Chapter 3: Secondary Design Synthesis

3.1 Introduction to Secondary Design Synthesis

Once the large group of design concepts has been reduced to four potentially viable ideas, further design synthesis was performed. This chapter discusses the secondary design synthesis, which included evaluation of pre-thesis design solutions, prototyping and testing of design concepts, and the final design selection.

3.2 Pre-Thesis Design Solutions

Two previous attempts were made to design a support arm for the Torrington 5203 Double Row Bearing before becoming the topic of this thesis. The initial approach was not as a design synthesis but rather as an iterative series of fabrication attempts by line workers at the Calhoun, Georgia facility. As a result of this iterative process, two prototype support arms were developed. At the same time, Jim Buchanan of Torrington Research and Development was addressing the same assembly problem at the Torrington Manufacturing Development Center in Norcross, Georgia. Buchanan’s work evolved into both a concept for the support arm, and a table top assembly station for prototype testing. This thesis builds from this prior work and further develops design synthesis and model fabrication. The following sections credit the aforementioned work as an introduction to the design synthesis of this thesis.

3.2.1 Calhoun Pre-design Fabrication

Initially the problem was approached not as a design problem but as a trial and error, iterative fabrication problem. Figures 3.1 and 3.2 are graphical models that illustrate the two configurations built by an assembly worker at the Torrington in Calhoun, Georgia. Both were constructed from steel conduit pipe with the use of home shop tools. After several iterative fabrication attempts, the model in figure 3.1 could be used to aid in bearing assembly, but with great difficulty.

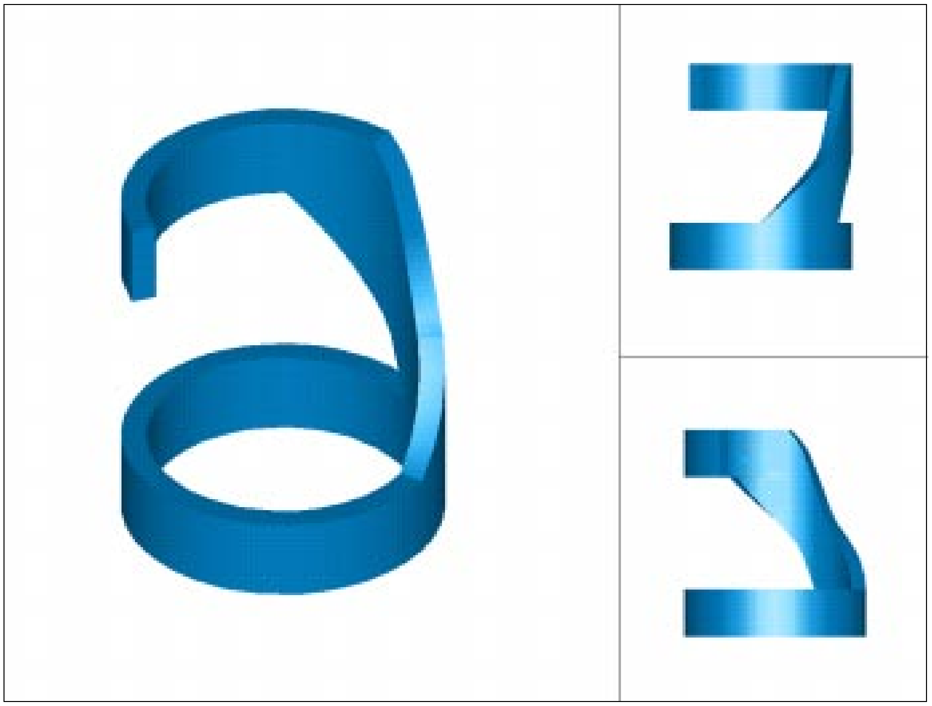


Figure 3.1 Computer generated model the of spiral support arm structure fabricated at the Torrington facility in Calhoun, Georgia.

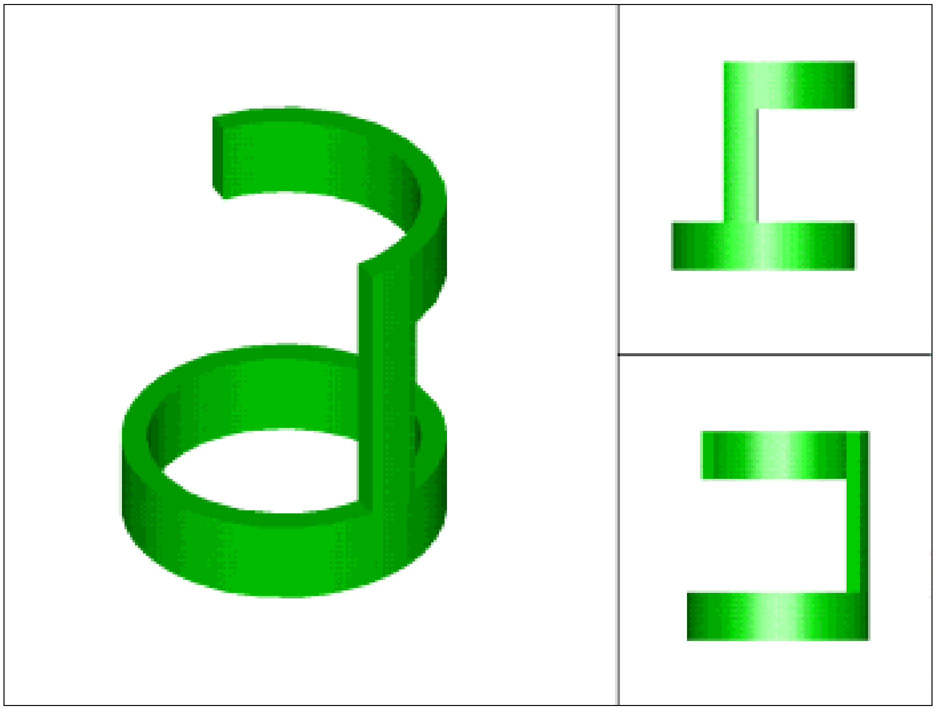


Figure 3.2 Computer generated model of the L support arm structure fabricated at the Torrington facility in Calhoun, Georgia.

3.2.2 Buchanan Design Concepts

Jim Buchanan, an engineer at Torrington's Manufacturing Development Center, also addressed the bearing assembly problem. His analysis consisted of three areas of development, the support arm structure, a concept for support arm motion actuation and construction of a bearing assembly station for prototype testing.

3.2.2.1 Buchanan Test Assembly Station

The most significant portion of Buchanan's work on the bearing support arm structure used in this thesis is the test assembly station. The test assembly station is similar to the assembly station used at the Torrington of Calhoun facility. It is, however, smaller and more portable. All major components are mounted on the top surface of the station rather than below. It also has capacity for the addition of experimental components, such as smaller pneumatic devices and mounting structures. It is pneumatically actuated and requires general shop air, pressure ranging from 80 to 100 psi. Figure 3.3 is a schematic draft of the complete test assembly station.

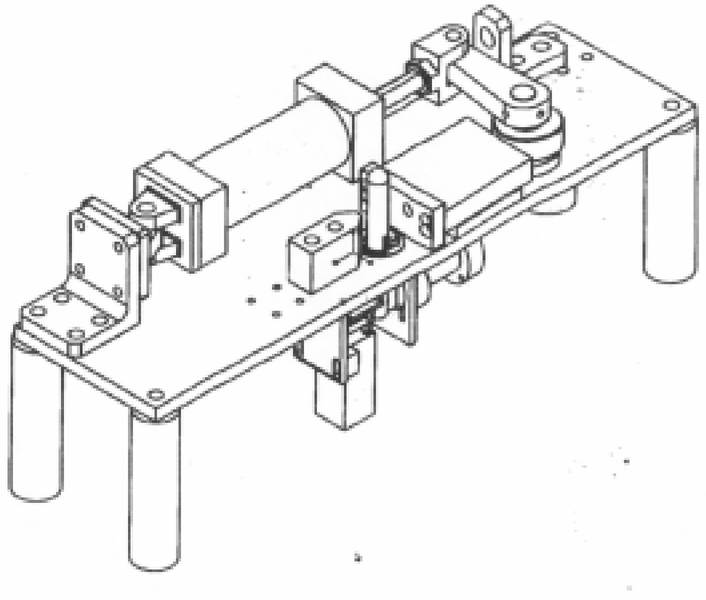


Figure 3.3 Schematic draft of the test assembly station. Faxed from Jim Buchanan of Torrington's Manufacturing Development Center in Norcross, Georgia.

The large pneumatic cylinder used for radial deformation of the bearing outer ring is mounted on the rear upper surface, figure 3.4. This pneumatic force is transferred to the large chuck that directly deforms the outer ring through an arm and cam system, as shown in figure 3.5. Rigidly mounted along the front of the test assembly station, opposite the large chuck, is the deformation anvil, which provides a stationary point against which the bearing outer ring rest as it is deformed. Both the chuck and anvil are shown in figure 3.6. The air source is regulated by a system of valves, one providing air to each pneumatic device, figure 3.7. In addition to the individual valves, each pneumatic cylinder has flow regulators at both their inlet and outlet to control the acceleration of their motion, if needed. These can also be seen in figure 3.4.

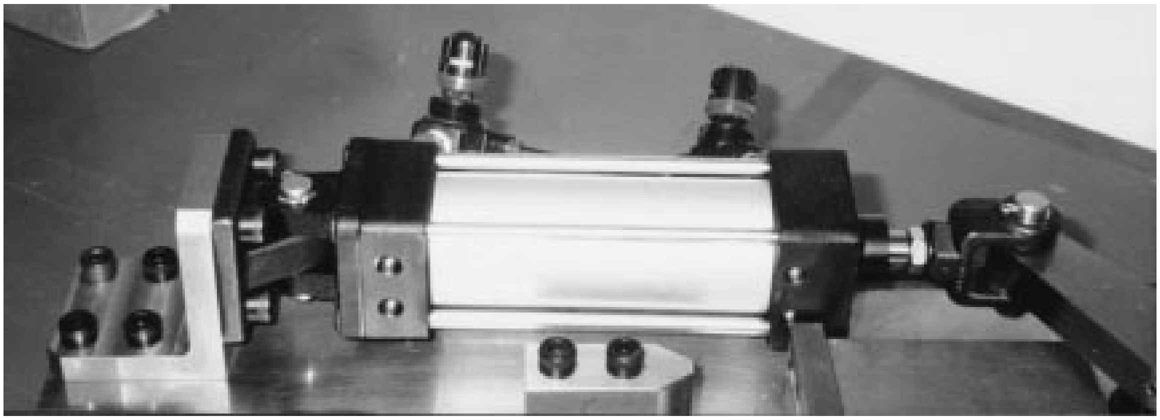


Figure 3.4 Large pneumatic cylinder for deformation of the outer ring during bearing assembly. Knobs along top are flow regulators to control cylinder aggressiveness.

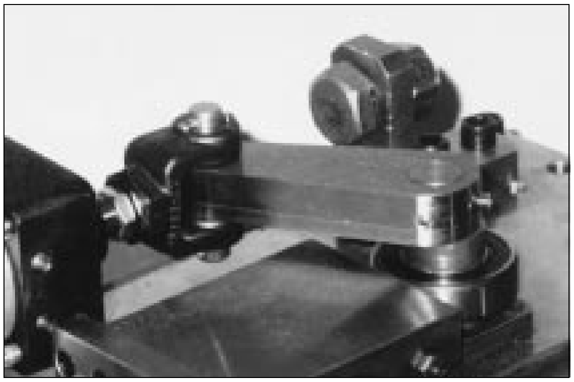


Figure 3.5 Arm and Cam system that drives the deformation chuck for outer ring deformation during bearing assembly.

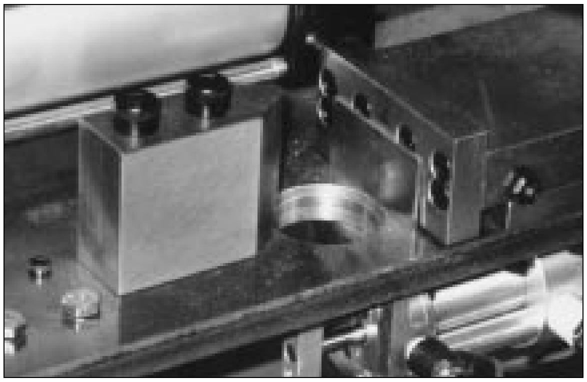


Figure 3.6 Anvil and square chuck, which deform the bearing outer ring during bearing assembly.

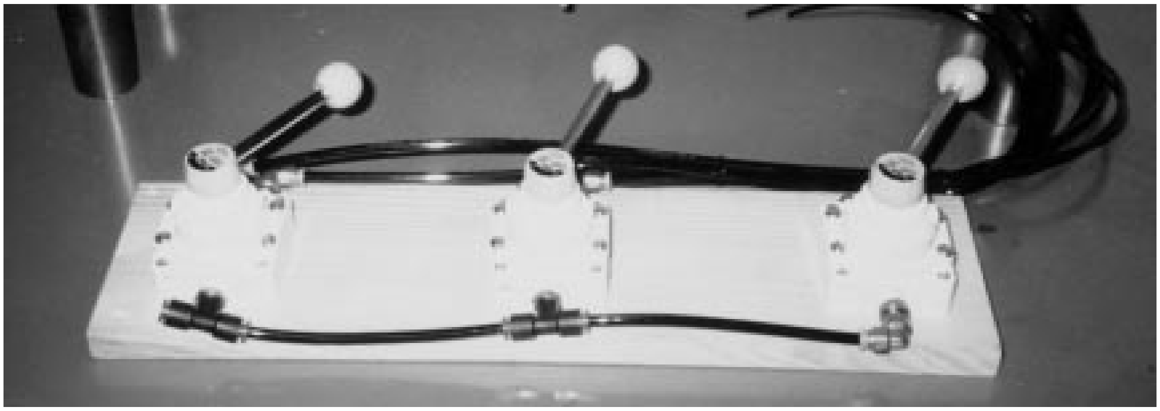


Figure 3.7 Valve system for controlling the pneumatic devices on the test assembly station. Left valve for large cylinder used for outer ring distortion, middle valve for medium cylinder (unused) underneath station and right valve for small cylinder (also unused).

Buchanan mounted a mid-size pneumatic cylinder underneath the test assembly station surface connected to a center rod. This was intended to aid in the offset or tilt of the inner ring during assembly.

3.2.2.2 Buchanan Support Arm Concept

Buchanan's design of the support arm was based upon his view of the bearing assembly process, which is described in the follow electronic-mail excerpt:

> ...My next approach led me to design the screw anvil fixture that you now have a copy of. The process would be as follows:
>
> 1. Load outer race into stand and clamp.
> 2. Load inner race onto shaft, slide race to one side
> 3. Load lower balls, snap inner into center position.
> 4. Insert screw anvil with a motion profile as follows:
>   a. Move fixture straight up into partially assembled bearing
>   b. While moving up, turn fixture about center of bearing
>   c. Stop vertical movement but continue turning motion until in position.
> 5. Move inner race to side opposite fixture
> 6. Load balls, snap inner into center position
> 7. Remove fixture by reversing motion profile.
> 8. Release assembled bearing from clamp.
>
> As you can see, the motion profile is tricky, especially within the space and budget constraints. I was able to successful test this on about 5 bearings by simulating the motion by manipulating the fixture with my hand...

Figure 3.8 shows Buchanan's support arm structure, which combines the screw and L shaped support arm models fabricated at the Torrington plant in Calhoun.

3.2.2.3 Buchanan Cam Design for Support Arm Motion

Buchanan drafted a conceptual cam device, in an attempt to produce the complex motion of the support arm. This motion is difficult to produce, however, and the cam profile needs further development. Figure 3.9 illustrates this concept, which was never proven, either theoretically or physically, to function as specified.

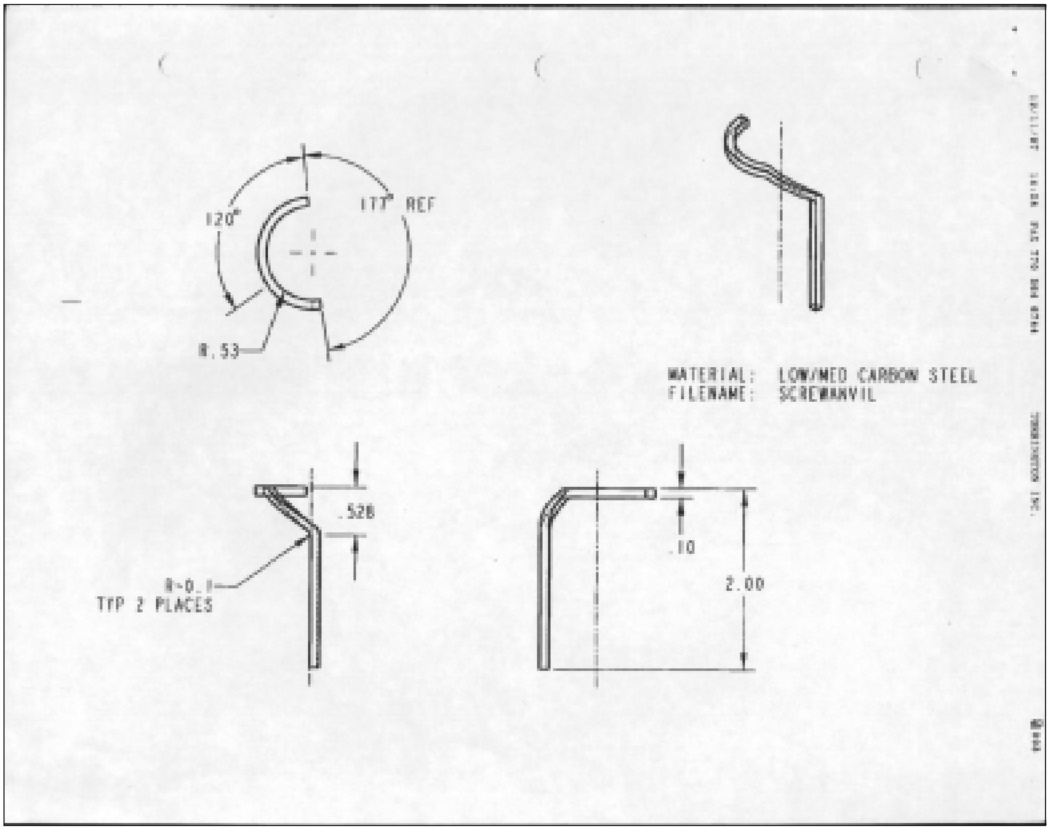


Figure 3.8 Facsimile of Jim Buchanan's "Screw anvil" structure for support arm application.

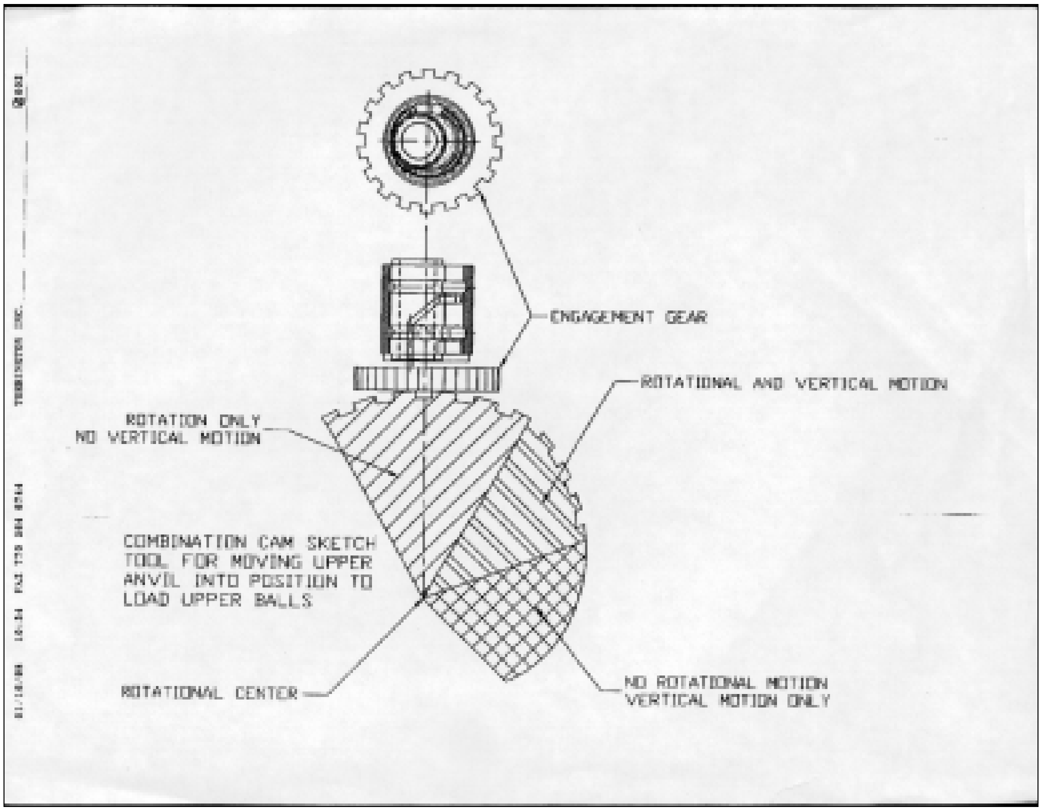


Figure 3.9 Facsimile of Buchanan’s cam concept design for support arm motion.

3.2.2.4 Limitations of Buchanan’s Initial Concepts

Buchanan’s initial approach to solving Torrington’s 5203 double row ball bearing assembly problem serves as a substantial foundation for this thesis. However, this thesis is a result of the need to improve upon, and continue to evaluate some of the limitations associated with the initial design concepts.

3.2.2.4.1 Support Arm Concept Limitations

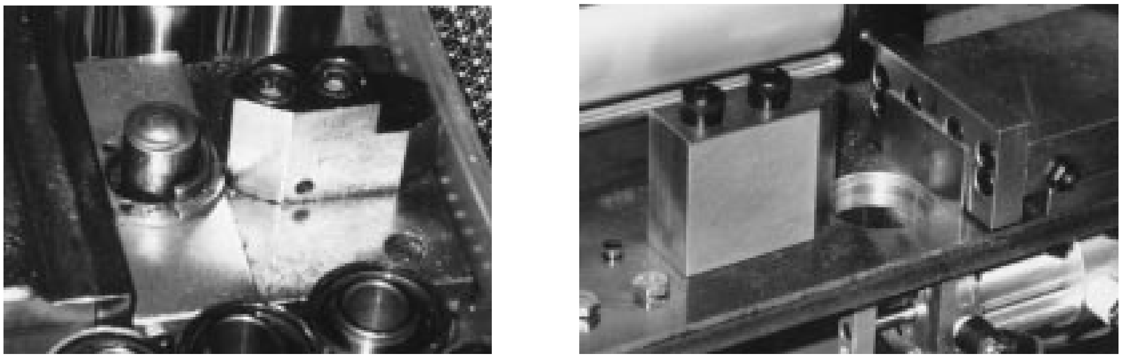
Buchanan’s support arm structure has a few configuration problems that prevent it from meeting the function specifications. As illustrated in figure 3.9 the support structure’s total height is to be 2 inches. If inserted to its full extent, Buchanan’s design far exceeds the required height to support the upper balls in the bearing assembly by approximately 0.5 inches. If the support arm is not to be inserted completely, then no reference is given to what extent it is to be inserted. In addition, no foundation or base was developed to guide the arm to the appropriate height to support the balls. The arm also is design to be 0.1 square inches thickness at all points, which does not provide sufficient structural stability. The horizontal arm of the support structure is small enough to be inserted into the bearing assembly, but it does not have sufficient extension to clear the lower balls and support the center four balls during assembly.

3.2.2.4.2 Cam Design for Support Arm Motion Limitations

The complex motion of this support structure needs to be reevaluated using a thorough design synthesis. The motion is complex due to the need for simultaneous axial and rotation. The current cam design can not be easily fabricated due to its complex geometry and its multiple gear-cam regions. Additionally, interface with the support structure is unspecified.

3.2.2.4.3 Test Assembly Station Limitations

The limitations that exist with the test assembly station result from variations between it and the actual assembly station currently used at Torrington. There are three major differences in the two assembly stations, which are illustrated in figures 3.10a and 3.10b. First, the test assembly station has an access hole in its base just below the bearing being assembled. This hole allows for ease of insertion of any test support arm structure. Second, the test assembly station does not have the spring loaded support plunger that supports the inner ring during bearing assembly. Third, the order of the assembly components is opposite for the test assembly station as compared to those in the Torrington assembly station. As illustrated in figure 3.10a, the assembly component on the Torrington assembly station from left to right are chuck, bearing, anvil while shown in figure 3.10b, the component order on the test assembly station is anvil, bearing, chuck from left to right. Because of this difference in order, during assembly the inner ring tilts to the right on the test station while it tilts to the left on the Torrington station illustrated in figure 3.11.



(A) (B)

Figure 3.10 Comparison of the (A) Actual Torrington of Calhoun Assembly Station to the, (B) Test Assembly Station to show problems or differences between them.

(A) (B)

Figure 3.11 Schematic, illustrating differences in tilting direction of the (A) test assembly station and that of the (B) Torrington assembly station.

3.2.3 Prototype Fabrication and Testing

After the first broad design group was reduced to three potentially functioning structured designs and one non-structured design, the next step was fabrication and testing. The three lowest scoring structured models were prototyped as well as the suggested design from Jim Buchanan. The original fabricated support arm structures from Torrington were included in the testing process to reevaluate their effectiveness. Other areas of consideration for part fabrication were materials and modes of fabrication. The mode of prototype fabrication was dependent upon the material selected. Slight modifications to the test assembly station were needed for prototype testing and simulation of the current bearing assembly process.

3.2.3.1 Test Assembly Station Hole Cover Design

Before testing of the design models, the test assembly station needed modification. Even though the test assembly station was intended for use as a platform to test prototypes of the ball support arm, it had to also be able to assemble the bearings as they are on the Torrington assembly station. Among the differences between the two stations, as presented in section 3.2.2.4.3, the most significant difference was the access hole through the base of the test assembly station. The other major difference was the inner ring support plunger in the Torrington assembly station, which was not a necessary addition to the test assembly station in order to replicate the assembly process of the Torrington assembly station. Because of the access hole, a hole cover was design and fabricated.

The hole cover was design based on several general and detailed specifications. The Torrington assembly station includes a bearing support plate with a lower ball support edge illustrate in figure 1.9b, which provides an edge for the lower balls to rest when inserted. To replicate the Torrington assembly station, the hole cover needed to incorporate such a support edge in its structure. The hole cover is necessary to sufficiently cover the access hole of the test assembly station to allow proper assembly of the bearing. The access hole was not only intended for use as an insertion point for the ball support structure, but also for a pneumatically actuated post that could aid in the offset of the inner race during assembly. This “offset post” idea is from Buchanan’s original test assembly station design. The hole cover was to be design for retention of this idea and the potential for its use in future design concepts. Other than the support edge of the hole cover, any other surface had to be flush with the assembly station top to allow for proper motion of the deformation chuck.

Detailed specifications for the hole cover include geometry of the hole, geometry of the support edge, and geometric considerations for the “offset post”. The hole dimensions are illustrated in figure 3.12. The hole has a diameter of 1.38 inches from the bottom of the platform through 2/5-inch and a diameter of 1.5 inches for the remaining 1/10-inch. The top 1/10-inch forms a fringe on which the hole cover can sit. In order for the hole cover support edge to properly support the lower balls it must fit into the clearance between the inner and outer ring of the bearing, which is 0.1657 inches radially. If consideration is made for the "offset post", its diameter is 0.638 inches and will move from the center of the bearing assembly to the point at which the inner ring is in contact with the outer ring.

The hole cover, illustrated in figure 3.13 was designed and fabricated based on these specifications. As seen in the side view, the support edge in 0.1 inches thick, easily fitting into the clearance between the inner and outer bearing rings. A slot was cut into the plate, 0.650 inches wide to allow for use of the "offset post". A smaller step was machined around the perimeter of the support edge to compensate for the slight difference in height of the inner and outer bearing rings. This small step height is 0.1 inches and the support edge height is 0.430 inches. To allow for a flush seating into the hole, the major surface height of the hole cover is 0.1 inches. During assembly the cover is seated with the slot against the deformation anvil and the support edge against the deformation chuck. In this position the bearing can then be assembled as they are at the Torrington plant in Calhoun, lacking only the spring loaded plunger.

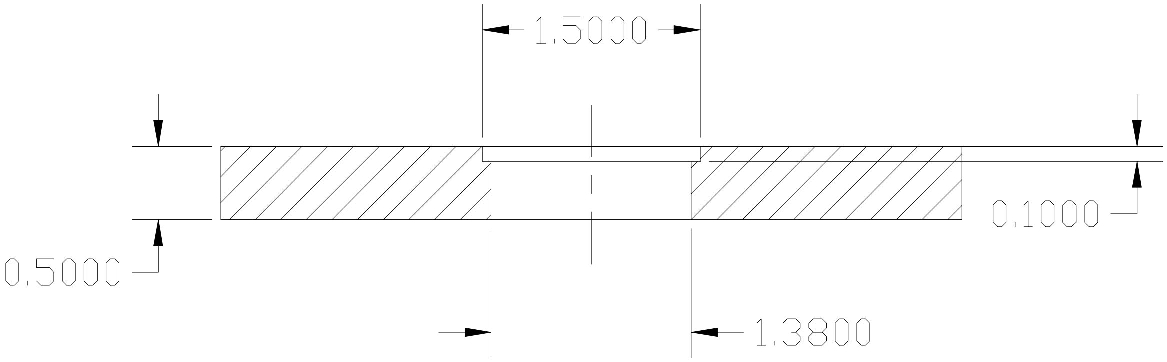


Figure 3.12 Cross-section of access hole in the test assembly station platform

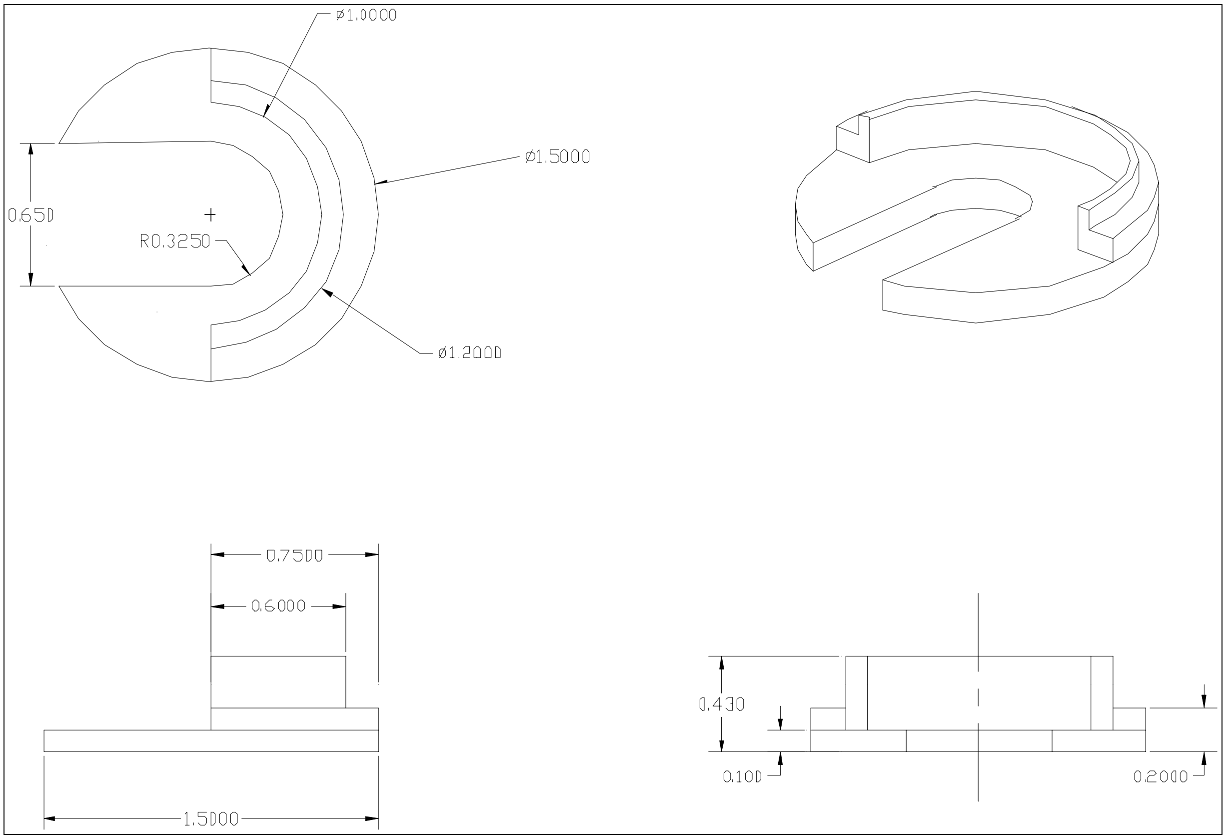


Figure 3.13 Slotted hole cover for test assembly station

3.2.3.2 Prototype Material and Mode of Fabrication

The material used for the prototypes dictated the mode of fabrication. The three materials considered for all design concepts except the sponge foam insert were, steel, aluminum and plastic. If the prototypes were constructed of steel they would have needed to be fabricated either by Torrington's machine shop or the university machine shop. Due to the need for multiple models and testing, the use of the university machine shop proved to be a costly method of fabrication. Location, time and cost of delivery made use of the Torrington machine shop also a less feasible choice for part fabrication. For the prototypes to be assembled using simple hand tools, aluminum or plastic would need to be used.

First attempts at fabrication consisted of metal shears and small aluminum parts. The aluminum proved to be difficult to form to the precise configuration needed and the metal shears could not cut to the scale of such a small component. In an attempt to produce a more accurate cut, a rotary hand tool was used. More precise cuts could be made, however the rotary tool was not robust enough to efficiently produce aluminum prototypes. As a result of the difficulties fabricating prototypes with aluminum, plastic became the preferred material.

The most difficult shape to form with plastic, without molding, is curved or rounding. To avoid having to form a curved section of plastic, plastic tubing was used as the raw material. PVC tubing was ideal for this purpose. For outer components, PVC pipe with inner diameter of approximately 1.6 inches and outer diameter of approximately 1.9 inches was used. This needed no modification to accommodate the bearings, since the outer diameter of the outer ring is 1.57458 inches. For inner components, PVC pipe with inner diameter of approximately 1 inch and outer diameter of approximately 1.3 inches was used. The inner diameter of this PVC pipe was sufficient to accommodate the inner ring of the bearing, which has an outer diameter of 0.9615 inches. The outer diameter of the PVC needed slight modification to accommodate the bearing outer ring, which has an inner diameter of 1.2930 inches. The outer diameter of the PVC was machined down to approximately 1.2 inches.

Materials used for the sponge foam insert needed to be both soft enough for easy insertion and formability but firm enough to support the balls and resist tearing during removal. Two closed foam polymers with different densities were used. The least dense material, foam typically used for electronic card shipping, had a density of 5.042E-3 lb_m/in^3 and a more dense material, typically used for mouse pads, had a density of 1.836E-2 lb_m/in^3.

3.2.3.3 Prototypes

The stepped support and the top inserted rigid “L” arms were fabricated using the PVC pipe described in section 3.2.5.2. In addition to these, a model of Buchanan’s “screw anvil” design concept was also reproduced in plastic.

Buchanan’s “screw anvil” design concept is illustrated in figure 3.8 while the stepped support arm and top inserted rigid “L” arm are illustrated in figure 3.14 and 3.15, respectively. Table 3.2 lists the dimensions of the fabricated stepped support arm, the top inserted rigid “L” arm and Buchanan’s “screw anvil” design concept.

In table 3.1, the component height describes its largest dimension and its width describes its second largest dimension. All lengths are measured from the extreme edges of each component. Curved components lengths are measured along the arc.

Table 3.1 Components Dimensions for fabricated prototypes

Stepped Support Arm		
Component	Mean dimension(inches)	
	length	width
Upper horizontal arm	1.2	0.159
Upper vertical arm	0.545	0.195
Lower horizontal arm	0.7	0.125
Lower vertical arm	0.425	0.199

Top Inserted Rigid "L" Arm		
Component	Mean dimension(inches)	
	length	width
Outer support arm	3.57	0.274
Horizontal connection arm	0.55	0.151
Vertical connection arm	0.95	0.218
Inner support arm	1.3	0.248

Buchanan's "Screw anvil" Design Concept		
Component	Mean dimension(inches)	
	length	width
Horizontal arm	1.3	0.29
Vertical arm	1.5	0.283

Sponge Foam Insert		
Mean dimension(inches)		
length	width	Thickness
1.0	0.58	0.1

Figure 3.14 Stepped support arm prototype.

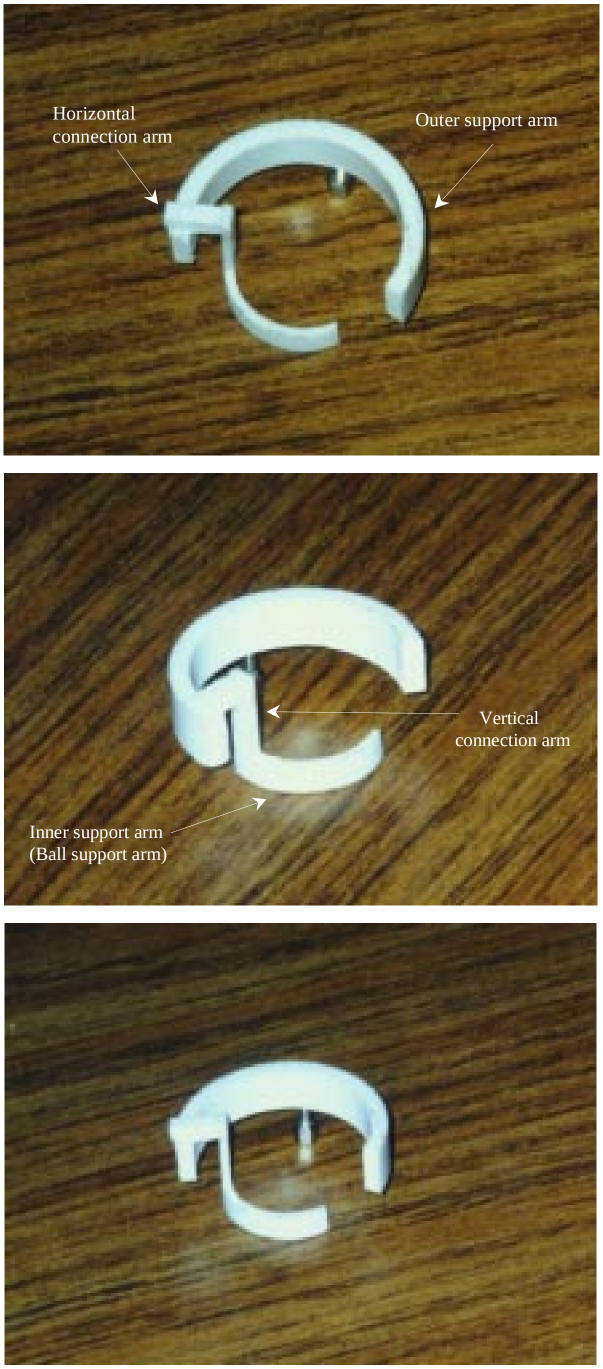


Figure 3.15 Top inserted rigid “L” support arm prototype.

3.2.3.4 Testing

With the prototypes fabricated, all three were tested on the test assembly station. The original fabricated support arm structures from Torrington were included in the testing process to reevaluate their effectiveness. In addition to the structured prototypes, the non-structured support or assembly technique was also tested.

For the structured prototypes, the bearing assembly was similar to the assembly process at the Torrington, Calhoun facility, with the exclusion of the center ring spring-actuated support plunger. With the O-ring removed from the bearing inner ring the plunger is not needed, because sufficient clearance is available for eight balls to fall into the lower race. Once the lower eight balls were inserted and snapped into the lower race of the bearing, the partially assembled bearing was removed from the deformation fixture. The prototype support arm was then inserted into the partially assembled bearing, making note of the ease of insertion and complexity of motion. After insertion of the prototype support, the partially assembled bearing was returned to the test assembly station and the deformation force reapplied. Normal assembly was then resumed, with the tilting of the inner ring, the insertion of the upper eight balls and snapping of the balls into the upper race. Each prototype was also evaluated for interference with either ring, proper support of balls, and robustness during assembly. Once the upper balls were securely snapped into the upper race of the bearing, the assembled bearing was removed from the assembly station. The prototype support arm was then removed from the assembled bearing. Ease of removal and complexity of motion was also noted for the prototype support arm removal.

With the gravity based non-structured assembly technique, the bearings were assembled two ways. One method was with the lower balls being inserted as in the current assembly process, after which the assembly station was rotated 90^o to insert the upper balls. The other method of assembly was complete bearing assembly with the assembly station in the 90^o rotated position.

3.2.4 Phase Two Design Selection

Phase two design selection evaluates the prototyped designs based on their performance on the test assembly station and potential for automation and implementation into the current assembly process. Areas of consideration for the structured prototypes include ease of insertion/removal, complexity of insertion/removal motion, interference with bearing rings during assembly, proper support of balls, and robustness during assembly. The ease of insertion/removal motion also dictates the design’s potential for automation. Table 3.2 gives a concise overview of the prototype evaluations. Scores are similar to those in phase one design selection: 1-met requirements fully, 2-partially met requirements, 3-did not meet requirements, or 4-needs further analysis. Evaluation of the non-structured prototype or assembly technique was evaluated independently and is discussed later in this section.

Table 3.2 Phase Two Design Selection

Prototype	Selection Criteria							Total
	ease of insertion/ removal	complexity of insertion/ removal motion	interference	ball support	robustness	implementation	General Fucntion	
Top Inserted Rigid “L” Arm	2	1	3	3	2	1	3	15
Stepped Support Arm	1	1	1	1	2	4	1	11
Calhoun Spiral Support Arm	4	3	2	1	1	4	1	16
Calhoun "L" Support Arm	2	2	3	3	2	2	1	15
Sponge Foam Insert	1	1	1	1	4	1	1	10

The Calhoun “L” support arm was the least functional of the four prototyped designs. Insertion and removal were easy tasks and the motion was a simple two step, axial then rotation. The interference and ball support did not meet requirements because the vertical leg of the “L” support arm came into contact with the lower balls when attempting to rotate the horizontal arm into a position to support the upper balls. This interference also prevented the horizontal arm from reaching the proper position to sufficiently support the upper balls.

The Calhoun spiral support arm was inserted into the bearing assembly easily, however removal was cumbersome. Once inserted, a spiral motion was required for it to reach its ball supporting position. Removal was awkward as a result of slight interference with the lower balls when executing the reverse spiral motion. It sufficiently supported the balls and met the robustness requirements because of its steel construction. The complex motion caused it to not meet the requirements for a feasible implementation into the current assembly process.

The top inserted rigid “L” arm could be inserted easily and motion was an axial motion followed by rotation. Removal was hampered by slight interference with the inserted upper balls. Because of the vertical connection arm, the horizontal support arm was not able to extend far enough to sufficiently support the necessary balls. Due to its top insertion, manual implementation would probably be easier than automation.

The stepped support arm could be easily inserted and removed from the bearing assembly. Once inserted the rotation, axial, rotation discrete motion sequence could easily be accomplished both manual and potentially as an automated process. Being made of PVC reduced the support arm robustness. Reconstruction with steel should increase it structural integrity. The stepped configuration also allows for rotation into position to support the required top row of ball.

The soft sponge was inserted easily and supported the upper balls very well. Its thickness played a vital role in its clearance both for insertion and removal. The less dense sponge material proved to be too formable for ease of insertion and too fragile for intact removal. The more dense sponge material, with a thickness of approximately 0.1 inches proved very easy to insert and remove from the bearing assembly. The thickness and density made it resistant to damage during removal from the bearing. Its robustness needs further analysis to show its effectiveness for a large number of bearing assemblies.

One of the two rotated assembly station techniques worked successfully. If the lower balls of the bearing were inserted with the assembly station in its original position and then rotated through 90^o, then the upper balls could successfully be inserted. Even though no feeder tube was constructed, the ball could be easily inserted by hand. Once the upper balls were inserted the bearing was snapped into its final assembled position and removed from the assembly station. If the lower balls were inserted with the assembly station in the 90^0 position they tended to roll too far around the circumference of the bearing preventing sufficient tilt of the inner ring so that the upper balls could be inserted.

3.3 Design Summary

Several ball support arm design concepts were introduced along with two Torrington fabricated design concepts. Through an iterative design process, from the structured and non-structured support concepts introduced, three potentially functioning concepts were selected based on design specifications and functional constraints. They are the soft sponge insert, the stepped support arm and the rotated assembly station technique. These ideas were then tested on a test assembly station for reevaluation against the functional requirements. The soft foam insert best met the functional requirements and can very easily be implemented into the current assembly process. The other two support arm structures also met functional requirements but need further developments for implementation. Potential implementation of the soft sponge insert and further analysis of the stepped support arm and the rotated assembly station technique are discussed in chapter 4.