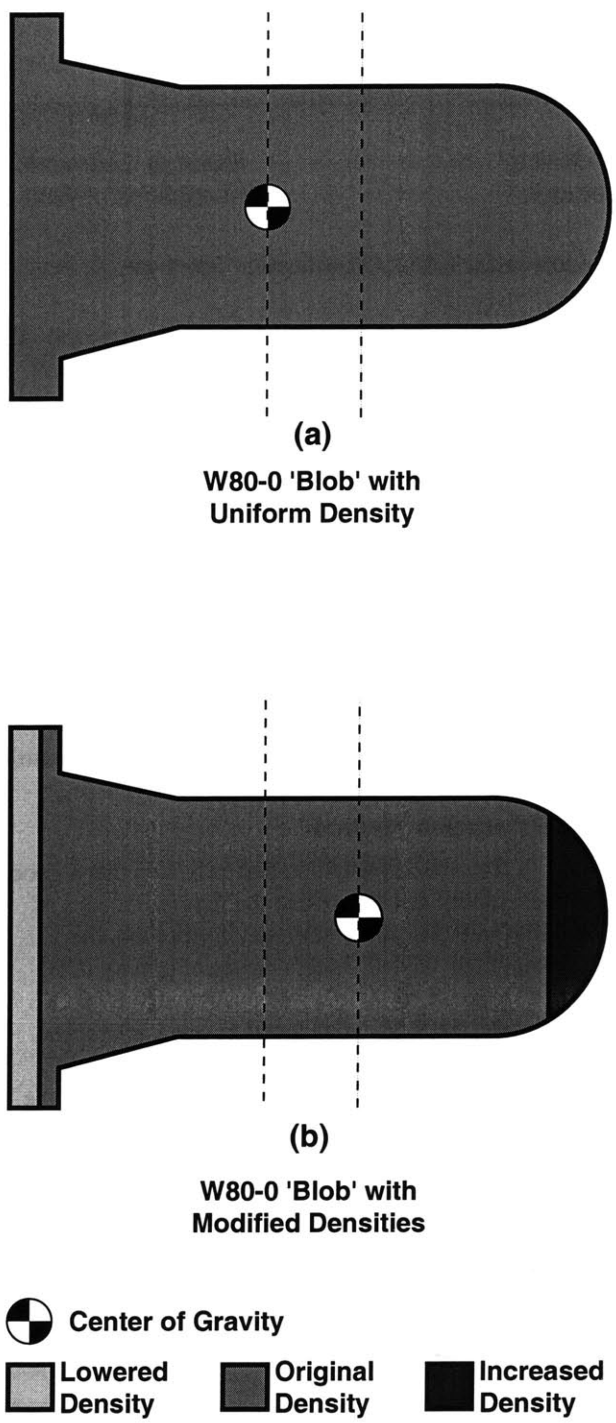


Figure 16. Center of Gravity Relocation via Density Change Method.

Partitioning Methods

I then investigated two other strategies that modeled a complex assembly using a sectionalized, solid mass to get the first two modes of vibration. One method was to model a complex structure with beam elements and lumped masses. (Figure 17(a)) The first step was to divide a structure into segments along its length and to calculated the sum of all the parts' mass within each segment. Each segment mass would be assigned to a point on a line, where the distances between points was representative of the actual distances between segments of the actual geometry.

One-dimensional beam elements are used to connect the lumped masses together. Each beam stiffness is determined by sampling cross sectional stiffness in between the lumped node positions of the structure. For example, say the cross section cut between segments 4 and 5 in Figure 17(a) is a star of aluminum surrounded by box of steel. The bending stiffness for both material cross sections is found by multiplying the elastic modulus, *E*, of each material by the moment of inertia, *I*, of the respective cross section. The bending stiffness values for the steel and aluminum would be added together, and the total would be assigned as the beam elements bending stiffness. This process could then be repeated for axial stiffness (*E* multiplied by cross sectional area), etc. Although some adjustments to the values might be necessary after the beam structure is completed, the first and second modes might eventually be matched with this method.

This process was the equivalent of converting a complex 3D assembly into a one dimensional beam problem. The dynamic behavior of a one-dimensional beam structure would be much simpler than a full 3D assembly to observe and adjust so that the mode frequencies would match those of the original Area Mount. In ABAQUS, after the beam dynamics had been properly matched, the one-dimensional model could be reconverted into a 3D model by tying 3D surface geometry to each node. So, for the example in Figure 17(b) we could assign a box surface to each of the nodes. These surfaces would move rigidly with the nodes, and forces applied to the surfaces would be translated to the node as well. If the W80-0 'Blob' was modeled this way, the Area Mount could be attached to the rigid surface, which was in turn assigned to nodes on the one-dimensional length. For small displacements, this method might work well. With large lateral displacements, however, there would be large angle distortions at the interfaces between the tied surfaces which could lead to unrealistic loads and displacements

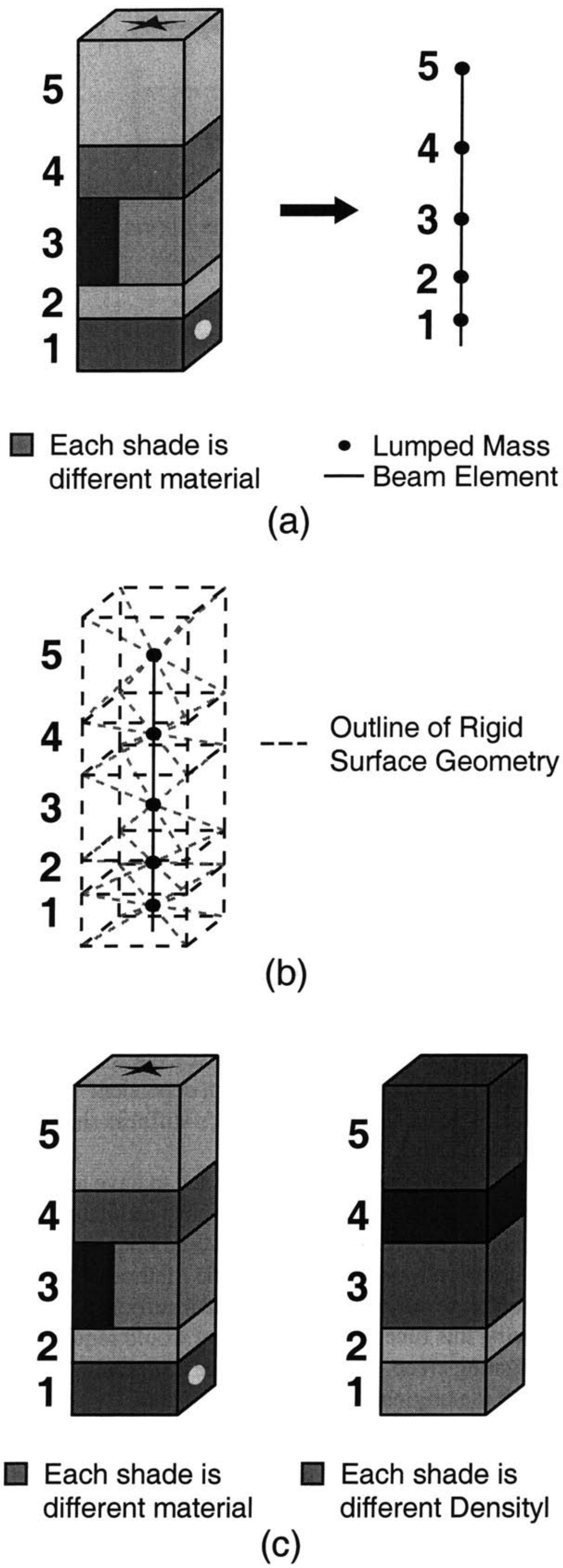


Figure 17. Segmentation and Bending Stiffness Approximation Method.

applied to the Area Mount model.

Another method of modeling a complex assembly was to partition the structure into segments with homogenous material properties. The resulting assembly is a three dimensional segmented solid with the same outer geometry as the original structure. Just as before, the total mass of original parts corresponding to each segment is calculated, but this lump mass is then divided by the segment volume to obtain a uniform density, which is assigned to the entire segment of the new model.(Figure 17(c))

Each segment stiffness would be calculated in a way similar to the one-dimensional model except that these values would be converted to a material stiffness for the segment. Note that with both methods, some judgement would have to be made about which cross sections of parts truly contributed to overall bending stiffness. For example, if you had a jar of marbles and you tried to calculate the equivalent bending stiffness of a cross-section, you might only include the cross section of the jar since the marbles do not have much distributed length, which would resist bending of the assembly.

Regardless of which partitioned model method was used, some basic analysis of W80 subcomponents would be necessary in order to calculate the cross sectional areas and material stiffnesses. This information was certainly classified. However, since the partitioned model lumped the characteristics from many parts together (by segment), the resulting partitioned model might be unclassified. While I would not be able to publish the classified analysis, its end product, the W80 'Blob' part, would characterize realistic dynamic behavior, and could be used to test new area mount designs in ABAQUS.

Needless to say, I did not make a decision to proceed with any of these methods based upon my own judgement of what was classified or not. My supervisor and I arranged a meeting with an expert in LANL's Security Division 7 who assessed the classification of these proposed technical methods. His felt that the method of moving CG location by varying arbitrary section density would lead to unclassified results. He agreed that the partitioning method required initial modeling work to be conducted in a classified environment. However, he also felt that the model resulting from partitioning would remain classified, despite having lumped values.

Due to the classification issues, work on a realistic ABAQUS W80-0 model was stopped and more emphasis placed on achieving empirical prototype development and testing. Fortunately, I would use apply my accumulated experience with ABAQUS to design development efforts.

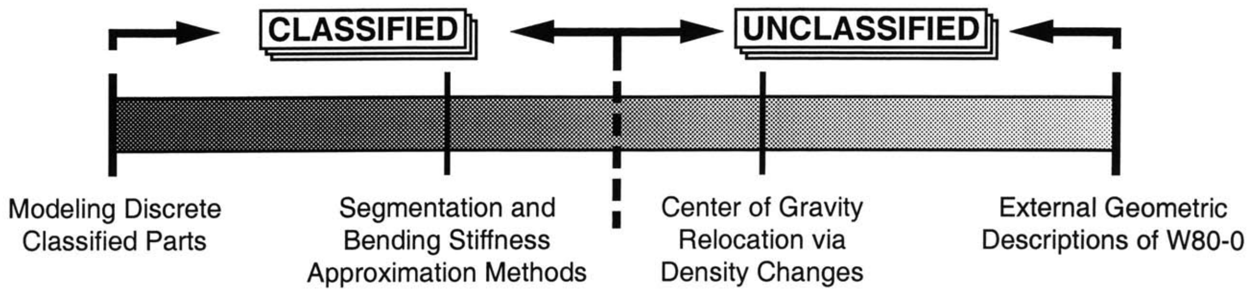


Figure 18. Technical Methods Superimposed on the LANL Classification Spectrum.

Chapter 3: New Design

Functional Requirements

The functional requirements are the basic tasks that must be performed by a design. For example, a functional requirement for a kitchen tool could be that it slices tomatoes. There is not necessarily only one or best way to satisfy the functional requirement, and this kitchen tool might use knife blades, wires, or lasers to cut the tomato. However, certain functional requirements have traditional implementations that have proven to be more efficient than others.

In general, the functional requirements (FR's) for the new Area Mount should match those of the original Area Mount. While the manner in which the new design meets the FR's may differ, the efficiency of the new implementation should match or, ideally, improve upon the original design. However, with many engineering problems, tradeoffs may eventually have to be made, and it was possible that a different area mount approach would have some aspects worse than the original while performing better overall.

The functional requirements which needed to be met by the new design are:

1. Mitigate shock and vibration delivered to the W80-0 aft end through the WH Can
2. Limit lateral deflection of the W80-0 aft end
3. Have an in-service lifetime of 20 years including over 60 insertion/removal cycles

Project Design Constraints

During initial development of the W80, design specifications were flexible, and the component designers negotiated technologies, dimensions, materials, etc. For example, when the LANL engineers needed

Functional Requirements Details

The first functional requirement for the new design was to mitigate shock and vibrations delivered to the W80-0 aft end through the WH Can. The new design should approximately match the original Area Mount's response to the Stockpile-to-Target Sequence shock and vibration environments. The damping and stiffness of the Area Mount should be approximately duplicated in the new design.

The second functional requirement was that the new area mount should limit lateral deflection of the W80-0 aft end as much as the original Area Mount. The Forward Mount already centered the W80-0 aft end in static conditions, but the compressed Area Mount provided a radial, distributed preload which reduced the displacements induced by other lateral forces applied to the W80-0 aft end. The preload behavior of the original Aft Mount is defined by the cellular silicone's load-deflection behavior, i.e. its deflection dependent stiffness. If possible, the new mount's stiffness should exhibit similar behavior.

Finally, the new design needed to have an in-service expected lifetime of 20 years. We estimated that the typical Area Mounts in service would not see too many insertion/removals, and a cyclic lifetime of 60 insertion/removals would be more than sufficient. Achieving this functional requirement would require investigating creep, wear , and fatigue issues; all areas in which the original Area Mount had faults.

Technical Design Constraints

Since the new mount must integrate with the Tomahawk and W80-0 systems, there are technical design constraints determined by the current design of the surrounding parts and system performance.

more space for a certain component, the Tomahawk designers initially objected but eventually relented and adapted their own design to the change. [16] The Area Mount redesign project did not have this latitude because the other parts had long been manufactured with specific properties set. Therefore, the design space of the New Area Mount project was constrained with respect to certain variables.

These constraints made New Area Mount design much more technically challenging. The geometry of the WH Can and W80-0 could not be modified, and they dimensionally constrained any solution to fit within the available volume between the bodies. The weight of the New Area Mount might not have to exactly match the original Area Mount, but it needed to be close.

A non-technical constraint was that the cost of producing the New Area Mount should not be unreasonably expensive as compared with the original mount. While it is difficult to precisely predict the cost of a part before it has been manufactured using actual production processes (a beta prototype), cost per unit can be roughly forecast based upon the complexity of the part, number of manufacturing steps required, and the cost of the manufacturing processes. While the Area Mount is an integral part of the Tomahawk/W80-0 mechanical interface, it is only one of many SLEP efforts which demand resources of their own. The final New Area Mount design should use the most effective and cost efficient technology to meet the functional requirements. In general, this constrained the technical design process by adding import to pursuing simpler technology solutions and cheaper manufacturing processes.

Design ownership issues also affected the technical design space, and the Area Mount illustrates a good example of how efficient division of organizational responsibility can lead to technical problems down the road. More than a few government design agencies and contractors had been involved with the TLAM-N development. Each party was responsible for a specific section of the missile/payload design, and many meetings were held in order to sort out common interface specifications and part ownership. Design ownership of the WH Can resided with General Dynamics, while LANL had design ownership of the Area Mount and Forward Mount. While these arrangements were logical and necessary, they inadvertently added to the necessity for an Area Mount redesign. The surface finish within the WH Can is one of the factors leading to the high W80-0 insertion forces responsible for Area Mount damage. Machining a smoother WH Can internal surface is a straightforward technical

The most important design constraint is that the new design should bear an overall similarity to the existing Area Mount design. Due to the success of the original design in nuclear tests in Nevada, a new design will meet with greater acceptance the more it echoes original design characteristics. What constitutes 'similarity' is not strictly defined, and colleagues involved in the W80's overall system performance would ultimately judge the sufficiency of a new design's similarity.

The second design constraint was that the design should have a weight close to that of the original Area Mount. This design constraint is much more straightforward as the Tomahawk has a limited amount of fuel to keep it aloft and significant increases in weight would detrimentally affect overall system performance. In addition the dynamic behavior of the W80-0 might change if we added significant weight to the Area Mount itself.

Another design constraint was that a new design should be as simply effective as possible in order lend itself to cost and time efficient manufacturing and installation. This constraint includes the issue of design for manufacturing, in which the part is designed to minimize the number and cost of manufacturing processes required. In addition, this constraint implicitly considers the pre-existence of installation, containers, and maintenance equipment for the W80-0. The original Area Mount allowed the W80-0 to be simply pushed and pulled in and out of the Tomahawk. An ideal new design would allow the same apparatus to be used for all in-service tasks while still correcting the original Area Mount design flaws. The impact upon the Navy's use of the product would certainly affect the design's acceptance regardless of its stand-alone ability to fulfill the functional requirements.

Finally, the new mount should operate under the other normal environments listed in the STS. These are biological, thermal, pressure, humidity, wind, suspended particles, chemical, EMR, and electrical environmental limits and ranges. Though these environments have less to do with actual mount function, the design needs to conform to these standards.

Concept Examples

Full concepts included two main functions, spring stiffness and damping. Some concepts integrated both of these functions, but other ideas related to only one of these functions at a time. Individual function concepts created natural opportunities to combine and permute many different 'full designs'. Five of the more interesting concepts are presented here.

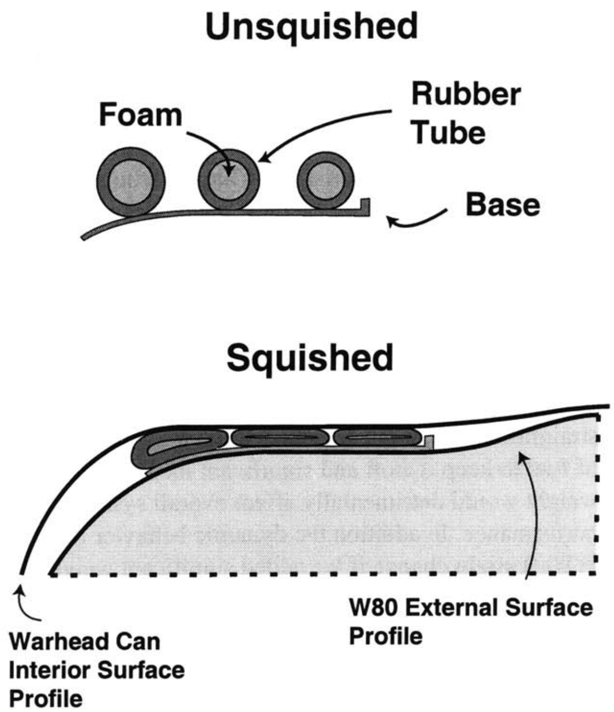


Figure 19. Squished Tubes Concept Sketch.

solution for reducing the friction. But as part of its SLEP activity, LANL can only re-engineer its Area Mount while the WH Can remains a General Dynamics responsibility apparently outside the purview of current SLEP activity.

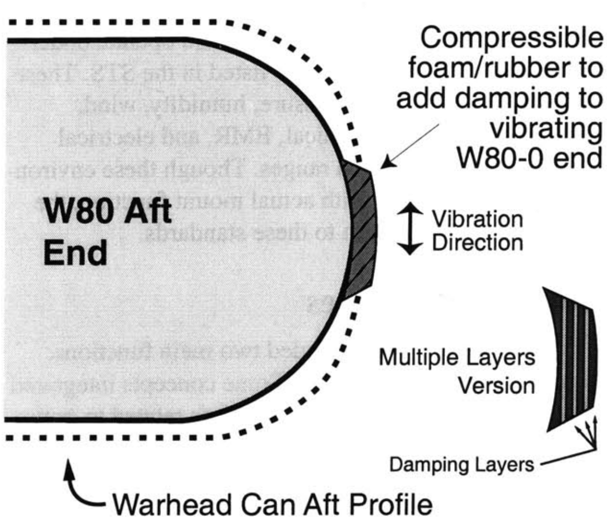


Figure 20. Damping Layer(s) Concept Sketch.

Squished Tubes

This concept consists of large elastomer tubes that circle the W80-0. They may have a core of damping material if the rubber does not provide enough damping by itself. As the device is inserted, the tubes get squished and pulled opposite the insertion direction. The tubes are attached to a base hoop part, which in turn attaches to the W80-0. This is a full concept providing spring stiffness and damping.

The appealing characteristics of this concept were that the rubber tubes might be able to occupy a similar volume as the original mount, but more tubes could be added if necessary. Also, given the commonness of rubber hoses, some candidate tubes could be readily available for prototyping and testing. In addition, this concept allowed for the same W80-0 insertion and removal procedures.

One of the concerns about this concept was the interface between the tubes and base (a Foam Mount-like part) had to be strong but not cause tearing when the tube was pulled during insertion and removal. In addition, it was not certain that a material truly existed whose combination of stiffness/tube diameter/wall thickness could supply the desired radial force. Consideration of the lifetime functional requirement naturally led to concerns about cracking, drying out, and compressive set of rubber after a long time in place.

During the insertion of this concept mount, the shape of the tubes would be stretched into flattened ovals as well as being squished. To truly test the concept stiffness, the tubes would need to be deformed to the inserted shape. However, such a test would require insertion and compression, i.e. two degrees of freedom in the testing apparatus would be necessary in order to capture the insertion deflection and rolling of tubes.

Damping Layers

The damping layers concept as applied to the W80-0 was an idea that could be used with other springs or full concepts. The principle behind this concept is to pack one or more layers of damping material between the device end and the WH Can. This principle is observed when a single damping layer and plate are attached to manufacturing machines to reduce vibration. [11] Perhaps packing multiple layers between surfaces would increase the effect. Since these layers lie in plane with the lateral vibration affecting the Area Mount, they should provide additional damping. This concept might be used to add damping to other full concepts that do not have enough available space or design freedom to meet damping requirements within the current Area Mount occupied volume.

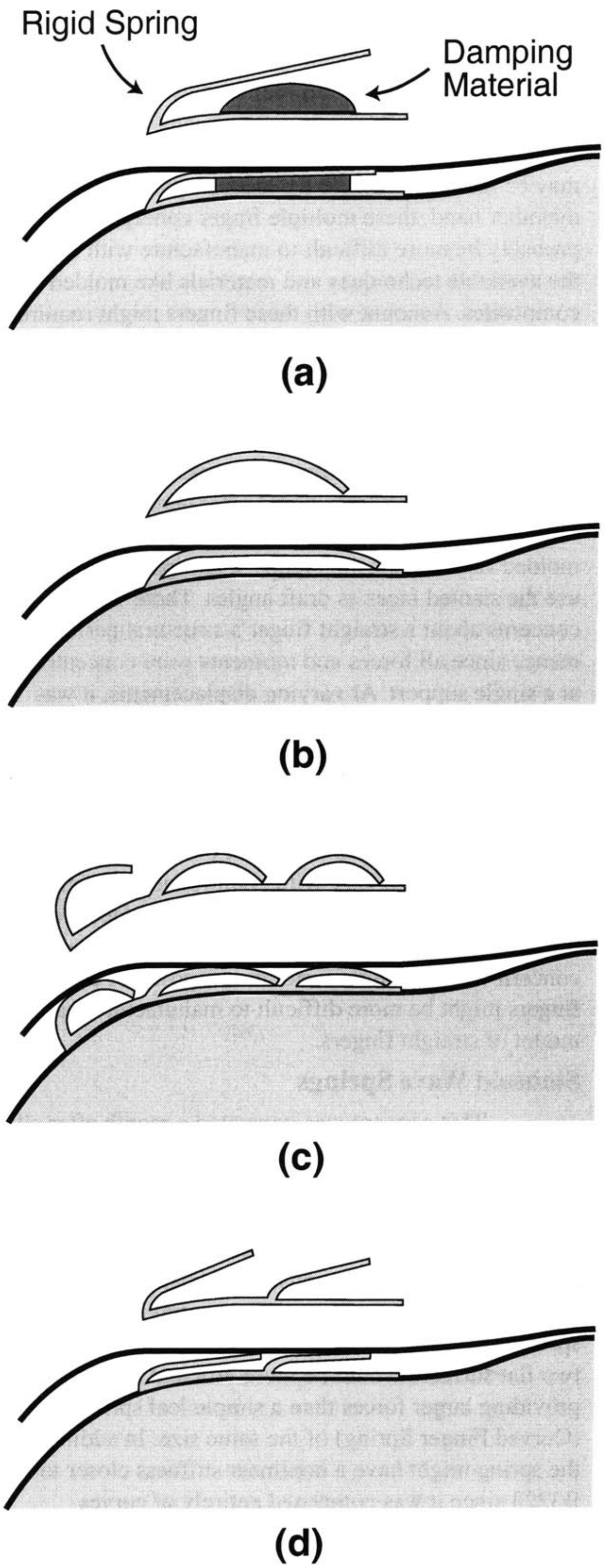


Figure 21. Finger Spring Concept Sketches.

A potential violation of the similarity design constraint was that the damping layers concept introduced forces at a different location of the W80-0 and WH Can than the original Area Mount did, and the effects of the addition needed to be considered. However, this concern was mitigated by the existence of another warhead, the W80-1, which has its aft end structurally mounted much closer to the pole. The vibrations for this other warhead are generally worse than those experienced by the W80-0 since the W80-1 is airplane-carried, and perhaps the damping layers would gain acceptance readily.

Finger Springs

The most promising concepts were the finger spring designs. Unlike the current Area Mount, these concepts separated the spring stiffness and damping into specialized materials and components. The finger springs were organized into two sets of options; Curved vs. Straight and Single vs. Multiple. The Straight fingers like those in Figure 21(a&d) have a curved base, but stick straight out and lie against the WH Can (Warhead Can). The Curved fingers are like those in Figures 21(b&c), and the right halves of the curves slide on the base ring while they are being compressed. This provides an additional point of support other than the cantilevered end, while also distributing the load better.

Varying the number of fingers along an axial length of the mount led to single and multiple fingered concepts. The concepts in Figure 21(a&b) have one finger while the other figures of spring finger concepts have multiple fingers bearing load. Some damping material location is suggested by Figure 21(a), and though other sketches might not have any explicitly drawn in, I generally assume that all these concepts would require some additional damping. These concepts' attributes were broken down into general and then specific pros and concerns.

The biggest 'plus' to the finger springs was their resemblance to the original Area Mount. Potentially, there might be twenty finger springs corresponding to the twenty original B3223 fingers, all of which occupied the same general area. In addition, the finger springs were fairly simple design concepts and required few materials and parts for the springs, damping, and bonding. Some concerns about these concepts were that they might be difficult to manufacture. In addition, with many tight curves, there were probably major stress concentrations that needed to be managed.

The single finger concept would probably be easier to manufacture than the multiple finger concept. As a simpler concept, the modeling, analysis, and prototyping would potentially move faster. However,

Concept Generation, Selection, and Combination

All the previous work done to investigate the problem issues, to build a knowledge base, and to understand design constraints was utilized in concept generation and development. Brainstorming new concepts for the Area Mount was at the core of my efforts. I spent large amounts of time speaking with other individuals about the specific issues or related topics in an effort to spark ideas. This group of contacts included the individuals I had met from other groups as well as other engineers in my team. In addition, I spoke to engineers who worked on totally different systems to see how they provided shock mitigation to their sensitive payloads.

Sketches and other concept visualizations were invaluable throughout the process. Main ideas could be illustrated more effectively with a sketch than with a verbal description. While crude sketches could be misinterpreted, different interpretations of the same freehand sketch could also lead to an even better concept after sorting through the differences.

During initial brainstorming and concept generation, any suggested concept was given consideration. Many of these ideas had little resemblance to the current Area Mount and represented significant shifts in operating principle. These extreme ideas would probably not survive the concept selection phase, but it was important to postpone judgement until after initial concept generation. While radical ideas might not actually make realistic designs, they sparked creative thinking which might lead to a related but more realistic concept along the same line of thinking.

Concept selection, combination, and further there was concern as to whether an extended finger would deflect predictably when depressed and deformed across a large area.

A specific advantage about the multiple finger concepts was that they might distribute force more evenly on the W80-0 surface than a single finger concept would. In addition, their smaller deflections may be more predictable for analysis and modeling. On the other hand, these multiple finger concepts would probably be more difficult to manufacture with some of the available techniques and materials like molded fiber composites. A mount with these fingers might require a mold with several pieces, increasing cost and process complexity. Finally, if these multiple spring fingers were each smaller and thinner than the single finger spring, their performance quality would be more sensitive to manufacturing tolerances.

Straight fingers could offer benefits with respect to simpler manufacturing; for example, with the molded fiber composite layups, a two-part mold could use the slanted faces as draft angles. There were major concerns about a straight finger's structural performance since all forces and moments were concentrated at a single support. At varying displacements, it was unclear whether the straight portion of the finger would stay in contact with the WH can.

Curved Fingers seemed better than straight fingers because the outward radial force would be supported at two points instead of one. In addition, the contact area would vary with compression smoothly, i.e. there would always be a significant surface area of the finger in contact with the WH can. The prevailing concern was that an area mount composed of curved fingers might be more difficult to manufacture than a mount of straight fingers.

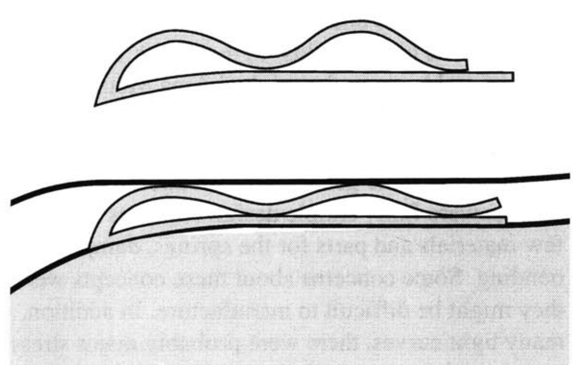


Figure 22. Sinusoid Wave Spring Concept Sketch.

Sinusoid Wave Springs

This concept was generated a month after all the previously mentioned ideas. In fact, I was presented with this possibility after approaching an ESA-EA engineer with questions about modeling the curved finger springs. He had considered sinusoidal wave shapes for other applications, and I adapted the idea into a mount design concept. The central idea was that a spring with a sinusoidal profile compressed between two flat surfaces would be more efficient in terms of providing larger forces than a simple leaf spring (Curved Finger Spring) of the same size. In addition, the spring might have a nonlinear stiffness closer to B3223 since it was composed entirely of curves compressed against flat surfaces. Essentially, the Sinusoid Wave spring was a special kind of finger spring but with a different profile.

The Sinusoid Wave Spring's complicated

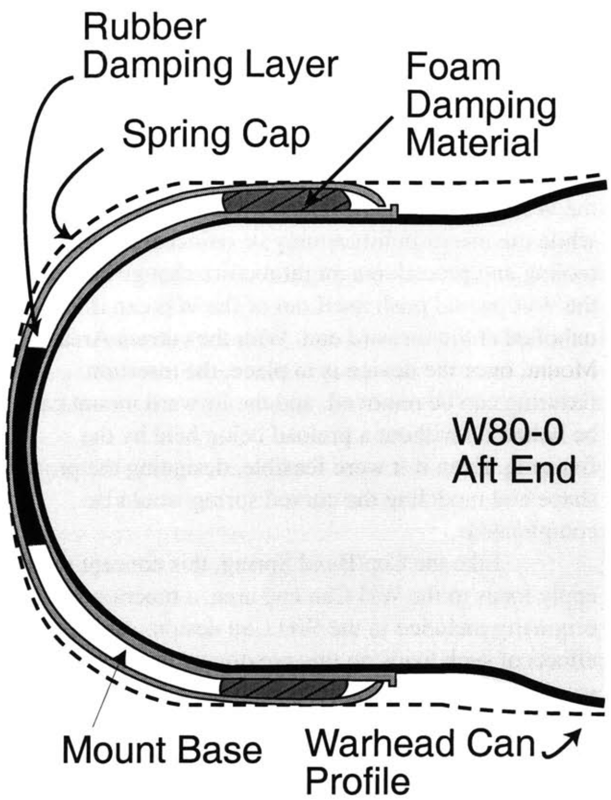


Figure 23. Cap/Band Spring Concept Sketch.

generation followed the first concept generation phase. Concept selection was managed by comparing the concepts with design constraints and determining which ideas had merit, needed adjustment, or were impractical. For example, to help with concept selection, I created a 2D outline template of the W80-0 and WH Can interface surfaces. After doing rough, quick-stroked sketches of an idea, I would try to draw this concept on the template to give it dimensional context. The template sketch was just one of the design constraint checks for a concept's viability as a solution.

While some concepts had obvious faults, they might have some attractive qualities that can be combined with other concepts to create new ones. Older, more general concepts can split into separate, more specific concepts through refinement. Further input may lead to new ideas as well. After all these new concepts have been created, concept selection criteria are applied again, reducing the number of concepts. [17]

Concept generation, combination, and selection iterations will reach a point of diminishing return as all the surviving concepts seem to theoretically fall within the design constraints. At this point, further development is necessary to verify that these concepts

geometry certainly posed the same problems in manufacturing as the curved finger springs. In addition, I was concerned about creating an analytical model for this concept.

Cap/Band Spring

The Cap/Band Spring was a concept that combined the Curved Finger Springs and the Damping Layers ideas. For this concept, the damping layer is placed between the device and the spring, another layer could be added between the spring and the WH can. The spring extends around the aft end of the W80-0 and is normally curved beyond the nominal positions of the WH Can walls. Upon insertion, the curves are flexed radially inward.

Though an interesting combination of ideas, there were a fair number of concerns with this concept. While the sketched cross section seemed like it might work, if the concept was considered in full three-dimensional (3D) representation, the cap assembly of springs could not remain a continuous hoop around the W80-0 unless hoop stress components came into play. One solution to this dimensional problem was to separate the cap into spring spokes, where all the springs join at the pole of the W80-0. The full, 3D design might have additional stiffness in the hub area that would still need to be calculated.

In addition, the adhesive bonds between the separate spring and base pieces (at the W80-0 pole) would have to be strong enough for the device to be withdrawn from the WH Can without peeling the cap assembly off the W80-0. This idea seemed more complex than the other ideas and might introduce unnecessary costs and manufacturing difficulty. Finally, the overall concept took up more volume than other concepts since it required space around the entire W80-0 spherical end.

Counter Curve

This concept was more out-of-the-box and novel than other concepts, and it confronted the issue of the large force (up to 4000 pounds) necessary to insert the original W80-0/Aft Mount Assembly into the WH Can. While outside the WH Can, the distance between the Counter Curve sides and the W80-0 sided would be *less* than the inserted gap between the W80-0 and WH Can. The apex of the uncompressed spring curve would jut out further than the nominal gap between the ends of the positioned W80-0 and WH Can. As the W80-0 is inserted, there are no reaction forces created until the spring apex contacts the back wall of the WH can. Then, the force required to push the W80-0 into place begins to increase as the spring flexes. Eventually, the lateral sides of the spring come into contact with the can be successfully implemented. In an ideal situation, one could pursue thorough development of all promising concepts and conduct a side-by-side comparison of how well they met design criteria. An educated decision could then be made about which concept was the best to use for final development and production. With limited time, I decided that I had to choose one concept to develop. I knew that the technical issues facing any of the surviving concepts would require extensive efforts. If I hoped to ever proceed to any kind of physical tests or experiments, I needed to pick one concept and run with it. Therefore, I selected the Spring Fingers with Damping Material concept based upon how well it *theoretically* fulfilled the design criteria as opposed to the others.

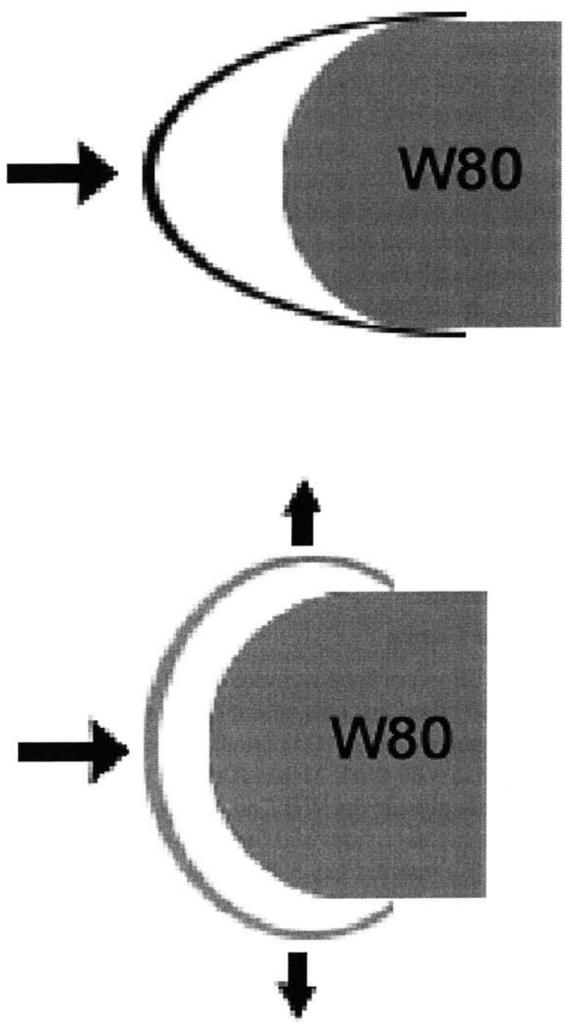


Figure 24. Counter Curve Concept Sketch.

WH Can inner surface. As the apex is pushed into its nominally compressed position, the spring side walls are further pushed against the WH can walls, providing a radial force.

Since most of the sliding material contact has been removed, the maximum force required to insert the W80 may drop significantly with this concept. But while the insertion forces may be reduced, the insertion tooling and procedures might require change because the W80 would push itself out of the WH can if left unbolted at the forward end. With the current Area Mount, once the device is in place, the insertion fixturing can be removed, and the forward mount can be bolted on without a preload being held by the fixturing. Even if it were feasible, designing the proper shape and modeling the curved spring would be complicated.

Like the Cap/Band Spring, this concept would apply loads to the WH Can end area, a function not originally included in the WH Can design. Again, the effects of such loads on this previously untouched area would need investigation. As with the tube concept, testing this concept would require two degrees of freedom in order to test force and displacements relative to the WH Can side and W80 sides.

Incremental Concept Designs

The most obvious design concepts were not really new technical ideas. One idea was to replace specific materials in the Area Mount while retaining the current part geometry. For example, to reduce the sliding friction, the Shoes could be made from a metal other than aluminum so that there would be no galling when the dry lubricant was scraped off. Perhaps a new cellular silicone or compressible foam could be made which would not experience a compressive set that relaxed below the design levels. However the Shoe 'fix' would only address the large insertion force flaw with the original Area Mount, and the development of a specialized foam was beyond the scope of my team's expertise and project purpose.

Another 'concept' was to make the Area Mount a Limited Life Component item and have them replaced every few years so that the compressive set would not pose an issue. This possibility had been entertained during original development, but a cyclic test convinced the designers that the Aft Mount would survive more than three times the number of insertion cycles expected during its service life. [12] The dry lubrication would certainly still wear, but enough lubricant would last for several insertion/removal cycles to be done without difficulty. While this 'solution' was theoretically possible, the additional nuisance created

Concept Development

My concept development efforts included modeling, analysis, prototyping, and testing. Though largely technical endeavors, modeling and analysis still required practical optimization and applied perspective. Prototyping and testing were the more tangible processes which required strategic planning.

I heard a recent inductee to the Inventors Hall of Fame comment that a key to successful devices was to "Prototype, Prototype, Prototype". Prototypes help move concepts from the theoretical realm to the real world. Many lessons are learned from a prototype and the process of making one, and it is important to realize that the prototyping process may have to be iterated before a final design is reached.

Assessing and Managing Risks

Before commencing with further development and prototyping, I tried to identify the risks and factors involved and plan accordingly. Building each prototype may require a non-trivial amount of time since each one requires its own model development. Then, actual dimensions and manufacturing processes must be selected and implemented. The most pressing risk was that modeling, analysis, and prototyping would take too much time, and I would never conduct any physical testing, which was one of my goals. The availability of manufacturing and testing equipment required by prototyping would have a large impact upon the time to build a prototype.

When discussing concepts with contacts in ESA-WMM, I made sure to ask what manufacturing processes were best suited for the concept and its prototype. Then I would ask which manufacturing methods and materials were readily available and practical. Often a tradeoff would have to be made between technical preference and practical needs. Other times, modeling and analysis were directed in ways that would lead to prototypes which could be manufactured with available materials and methods. In addition, I contacted MIT staff to assess what equipment was available on campus that I could use if my test work carried over into the Spring semester at school.

To minimize the time necessary for each prototype build, I followed the well-known KISS philosophy, which stands for 'Keep It Simple, Stupid'. This recommendation was appropriate for my prototyping effort since I did not have a great deal of time to work with. My prototype development path needed to be focused enough so that the prototype would provide useful technical and experiential data that could be used to refine the design. At the same time, the path needed to be 'simple' enough that I did not waste too much time on complicated details that by the replacements might not warrant the expense required by such frequent operations.

Overall, it seemed that while incremental 'fixes' could be pursued, a new design that solved the core problems might be the best solution in the end. Regardless, an investigation of new design possibilities was prudent and necessary for an informed judgement of the best future course of action.

Concept Selection

I decided to pursue the Straight-Single Finger Spring and the Curved-Single Finger Spring concepts for initial development. Later on, I decided to pursue the Sinusoid Wave Springs as well. While many of the above concepts had potential to fulfill the functional requirements, I felt that the Finger Spring and Sinusoid Wave Spring concepts were the most in line with the design constraints. The Finger Springs would be probably be made of plastic or composites versus the Area Mount's cellular silicone, but the general action of the new mount would resemble the original's if the springs were located in the same places as the cellular silicone 'fingers of the Pad Mount.

In addition to these technical reasons, the selection process involved prioritizing concepts that I believed could progress the furthest during the limited time period. Concepts that would require multi-axis testing equipment were prioritized lower than those that could be tested in one dimension. Concepts requiring heavy materials development or complicated manufacturing processes were placed lower than concepts with more readily manufactured prototypes. If more resources and time had been available, the best course of action would have been to pursue development of several varied concepts and ensure a diversity of thought and options. With limited time, however, the prudent course of action was to focus my energies on the most promising concepts.

Concept Development

The concept development process would move an abstract concept closer to application via analysis, prototyping, and testing. The goals of these activities were to show whether the concept could succeed at fulfilling the functional requirements within the design constraints and, if it succeeded, to determine the appropriate physical dimensions, materials, and characterization models.

'2D' vs. 3D Model and Prototypes

Unlike linear shock absorbers, the Area Mount mitigates shocks and vibrations along two axes since it forms a ring around the W80-0 aft. However, one can imagine the Area Mount as a circular array of identical, compressible slabs of cellular silicone. Each of these individual slabs acts as a linear shock absorber, and the Area Mount only arrays them in a circle. (Figure 25)

Observing this symmetry, my adviser and I realized that the problem of matching overall Area Mount performance could be broken down into two sub-problems. The first problem was matching the individual characteristics of a new design finger spring to Area Mount finger performance. The second problem would be to then match the performance of a hoop of such springs to the overall Area Mount performance. If the first problem were handled well, the second problem might require less work than if we tried to model, prototype, and test entire new mounts designs from scratch. Therefore, it was decided to begin the development process by focusing on a single finger section of the Area Mount and new mount.

Curvature Approximation

Another simplifying approximation was to model the fingers as basic extruded profiles (Figure 26). That is, the side profile of the fingers was kept constant and extruded in the orthogonal direction. The actual Area Mount finger had a mostly common profile but was extruded in an arc with a radius of the Foam Mount outer surface. If one placed an Area Mount finger on a flat table, the most the bottom surface of the finger would diverge from the table would be 1.5mm. The extruded arc length would be 41mm long. The ratio of the length to maximum arc height is large enough that for a first cut analysis, the plane extrusion model is sufficient, and hoop stresses can be neglected.

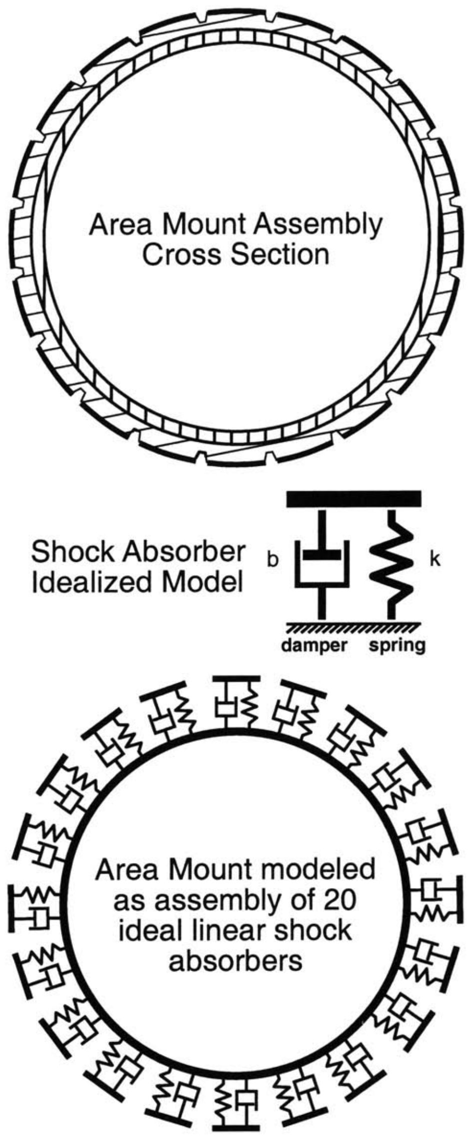
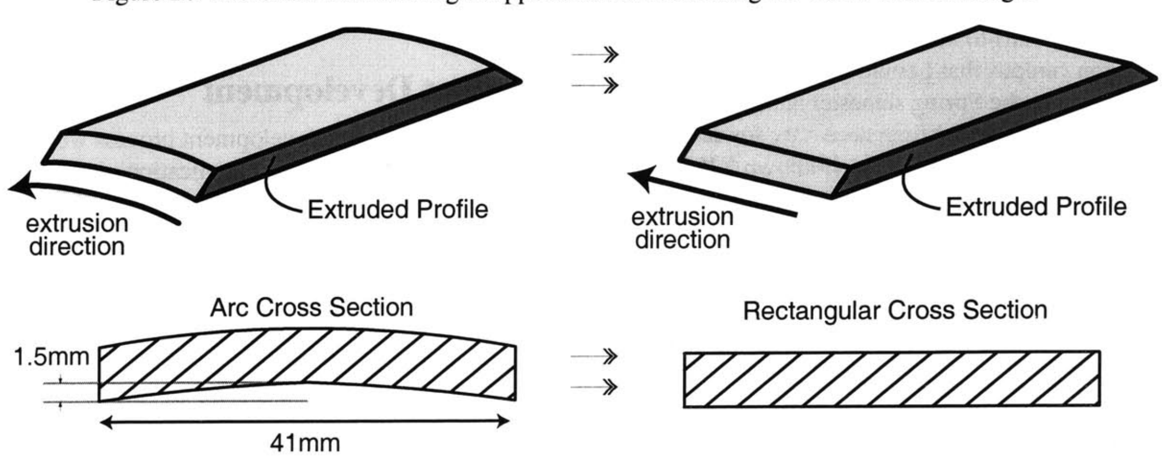


Figure 25. Approximation of Area Mount into assembly of Linear Components.

Figure 26. Arc Cross Section Finger Approximated as Rectangular Cross Section Finger.



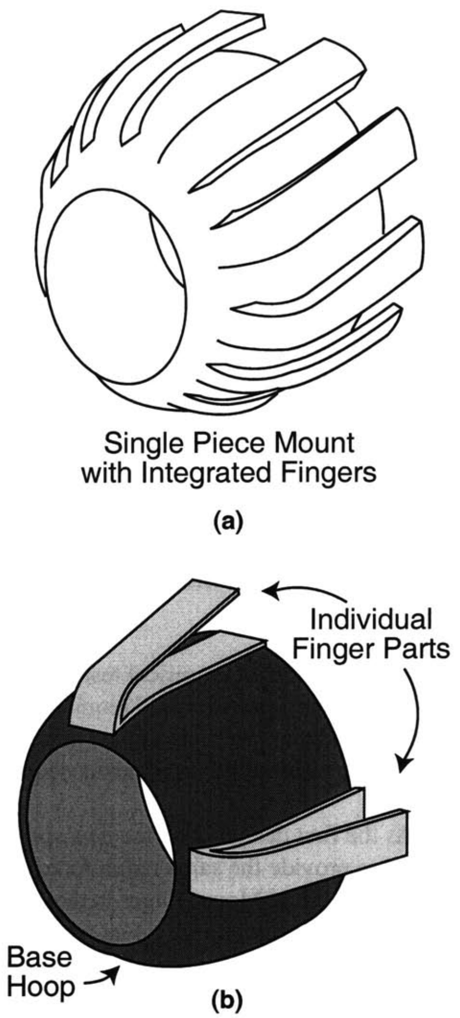


Figure 27. Single Part and Multiple Part Manufacturing Concepts for New Area Mount.

would not appreciably contribute to the lessons learned and might change for the next prototype anyhow.

'2D' vs. 3D Model and Prototypes

As I thought about ways to pursue efficient concept development and prototyping, my adviser made a recommendation to simplify my design problem from the total 3D problem to a simplified "2D" model. To make this decision, it was important to consider technical issues like preservation of relevance and manufacturability. However, the key driver for this decision was a practical need for effective, efficient development.

As long as the simplified model was technically relevant to the larger problem, much of the modeling, analysis, and fabrication experience accrued during the 2D development effort would be directly transferable to a subsequent 3D design and prototype effort. The same valuable experience would be gained

Manufacturing Insight

While considering the approximations that reduced the complex hoop model to simpler components, I realized that the same idea could be applied to the final, physical design of the New Area Mount assembly. Previously, the New Area Mount had been envisioned as a single molded part, which would have multiple spring fingers extending from a common base. This design reduced the number of parts required, but manufacturing such a large (11in. diameter) and complicated part would require a complex, expensive mold, if one could even be made at all. As I analyzed single finger segments, I realized that there was no particular reason (besides minimizing part quantities) that the new mount had to be molded in large chunks. The fingers could each be molded or pressed individually and then attached to a thin hoop surrounding the W80-0. (Figure 27(b)) There were numerous advantages to this approach. First of all, the finger profile could take on whatever shape we liked, as long as it had sufficient draft angles in the direction of the extrusion. (Figure 28) This extra design flexibility made more efficient and resilient finger geometries possible. In addition to greater freedom, the molds for the fingers would be much smaller and cheaper, and the base hoop could be easily extruded, filament wound, etc.

Spring vs. Damping Focus

The dynamic behavior of many devices can be modeled as a combination of three kinds of elementary components; masses, springs, and dampers. As a shock absorber, the Area Mount could basically be modeled with springs and dampers without mass since the W80-0 end was the important mass value. A fundamental idea underlying the Finger Spring concepts was that spring and damping behavior would be uncoupled into separate parts rather than coupled within a single material like the cellular silicone or other compressible foam. A devoted 'spring' part would be made of a material more rigid than the cellular silicone. This rigid material would probably relax and creep less than the cellular silicone, and the mount could perform to specifications for longer than two years. The devoted 'damper' material would not have to bear a significant static load and could be expected to perform consistently for a longer time.

It was decided to first focus upon designing the spring component of the Finger Spring concepts and then add damping later. The spring component was important for the static and dynamic performance, while the damping material only played a critical role in dynamic performance. In addition, discussions with other engineers left the impression that designing for appropriate damping was something of an 'art' and

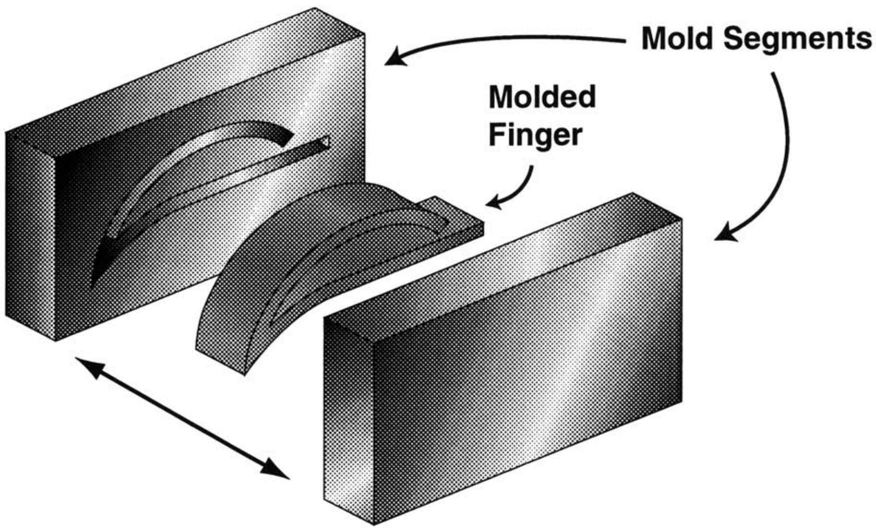


Figure 28. Potential Molding Method for a Single Finger of Multi-Part Area Mount Assembly.

faster than if I had to spend more time and money building a complicated 3D model and prototype that I know was only experimental.

The 2D-based prototype model was more financially efficient than a full 3D prototyping effort especially considering manufacturing costs. Whether injection molding, machining, pressing, or casting a part, the manufacturing and material cost to make an Area Mount-sized part could be expected to be many times larger than the cost to produce a part with a small fraction of the volume.

Given the technical and practical considerations, I began focusing development efforts on a single finger portion of the Area Mount. Instead of trying to match total mount performance from the start, a design was pursued which would duplicate the behavior of a single finger. After development for a finger replacement was complete, development for a complete mount could be pursued using combinations of the models and perhaps the existing prototypes from the single finger development process.

Modeling

Analytical and numerical models often attempt to predict behavior by approximating or relating a complicated device to simpler parts and components for which behavior is well-understood. The power of this principle is at the core of engineering philosophy but is clearly evident in other areas like financial modeling and optimization. The assumptions behind these decisions make or break the utility of the model. If the model simplifies too much, the predicted behavior will not accurately demonstrate real world behavior. If the model is very complicated, the underlying system of required large amounts of empirical testing. Dynamic testing of damping response would require equipment more complicated than a simple universal tester, which was all that was required for load versus displacement testing.

As the first design goal, the new spring should be designed to provide the same radial force outwards as the compressed Pad Mount finger in the nominal inserted position. However, individual Area Mount fingers experience more than the nominal % deflection during shock excitation. As the second design goal, an ideal spring would exhibit nonlinear load-deflection behavior like the cellular silicone for the range of deflections experienced by the Area Mount during shock response. Potentially, simple deflection experiments could roughly evaluate a spring's dynamic response similarity to the original. If the new spring's load-deflection curve matched the cellular silicone's curve (Figure 8), there would be greater confidence that the new spring would have the same stiffness as the Area Mount throughout a dynamic perturbation.

Modeling

Throughout model development, knowledge searches were conducted using library resources, handbooks, textbooks, papers, and personal interviews. From these sources and my classwork, basic models were created for the Straight, Curved, and Sinusoid Wave finger springs. The goal of these models was to come reasonably close to dimensions and material properties that would be used to build prototypes for testing. When inputted into the model expressions, usable dimensions characterized spring fingers that supplied the necessary loads without having stresses

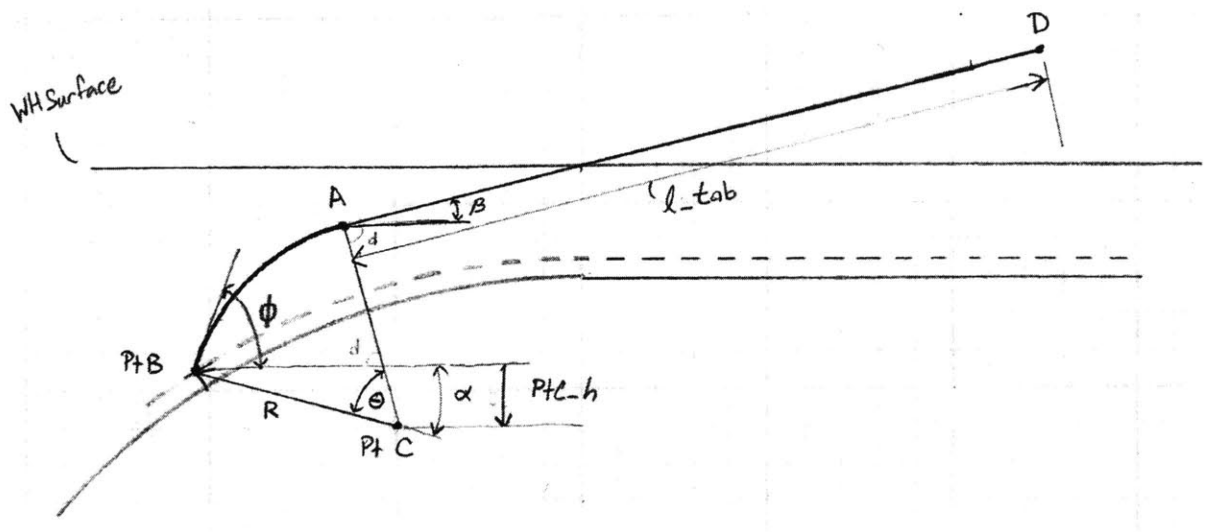


Figure 29. Sketched Geometry from Straight Finger Analytical Model.

equations may not be solvable or will take a very long time to compute. A mark of a good engineer is her ability to accurately model real, complex systems while using the fewest number of components.

In a design problem, device behavior is often influenced by many parameters, which are included in the model. While these parameters may individually cover a large range of values, only special combinations will lead to the desired behavior of the entire system. For large models, iterating computation for all possible permutations of all parameters would take an impractical amount of time. One approach to simplifying the problem is to determine which parameters affect system behavior the most. Then, only these sensitive parameters are iterated through computation while the other parameters are held constant. This series of computations requires less time than exhaustively iterating all parameters, and a working set of values is found faster.

Analytical and numerical modeling methods were both employed during my development efforts, with varying degrees of success. When investigating shapes for the Straight and Curved finger spring profiles, I analytically approximated the profiles using combinations of models and expressions from engineering textbooks, craft handbooks, and other technical sources. However, I had difficulty finding model components that matched the specific load distribution and end constraints of the spring concept. Still, I formed the model using the available approximate shapes and equations. I decided which parameters had the most bearing upon the spring's performance and iterated the equations through ranges of these values in search of behavior matching the force levels of the original Area Mount fingers. The result was a range of larger than the yield strength of the spring material. For initial Finger Spring analyses, the Young's Modulus and yield strength values were taken from a set of fiber composite layup properties furnished by an ESA-WMM engineer.

Straight and Curved Analytical Models

Straight and Curved Finger models were created within Matlab scripts. Figure 29 shows the first Straight Finger model, which used a formula for curved beam bending from Marks handbook. [13] The load is applied at the beam's end in the radial direction. The geometric inputs were the curved beam radius and the location of the encastred beam base. While many of the models were usually written with the load as the input, my models were created with the geometry as the input and the loads as the output. The W80-0 and Tomahawk positions are pre-determined, so for a given geometry, the y-component of beam end's final displacement is known.

Initially, I had difficulty finding references that had good models for curved beams. While many handbooks had leaf spring equations, the curved beam sections of the spring fingers had two major differences from leaf springs. The leaf spring expressions generally assumed that the end of the leaf was pinned rather than encastred. Also, they mostly assumed that the load was applied at a point, but the finger spring is depressed by an area section of the WH Can. Eventually, I located a reference that had expressions for a curved beam being bent against a surface.

When a curved beam is bent against a surface, the surface shape limits the deflection and shape of the beam. This limit enables the beam to withstand a larger

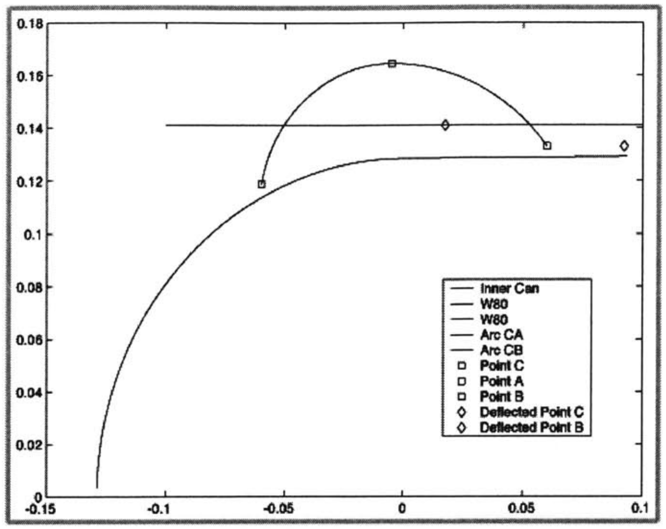


Figure 30. Plotted Geometry from Curved Finger MATLAB Analytical Model.

finger dimensions which should 'work', if the modeling assumptions were correct. Verification and refinement of these results was necessary before beginning physical prototyping.

Numerical models like finite element analysis (FEA) were subsequently applied to the design as a check and refinement of the initial analytical models. One benefit of an FEA model is that adjustments can be made more easily to part, material, and perturbation properties than in a physical model. The iteration required to match the model dynamic behavior to the actual W80-0's would certainly be easier for a FEA model than for a physical part assembly. In addition, the

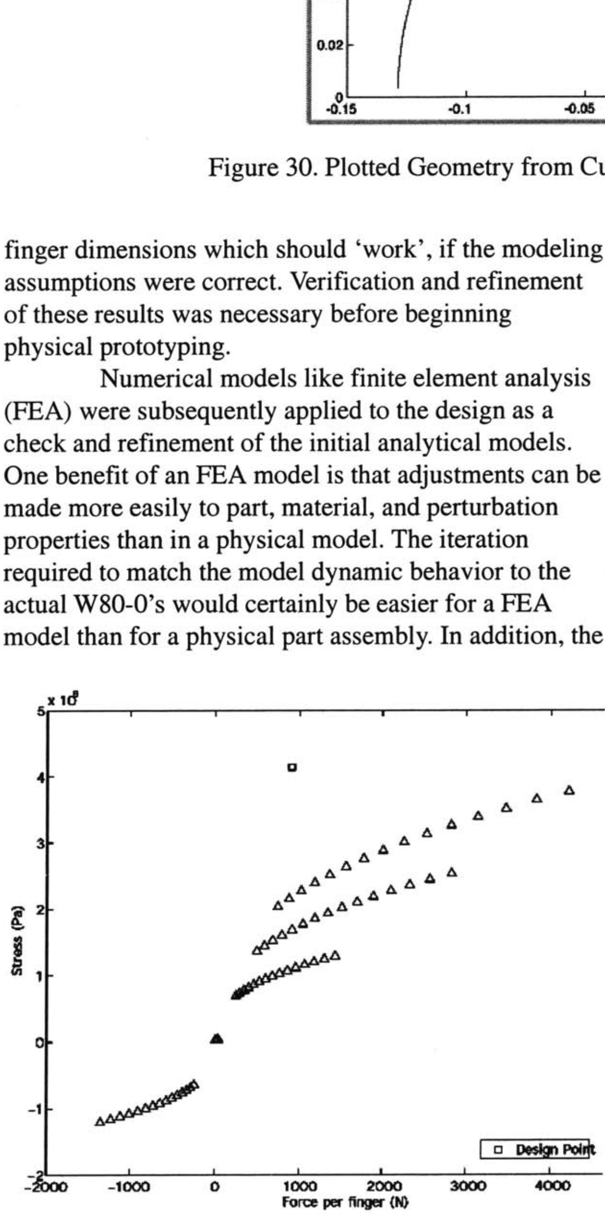


Figure 31. Iterated Analytical Model Results Plotted Relative to Design Point.

end load because more of the beam can absorb strain energy rather than concentrating it at the beam base. The design stress of the bent beam is inversely proportional to the initial radii of the spring finger and surface. [14] In the Curved Finger Spring model, the WH Can surface was flat (zero radius), and only the radius of the curve determined the final stresses within the beam.

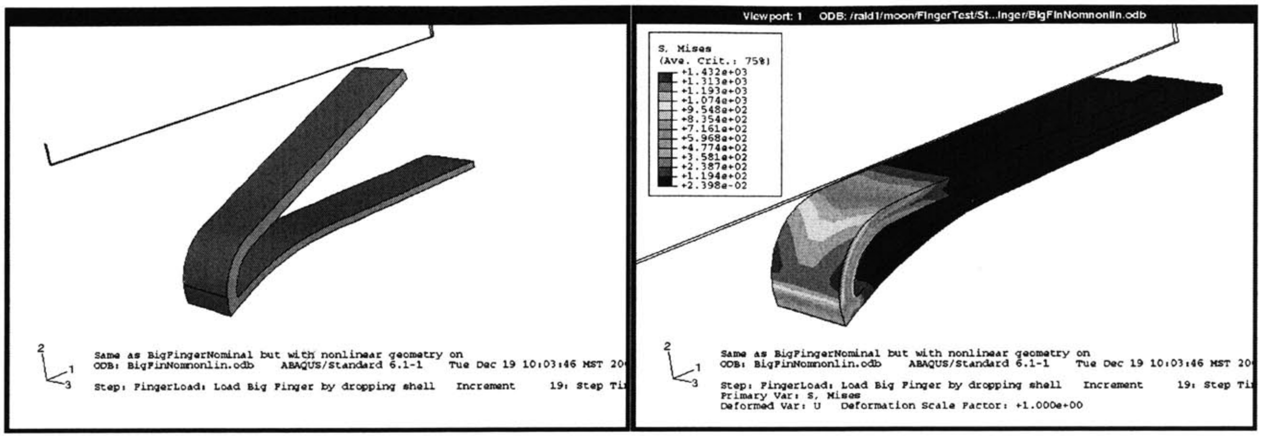
Even with this distributed load model, some large assumptions had to be made. First, the attached base of the curve was assumed to be pinned rather than encastred. Also, it was assumed that any deformed beam section would stay in contact with the WH Can after making initial contact.

Figure 31 is a sample of how Matlab was used for both the Straight and Curved finger models to visualize possible combinations of dimensions which provided the necessary force but had manageable stresses. Key values such as beam thickness and radius were iterated and compared graphically against design threshold points. These graphical representations helped make clear which parameters had the greatest impact upon the force and stress levels predicted by the model.

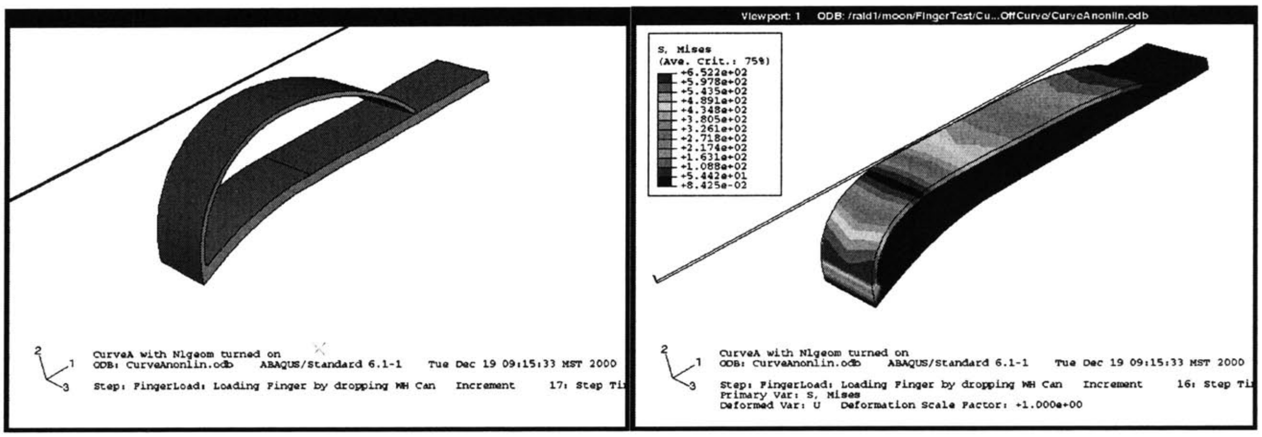
Later on, some better expressions for the finger spring loading were found within Roark's Formulas for Stress and Strain. [15] These expressions included the proper constraints as well as handling distributed loads. However, by this point, I had already moved onto numerical analyses that highlighted the detrimental impact of the earlier constraint assumptions.

Straight and Curved Numerical Models

Dimensions resulting from the Matlab analytical models were used to create parts in ABAQUS. These parts were then 'tested' by compressing them to



(a) Straight Finger Spring



(b) Curved Finger Spring

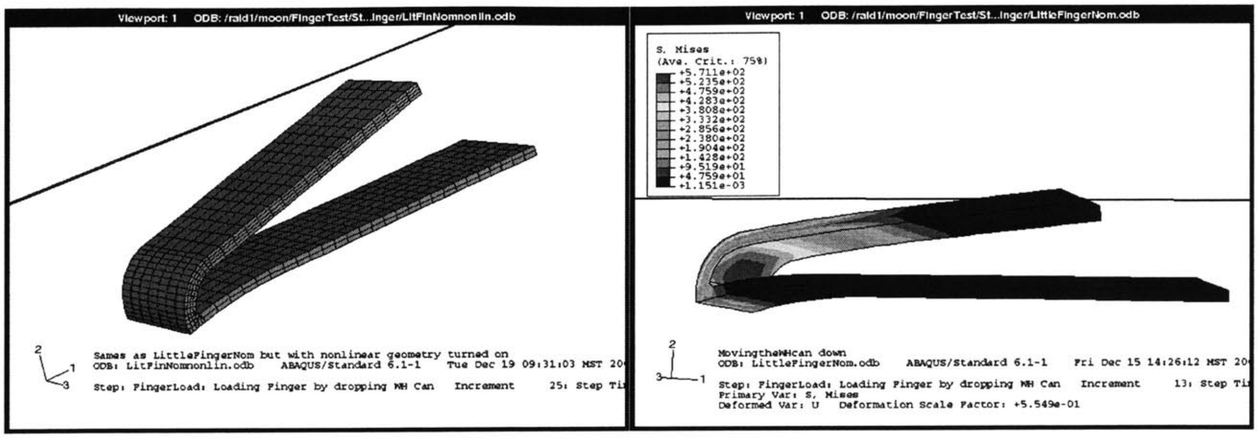
Figure 32. Undeformed and Deformed FEA Models of Spring Fingers.

cost of simulations is much lower than manufacturing the actual parts. With the computer model, parts can be 'destructively' tested and instantly 'recovered' for the next simulation.

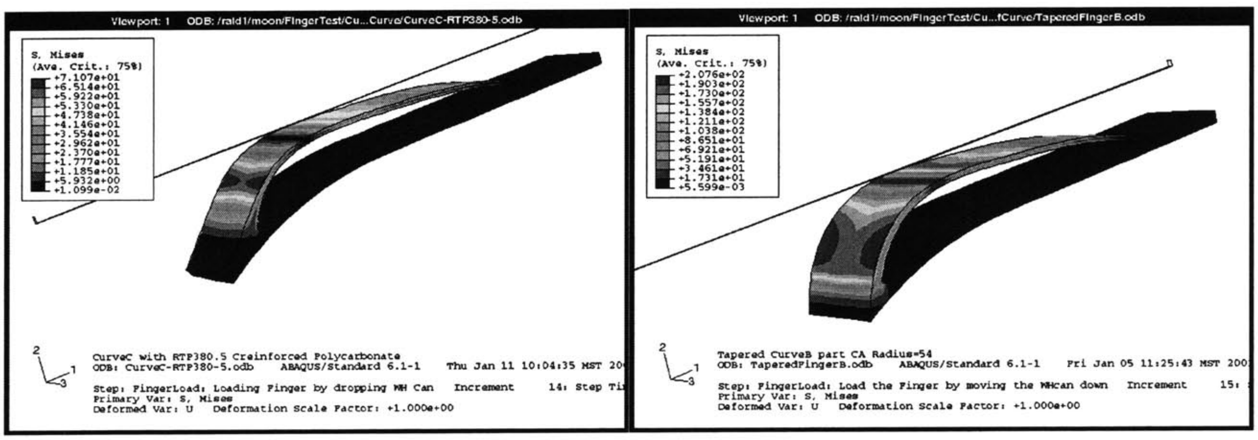
While the results of a FEM analysis may look impressive and 'realistic', it is important to remember that the quality of the model and its results depends upon the key assumptions made while building the model and constraints. With a physical model, as long as the test instrument is properly instrumented, the test results will reflect the natural behavior of the test assembly. All the natural forces, surface interactions, and constraints are true to life and automatically in effect. With an FEA model, the expected behaviors, phenomena, and interactions must be consciously included in the model. If important phenomena are misrepresented or not included, then the results may not accurately represent true behavior of the assembly.

the nominal displacements. The results showed large stresses that were orders of magnitude higher than the values predicted by analytical models. The locations of these high stresses were at the base locations of the finger springs. Figures 32(a&b) and Figures 33(a&b) show the stress concentrations located at the bases of Straight and Curved Finger Spring ABAQUS model parts. The constraint assumptions made in the analytical models had neglected important behavior, which led to stress effects evident in the numerical model but absent in the Matlab models.

Several attempts were made within the numerical models to alleviate the stress concentrations. Geometrical and material variability were investigated. Dimensionally, curve radii were reduced, tapers added, base points moved, and beams were thinned to no avail; the stress concentration was still too great. For a given geometry, reducing material modulus of elasticity decreased the reaction force and stress linearly. Real



(a) Alternative Straight Finger Meshed and with Stress Concentration at Bend



(b) Various Tapered Finger Springs

Figure 33. Variations of Straight and Curved Finger Spring FEA Models.

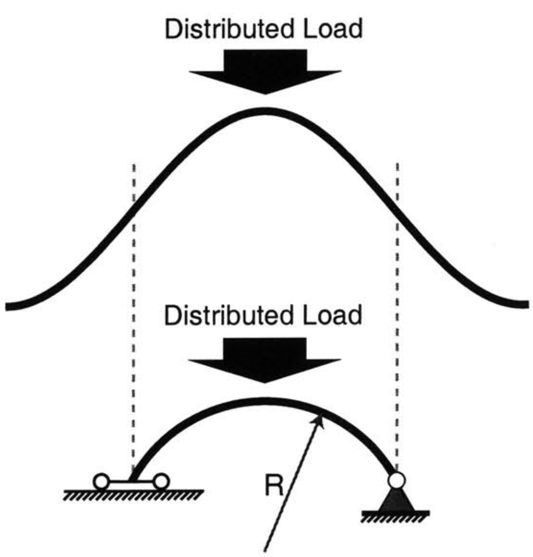


Figure 34. Sinusoid Wave Spring Finger Arc Approximation Analytical Model.

materials come in many combinations of elasticity and stress that do not vary linearly, but none were found that did not 'break' within the ABAQUS model test. At best, the stresses created by the geometry were four times the material yield strength. It became clear that a major shift in geometry was necessary, as it was inefficient to continue making small refinements to the ABAQUS model dimensions.

Sinusoid Wave Analytical Model

For the Sinusoid Wave finger spring design, an expression relating force and compressed displacement was sought. One half-period of a sinusoid can be approximately modeled as an arc with one end pinned and the other end constrained vertically. (Figure 34) This arc is then loaded with a distributed force on the arc's top surface. This model corresponds with expressions in Roark's Formulas for Stress and Strain. However, these expressions needed to be rearranged such that the vertical displacement of the top of the arc

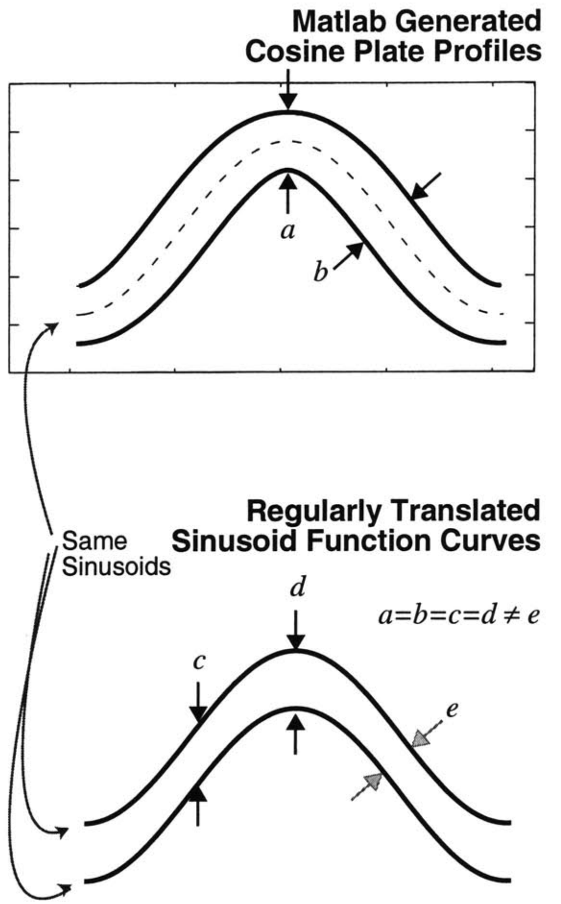


Figure 35. Translated vs. Derivative Generated Sinusoid Wave Spring Profiles.

Prototype and Test Design

During concept development, multiple prototypes can be made to illustrate and explore different areas of performance. For example, in one of my design classes, we made two different prototypes of a tripod we designed. One prototype was an aesthetic model, which looked like a saleable product but did not actually work. The other prototype was a functional model that had fully operational mechanisms but lacked aesthetic detailing. Each of these prototypes was developed keeping the testing method and its data type in mind. The aesthetic prototype focused on appearance because it was used to collect user opinions and visual impressions. The other prototype was created for performance testing, so realistic functionality was critical. Similarly, the finger spring prototypes design needed to interface with the test design.

was used to solve for the resulting vertical force instead of vice versa. [15]

An expression for maximum stress in the sinusoid was found by using an inverse problem. The idea was that the stresses created by bending a plane into a sinusoidal shape would be equal in magnitude to the stresses created by flattening a sinusoid. A sinusoid shape was generated by the generic function, $F(x)=(-a/2)\cos(2\pi x/L)$, where 'a' is the peak to peak amplitude and 'L' is the period length. The radius of curvature, ρ, of a function can be found with the expression $\rho = [1+(F'(x))^2]^{3/2}/(F''(x))$.
The expression for maximum radius of curvature, located at the sinusoid peaks, is $\rho_{max} = L^2/(2a\pi^2)$. Remembering that the sinusoidal plate has a finite thickness, t, the stress, σ_{max}, at the peak surface was derived and equaled $(\pi^2 Eta)/L^2$.

Sinusoid Wave Numerical Model

A Matlab script was written to create the sinusoid plate geometries for ABAQUS/CAE. Merely offsetting two sinusoidal curves with the same magnitude and phase would not generate the correct plate surfaces because such a part would not have uniform thickness. (Figure 35) The Matlab script used a cosine function and its derivative to generate separate top and bottom profiles of a part with sinusoidal centerline and uniform thickness. The amplitude, period length, and number of periods were the varied parameters.

The top and bottom profiles were inputted into ABAQUS/CAE and were used to generate sinusoidal curve plates. Experience gained from the Straight and Curved Finger Spring models affected the new models. The initial sinusoid dimensions had less extreme radii of curvature, and the sinusoidal wave plate was simply compressed between two flat surfaces.

Over forty ABAQUS jobs were completed with sinusoidal wave parts. These many iterations investigated the effects of varying phase, amplitudes, plate thickness, period number, end constraints, and material elasticity upon reaction forces and maximum stresses. However, these iterations were not randomly splayed throughout the design space. On the contrary, usually only one variable was changed between runs, so that the trend of its direct effects were observable. Even with this focused approach, some decisions needed to be made about which parameters needed to be set. One such decision was to always set the nominal displacement of the sinusoid spring equal to the nominal displacement of the original Area Mount finger, 3.45mm. While larger or smaller displacements were possible, setting the value simplified the design problem and further complied with the similarity design

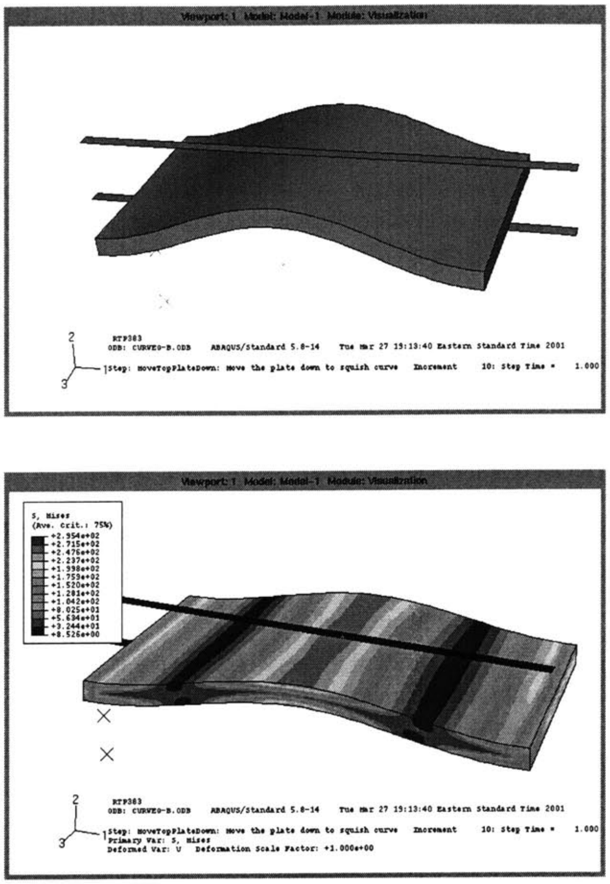


Figure 36. Undeformed and Deformed FEA Models of Sinusoid Wave Spring.

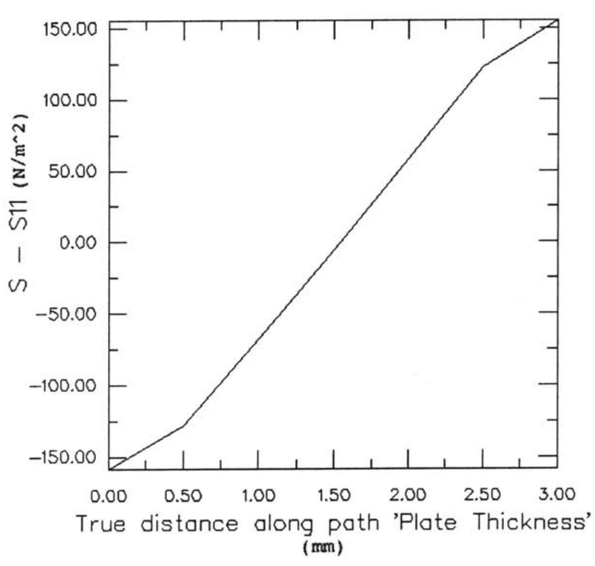


Figure 37. Axial Stress along Path Through Spring Plate Thickness.

constraint. In addition, if the displacements were increased too much for the same geometry, the maximum stress increased exponentially.

The material properties used were from a series of injection moldable carbon-reinforced polymers manufactured by a specific vendor. Their elastic modulus in tension values ranged from 2.4-12.4GPa, and their yield stress values ranged from 65-152MPa. Using these real values showed quickly whether a particular set of dimensions resulted in a realistic part. Though the material stress values played no explicit part in the ABAQUS model, they were compared with the ABAQUS stress values and served as design goals, i.e. the parts were iterated until the model stresses were at least 1.5 times smaller than the yield stress.

I did not want the sinusoidal spring to be longer than the current Area Mount fingers. While the Sinusoidal Finger Spring modeling effort was more refined and focused than the Curved and Straight Finger modeling efforts, after many ABAQUS model iterations, the nominal sinusoid wave length were being stretched near the limit as stress levels were kept below the safety factor value. However, these lengthened springs were not even providing 30% of the nominal Area Mount load. Some of the shorter sinusoids could be paired together, but their forces were still insufficient. (Figure 36)

Bending vs Membrane Stress

All the suitable materials that had been found had unfavorable yield strength to elastic modulus ratios. However, the yield strength and modulus of elasticity values used throughout most of the numerical modeling were for tensile behavior. The largest stress concentrations were consistently located at the lower surface of the sinusoid spring's peak. The default stress displayed by the ABAQUS postprocessor program ABAQUS/Viewer is the von Mises stress, which is a value that combines all the directed stress components into a single scalar value. Figure 37 is a curve taken from a sinusoid part model result, which shows the S11 (W80-0 axial direction) stresses through the spring plate thickness at the high stress concentration sinusoid peak.

The curve is sloped such that the S11-stress values on the opposite surfaces have approximately the same magnitude but opposite signs. This indicates that the membrane stress component is small while the bending stress dominates. A profile with a mostly horizontal line would imply that the membrane stresses were dominant. If the bending stress is dominant, then the flexural modulus and strengths may be more appropriate than the tensile values to use in the models. For most of the materials being considered, the flexural modulus of elasticity was generally smaller than the

In general, a component prototype and its test should be designed with at least one specific metric goal. While specific metric goals give purpose to a component prototype and test, I did not want the prototype to be so specialized for the test that the results had little bearing on true performance characteristics. To prevent this from happening, the test would ideally be applicable to the cellular silicone fingers as well as the prototype spring. This way, even if the test included or neglected phenomenon, differences between the original and prototype fingers could at least be understood within the test's context. Even if the prototype's performance was related to the original part, I needed to understand how my compression test differed from the actual compression caused by W80-0 insertion into and dynamics within the WH Can.

As with modeling, testing can be an iterative process. However since physical parts require labor and consume tangible materials and resource, the iterations may have to be even more focused. Prototypes need to be efficient in the sense that they sufficiently represent

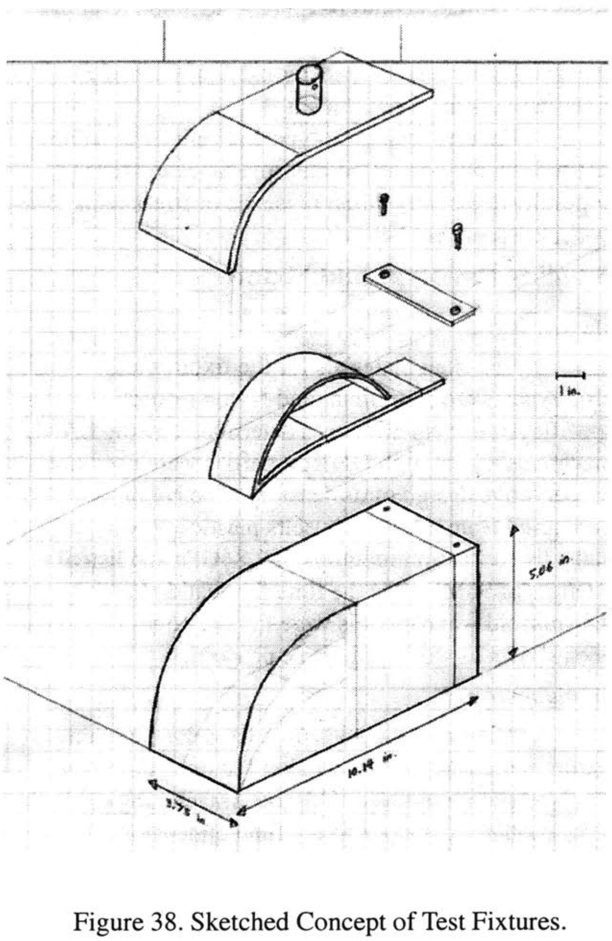


Figure 38. Sketched Concept of Test Fixtures.

tensile modulus of elasticity. At the same time, the flexural strengths were generally larger than the tensile strengths. Suddenly for the same modulus of elasticity, I could change the geometry to produce larger forces while remaining below the new threshold yield strengths.

Though there was no real 'magic' involved with this change, whether the flexural modulus and strength values were the correct values to use would need to be confirmed by actual prototype testing. It was quite possible that in the sinusoid spring application, the most realistic modulus and strength values were somewhere in between the tensile and flexural values. In fact, physical testing was generally required to verify the results obtained by the numerical models.

Prototype and Test Design

Since we had decided to focus on the spring component, spring stiffness was a clear metric goal. A load versus displacement test would characterize prototype stiffness behavior. After consulting with the ESA-MT contact and my supervisor, the test fixtures, prototype interface shape, and testing method were planned and drawn. The conceptual drawing of the test fixtures is seen in Figure 38.

The prototype shape was mostly determined by the results of the numerical modeling. It was desirable to preserve the exact dimensions used in the ABAQUS models so the test results could directly verify the numerical results without the addition of testing artifacts. However, extra features had to be added to the prototype so the test fixture could be used with many different test pieces. In service, the Area Mount was attached to the W80-0 with epoxy. For testing, the attachment method needed to firmly hold the prototype against the fixture, but the method also had to allow the prototype pieces to be easily exchanged. We decided upon a mechanical clamping method where prototypes would be built with an extra inch of material, which a bar would clamp onto the bottom fixture. In addition, the fixture accommodated a B3223 finger section from an Area Mount. Since the fixtures only moved within the vertical axis, there were no large forces which could displace the test-piece, and the bolted bar should be sufficient.

The test would be conducted on an Instron with a 2-5kN maximum capacity load cell. It is good testing practice to avoid working solely within the lower 10% of a load cell's range, and the nominal load of the Area Mount B3223 finger was about 900N. Since I wasn't absolutely sure how well the ABAQUS model would predict the prototype finger springs, I decided that the load cell's minimum range should be at least 2kN. The Instron would have the load cell mounted on the tested aspect of a real part, but do not waste resources duplicating extraneous features. For example, my adviser, supervisor, and I all envisioned the new mount manufactured for production with injection-molded parts. Yet, designing and manufacturing proper molds is an expensive and time-consuming endeavor. Other cheaper manufacturing methods were investigated which would yield a prototype with approximately the same geometry and material properties as an injected-molded part.

Building Prototype and Fixture

Primary needs and goals for the test came out of the original project goals and were reinforced by the technical analysis done so far. As part of my thesis experience, both my LANL supervisor and MIT adviser had a strong desire to see some tangible results of my experience. Physical prototypes and tests would provide valuable experience in turning theoretical designs and models into physical deliverables.

Conscious of the deadline, quick fabrication of test fixtures and prototypes was required to ensure enough time to run the tests and do the thesis write-up. Costs needed to be practical enough to make the test financially feasible. Simultaneously, the potential technical information revealed by the test needed to be significant enough to justify the associated cost.

During the design of the prototype and test, we had always been conscious of the potential manufacturing methods that were available. However, there were still many decisions to be made about how, who, and where should the actual components be obtained and made. Potential raw materials suppliers were outside vendors, LANL groups, or MIT supplies. The potential manufacturers were LANL, outside companies, MIT, or myself.

The selection of material providers and manufacturers was split into two optimizations; one for the fixtures, the other for the prototypes. In terms of performance, the fixtures required dimensional stability, and only one set would need to be made. Many materials would perform these tasks well, which simplified the materials provider aspect; any of the three potential supplier categories could meet the need aptly. Two of the fixture parts had a complicated shape since they replicated the interior profile of the WH Can and the exterior of the W80-0. While I could not fabricate parts with such complicated geometry, any of the other three manufacturing entities could. In the end, most of the fixture parts were manufactured at LANL. At the time the fixtures were designed, I was still working in Los Alamos, and I was able to personally meet with the group who would machine the parts. The benefit of this interaction was rapid discovery and solution of design its crossbeam. The crossbeam would be lowered to compress the test piece between the fixtures. The displacement of the crossbeam and the force measured by the load cell would be recorded.

The bottom fixture would be an extruded half-profile of the W80-0 aft end. Although the original finger width was 35mm, the bottom fixture would be wide enough to accommodate two fingers. The bottom surface of the upper fixture had a portion of the WH Can profile corresponding with the W80-0 section profile. The upper fixture did not extend all the way to the pole because I wanted to be able to deflect the spring beyond nominal displacements. The top surface of the upper fixture was arbitrary and only required that an adapter part be integrated into the fixture or attachable. The adapter part would mount the upper fixture onto the load cell. A lower adapter plate would be made for the bottom fixture, but it may not be necessary since the bottom fixture can be aligned and rested on the Instron's table.

Potentially, the same fixturing could be used to test full finger concepts if damping material were added to the spring components. The added material's effects on spring stiffness could be quickly acquired with the same setup, and results could be directly compared with the spring-only results with a good assurance of a consistent testing environment.

Finally, each prototype and cellular silicone test-piece would be tested multiple times in order to hopefully detect any initial presence of stress relaxation or cycle dependent behavior.

Building Prototype and Fixture

Materials

The final materials for the fixtures and prototypes were Aluminum and Nylon respectively. The specific Aluminum alloy was determined by the LANL machine shop, though 6061 properties were used in my conservative design of dimensions. The Nylon was purchased from a Massachusetts plastics vendor and had a listed flexural modulus of 2.84GPa and listed strength of 96MPa. By the time fabrication had begun, the sinusoid wave models were the only ones which had been shown to work with these properties.

Manufacturing

The exact methods used to make the main fixture pieces are not known, but I assume the LANL machine shop employed traditional machining methods reduce Aluminum stock to the final dimensions. I personally machined the upper adapter for the top fixture using a combination of lathe and mill on 4" diameter Aluminum stock.

The prototypes were fabricated using a

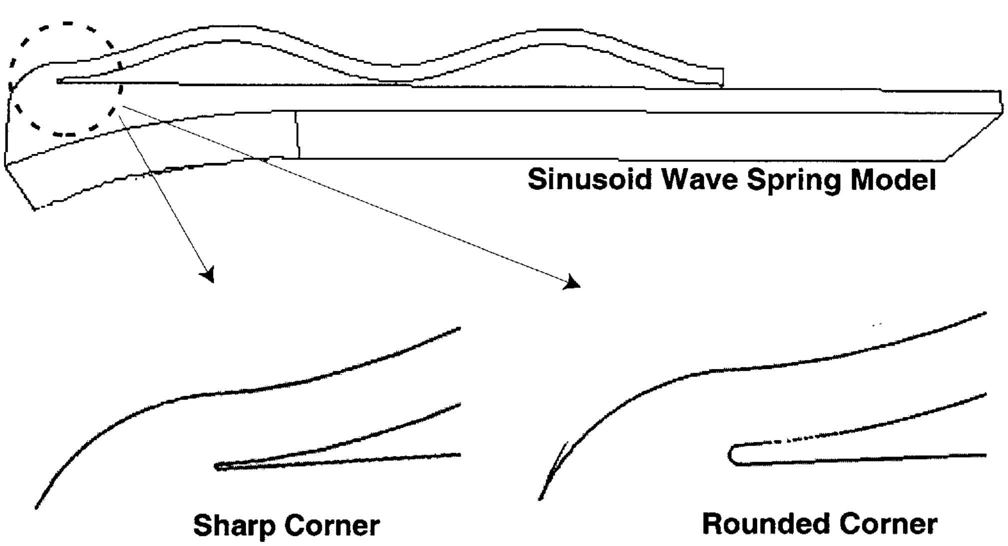


Figure 39. Difference in Profile Caused by Finite Stream Width of Waterjet Cutter.

drawing inconsistencies and issues. The cost of doing the manufacturing 'in-house' was approved by my supervisor and was cheaper than expected.

For the prototypes, other issues played into deciding where to go for the materials and manufacturing. The prototype spring fingers had their geometry roughly determined by the ABAQUS and analytic models. Material properties had been an important part of the models, and the prototypes needed to use materials with the same values. Only third party plastic vendors had the diversity of material selection we needed for the specific designs we had in mind. While product diversity led us to a set of potential vendors, selecting the final material was influenced heavily by cost. Materials with greater stiffness and strength might be ultimately desired for a real production part. However, these materials were often more expensive than less strong and less stiff materials that still could work with some the previously modeled geometry. While later tests would surely need high-grade materials with final dimensions, my preliminary test could still obtain generally useful information from the cheaper materials.

Since the material choice so heavily influenced the prototype dimensions, I decided to manufacture the prototype pieces myself. The dimensions for the prototype only solidified once the material was chosen, and I could deal with all the unknowns personally. It would have been more time consuming to send the materials to an outside manufacturer and then work out all the final dimensions with them over a long-distance. waterjet cutter in the MIT Laboratory for Manufacturing Productivity. As previously discussed, injection molding is envisioned as the method which will be used create the production version of the spring fingers. However, the water jet offered a quick and cheap way to flexibly manufacture experimental prototypes. While mold pieces would require additional design and significant resources, the waterjet required only the raw part materials and a .dxf file with a tool path. If a different set of prototype dimensions were desired, the .dxf file could be easily adjusted with software. Modifying molds would require almost as much effort as making the initial set.

The waterjet cutter uses a high pressure stream of water loaded with abrasive particles to cut/wear a path through a workpiece. The particle-laden stream had a finite width of 0.030in. One disadvantage to using the waterjet was that the path thickness meant that interior corners were limited to a minimum 0.030in. radius. Figure 39 shows that the originally designed profile had a sharp corner where the sinusoid wave met the finger base. It also shows a detail of how the corner had to be enlarged to accommodate the waterjet path. Also, a 0.030in. extra gap was included between the bottom of the sinusoid wave and the finger base.

The Nylon material was initially 1.5in. thick. The waterjet's tool path speed was set for a conservative thickness value, but the path 'walked' a small amount as it progressed through the part. That is, the exit direction of the path was not exactly parallel with the input direction.

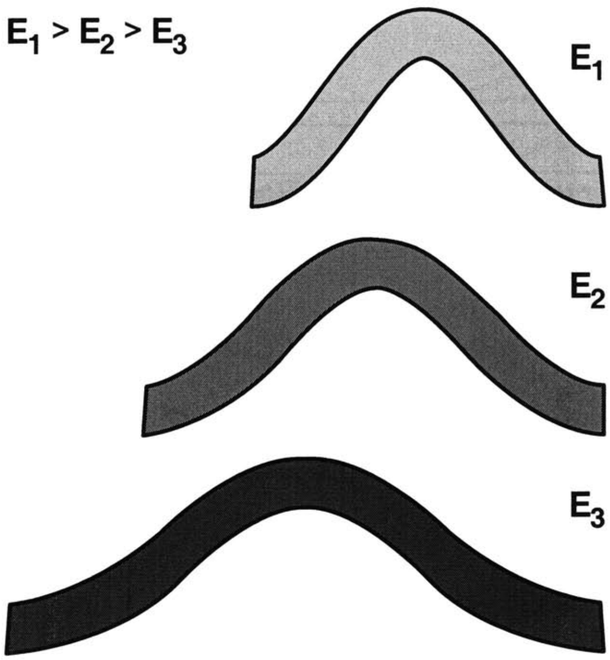


Figure 40. Inverse Relationship Between Elasticity and Period Length for Constant Force.

In addition, building the prototypes myself was more cost-efficient since I could be using facilities available to the MIT Mechanical Engineering community at a fraction of the cost of outside facilities, including LANL.

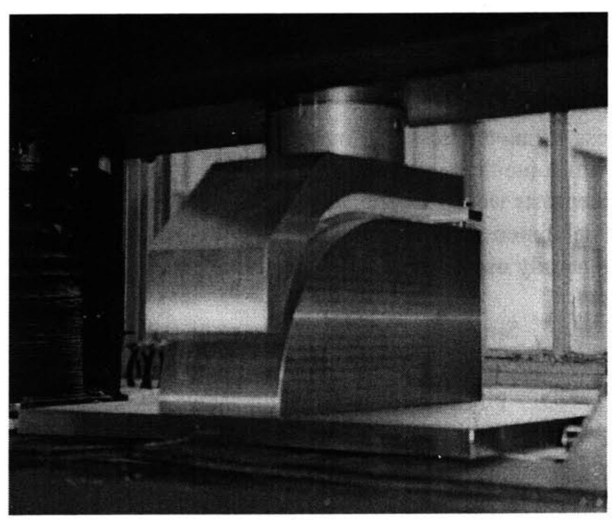
It was originally hoped to purchase multiple materials with different properties. Each set of properties' respective sinusoid wave shapes could then be tested, but unfortunately, only the Nylon was available in time for the testing runs. However, a method of setting dimensions with respect to varying modulus of elasticity was developed. From the forty-plus ABAQUS jobs conducted with the sinusoid wave spring, a mathematical expression was created which related the elasticity of the material to the period of the sinusoid plate generating function. In general, material elasticity was inversely proportional to the period length for a given displacement and reaction force. That is, sinusoid wave plates made of stiffer materials were shorter in length than plates of less stiff materials. (Figure 40)

Running the Experiment

Figures 41(a&b) are pictures of the experiment setup. In Figure 41(a), t he Instron and fixtures are observed on the left, and the data collection computer is on the right. Before setting up the fixtures, the load cell was calibrated with two known values. The first values was the no-load value for which the Instron was adjusted to report a value of zero. The second value was set by placing the load cell on a physical scale and adjusting the slope of the Instron output to intercept the scale's value. This calibration was not extremely precise, but the purpose of the experiment was to get a general understanding of the sinusoid wave plate's performance, so high resolution precision was not paramount. After setting up the fixtures, a practice test was run. The Instron successfully outputted displacement and load data to the computer, which added time increments to the data.

The data for the sinusoid wave spring

(a)



(b)

Figure 41. Load vs. Displacement Test Setup.

Running the Experiment

To run the experiment, I contacted a staff member responsible for the test equipment. Together, we scheduled times to setup the equipment and run some preliminary tests. After I was more familiar with equipment operation, I was able to run tests without supervision.

Unfortunately, due to the time constraints, only three samples were tested; one B3223 finger from an Area Mount and two sinusoid wave spring fingers. The law of large numbers dictates that testing of more specimens leads to an empirical average closer to the true mean, and for later tests, a larger number of parts should be tested. However, was not much time was left for a writeup when these tests were conducted, so the tests were halted after the above samples provided enough data to get a basic understanding of their load vs. displacement characteristics as compared with the original B3223 cellular silicone. Obviously a more thorough set of experiments would be a good start for future efforts to understand the effectiveness of these sinusoid wave springs as potential New Area Mount components.

testpieces were collected first. The first run's load vs. displacement data seemed to be too far translated to the right. The extra gap due to the waterjet's cutting path had allowed the sinusoid wave to rotate before it provided significant load resistance. A 1/32in. thick slat of aluminum was placed between the sinusoid wave and the finger base to fill in the gap left by the water jet path. The remaining load vs. displacement tests were run with the Aluminum plate inserted.

Initial Test Results and Discussion

Figure 42 shows the average load vs. displacement behavior for each of the test pieces. Several notable problems are immediately evident. The load at nominal displacement (3.45mm) was originally calculated to be about 900-1000N. However, the data shows that at the nominal displacement, the reaction load was recorded as approximately 420 N for all three pieces. There are more than a few possible explanations for this discrepancy.

First, due to the geometry of the load cell and Instron crossbeam, the top fixture and adapter were not entirely rigid. In fact, with no load on the fixtures, the

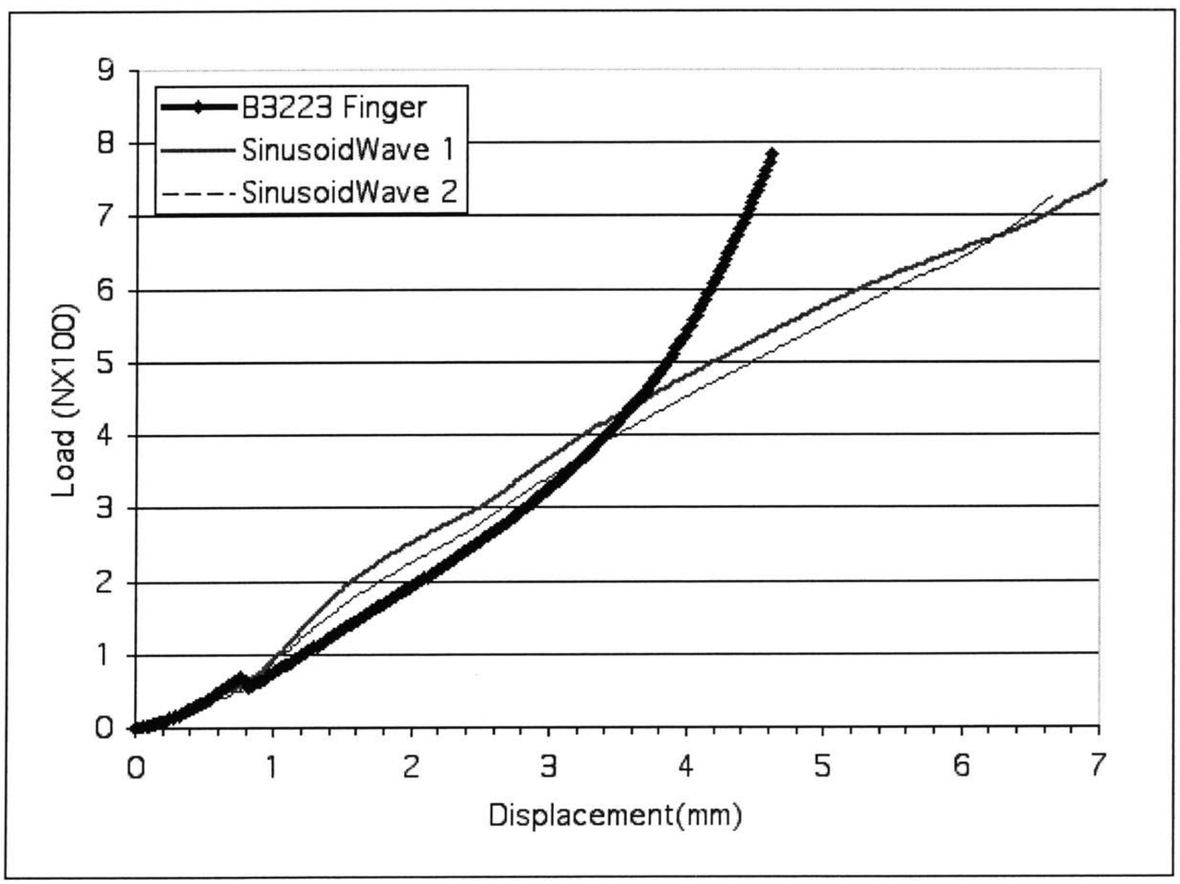


Figure 42. Load vs. Displacement Averaged Results for Cellular Silicone and Sinusoid Wave Spring Fingers.

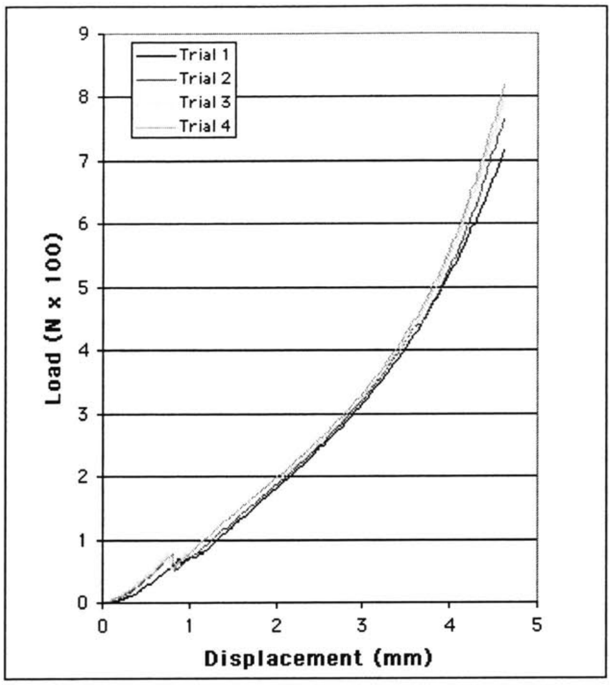


Figure 43. Cellular Silicone Load vs. Displacement Results by Trial.

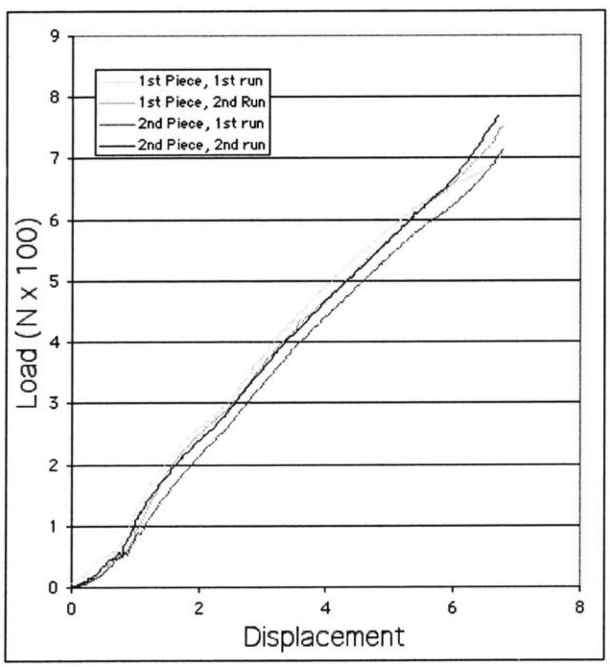


Figure 44. Sinusoid Wave Spring Finger Load vs. Displacement Results by Trial.

fixture was loose enough on the load cell that it could be angled several millimeters in any direction. As the fixture was lowered onto the test pieces, there was clearly an angle between surfaces which were supposed to be parallel. In addition, the there might have been parts of the adapter contacting the crossbeam which may have reduced the load measured by the load cell since the crossbeam supported a fraction of the load. The loose fixture probably caused the ridge in the cellular silicone data at 0.8mm as well. Finally, the load cell was calibrated with at least a 3% error in the load reading, and this error probably contributes to the problem, although it certainly cannot bear sole responsibility.

Additional errors with the springs tested could have been caused by imperfections in the geometry caused by the waterjet machine used to cut the part profiles. Upon closer inspection, one notices the non-uniform thickness of the sinusoid wave segments.

The two Sinusoid Wave Springs' load vs. displacement behavior indicates a mostly constant spring stiffness. So far, these springs do not seem to exhibit the nonlinear stiffness behavior seen in the cellular silicone. This may be because the sinusoid wave period length was much longer than the thickness of the part. With this ratio, the 'arc' segments of the sinusoid curve may be better modeled as simply supported beams. This kind of approximation is often used for modeling long curved cantilevers as straight beams [18] much like my earlier approximation of the arc cross section of the B3223 finger as a flat rectangle.

If made from a stiffer material, the sinusoid period can be reduced, and the spring's radius of curvature will decrease in order to provide the same load at a given displacement. Since this spring may be more curved than those tested, it may exhibit more nonlinear stiffness.

The results of this test were by no means conclusive, but the results indicate good directions to pursue with regards to future test pieces. Stiffer materials should be used to make the sinusoid wave finger springs, so the effect (or lack thereof) of more curved sinusoids upon nonlinear stiffness behavior might be noted. However, before spending more time creating more prototypes, this same test should be run with a corrected adapter or even on a different machine where there will be less error introduced into the data by the setup itself!

Chapter 4: Future Paths

Transition

The work I have done so far will hopefully satisfy MIT standard for a sufficient thesis. However, my cumulative research and work on the W80-0 Area Mount redesign will be useful only if the knowledge and ideas are successfully transferred to the next engineers who will steer this project forward beyond the limited scope of what has been done so far.

Lawrence Livermore National Laboratory and Sandia National Laboratory are the new stewards of this work. Since the W80 was designed and developed under the Los Alamos National Laboratory, effective transferal of the project should require substantial conversation and collaboration. While the responsibility for the system will be transferred by the authorities beyond the laboratories, both laboratories have to ensure that the technical knowledge and history is brought to the new project workers as well. Physical and digital documents, files, and other records relevant to the project will be passed on to create a resident archive at the new facility. Though I have described problems I had unearthing the history of the W80-0 Area Aft Mount, if the transfer of W80 knowledge is done thoughtfully and thoroughly, the laboratories will discover documents regarding many of the details missing from my analysis and background search. Hopefully the laboratories will take advantage of the thorough knowledge search to organize the results in a way that preserves (or establishes) technical relevance and that facilitates accessibility.

My experience with Los Alamos has shown me that regardless of the state of the physical archives, much of the relevant knowledge pertaining to the W80 is held within the minds and memories of LANL employees. Their intellectual knowledge must also be transferred if the new project engineers hope to continue work on the W80, much less seek additional improvements like a new Area Aft Mount or other components. For my part, I will meet with engineers at Lawrence Livermore National Laboratory and present my research and basic design ideas to them. I do not expect that their design efforts will mirror my own; indeed, there is a strong probability that the New Area Mount will not look like any of my concepts at all. However, I am confident that my work will give them extra perspective with respect to this issue. Moreover, my research of problem's background will undoubtedly help their understanding of the context in which the Area Mount, and even the W80 as a whole, was designed.

Suggested Next Steps

Refine Concepts

A natural next step for this project would be to conduct many more tests and experiments using the current setup and to eventually have a spring concept that matches the Area Mount finger's load-deflection behavior well. There may be additional tests that require additional fixtures or facilities along the way to this goal.

The next step would be to add damping to the spring concept and working on the concept as whole. Although the spring component should bear most of the static load, an appropriate damping material may also provide a non-negligible stiffness which will require adjusting the spring component design again. However, such adjustments should be easier to make after thorough testing has established the spring design.

The spring and damper concept must be adapted to the curved surface and base of the WH can and W80-0. For example, one could change the rectangular cross section of the spring fingers to a box with an arched top. (Figure 45) The moment of inertia for the new cross section must be calculated and worked into the analytical and numerical models to create new springs. The finger base may be shaped to fit

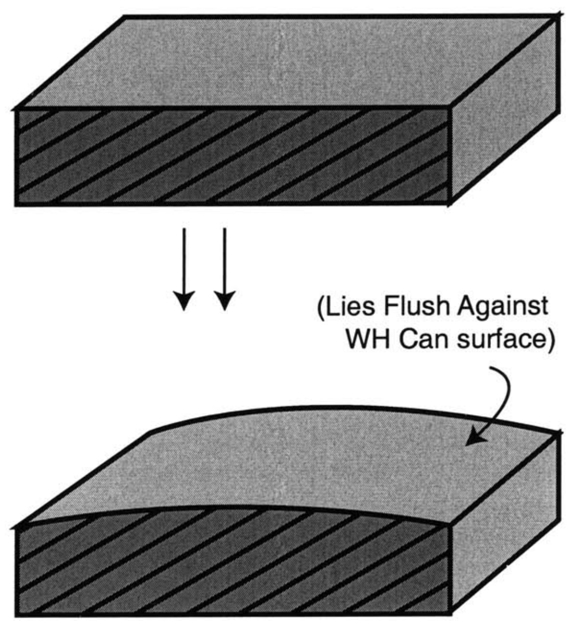


Figure 45. Rectangular to WH Can Mated Surface.

Retrospect and Personal Development

Among the many lessons learned during this project, I have taken away a better understanding of:

How professional technical issues are related to organizational needs and resource limitations.

How design constraints can play a critical role in addition to functional requirements for a redesign/reengineering project.

How applying constant low-level attention to developing issues can be a superior approach to sporadic crisis troubleshooting.

As I reflect on my project's progress, I see many areas where the work could have been better developed, where the path forward could have been better organized, and where time could have been better managed. In spite of these shortcomings, I know these experiences also served to help me develop personally and professionally in the same areas. Looking to the future, I look forward to implementing the project and technical issue management lessons I have learned and continuing to improve on these skills.

the W80-0 curve without affecting performance.

Complete Dynamic Model

The engineering successors to this project might be able to complete the numerical dynamic model of the W80-0, WH Can, and mounts since they may be working solely in a classified environment. They could then numerically test the concepts' potential performance and approach the design from that angle. At some point in the future, there may even be the opportunity to resume physical testing and build full W80 dynamic mockups for shock and vibration testing.

Path to Production

The road to final production will involve many more steps such as further iteration of concept generation/development by the engineering successors, evaluation of the design with respect to the other normal STS environments, peer review, selection of production material and labor suppliers, and redesign of the part with respect to manufacturing needs. Whatever the final path will be, there will certainly be many more technical issues requiring attention and providing challenge for the design engineer.

Bibliography

[1] Luke, H. H., Los Alamos Scientific Laboratory Memorandum to J. C. Stevenson, "Tomahawk Aft Mount" WX-1-E-70-978. 26 October 1979.

[2] Luke, H. H., Los Alamos Scientific Laboratory Memorandum to J. C. Fuller, "Insertion/ Extraction (I/E) Cyclic Test of the W80-0 Aft Mount" WX-1-E-81-644. 22-26 June 1981.

[3] Castelli, V. "Friction." Marks' Standard Handbook for Mechanical Engineers. Eds. Eugene A. Avallone and Theodore Baumeister. New York: McGraw-Hill, 1996. 3-23.

[4] Salazar, L., Los Alamos National Laboratory Memorandum to P.A. Miles, "W80-0 Insertion Forces" WX-1-84-214. 23 March 1984.

[5] Sandoval, C. W., Los Alamos National Laboratory Memorandum to E.D. Aragon, "W80 Aft Area Mount" ESA-WMM-96-062. 11 March 1996.

[6] Gibson, L., and Ashby, M. Cellular Solids: Structure and Properties. Cambridge, UK: Cambridge University Press, 1997. 125, 245.

[7] Air Force Materiel Command. Joint Air Force/Navy Stockpile-To-Target Sequence (STS) For the W80 Common Warhead (U).7th rev. 27 June 1996.

[8] Sieger, W.J., Sandia Laboratories Memorandum to T.K. Hill and C.A. Davidson, "W80/ Tomahawk Depth Charge Environment". 2 August 1979.

[9] Inlow, Rush, Department of Energy Memorandum to Commander of Air Force Weapons Laboratory/NTSW, "Revision to W80 Stockpile-to-Target Sequence (STS)."

[10] Mahn, D.A., and Cawlfield, J. L., Vibration Test of W-80 (Modified W/H) in Payload Section. 7 February 1979.

[11] Slocum, A. H. Precision Machine Design. Dearborn, MI: Society of Manufacturing Engineers, 1992. 341.

[12] Luke, H. H., Los Alamos National Laboratory Memorandum to J. C. Fuller, "Technical Information Meeting (TIM) Concerning a Tomahawk Aft Mount Cyclic Test, February 5, 1981 and Aft Mount Installation, February 6, 1981" WX-1-E-81-112. 12 Feb. 1981.

[13] Vidosic, J.P. "Mechanics of Materials." Marks' Standard Handbook for Mechanical Engineers. Eds. Eugene A. Avallone and Theodore Baumeister. New York: McGraw-Hill, 1996. 5-42.

[14] Howell, John D. "Cantilever Springs that Roll with a Load." Spring Design and Application. Ed. Nicholas P. Chironis. New York: McGraw-Hill, 1961.

[15] Young, Warren. Roark's Formulas for Stress and Strain. 6th ed. New York: McGraw-Hill, 1989.

[16] Conner, A.L., Los Alamos Scientific Laboratory Memorandum to Distribution, "Tomahawk/W80 Technical Interchange Meeting" ADW-PM. 22 Sept. 1976.

[17] Ulrich, Karl T., and Eppinger, Steve D., Product Design and Development. Boston: McGraw-Hill, 2000. 142.

[18] Chen, C. G., Microcomb Fabrication for High Accuracy Foil X-ray Telescope Assembly and Vector Gaussian Beam Modeling. Unpublished, 2000.