

BIOMECHANICAL ANALYSIS OF A CRICKET FILIFORM HAIR
SOCKET UNDER LOW VELOCITY AIR CURRENTS

by

Kanishka Bhuwanchandra Joshi

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ABSTRACT

Filiform hairs of crickets are of great interest to engineers because of the hairs' highly sensitive response to low velocity air currents. In this study, the cercal sensory system of a common house cricket is analyzed. The sensory system consists of two antennae like appendages called cerci that are situated at the rear of the cricket's abdomen. Each cercus is covered with 500-750 flow sensitive hairs that are embedded in a complex viscoelastic socket that acts as a spring and dashpot system and guides the movement of the hair. When a hair deflects due to the drag force induced on its length by a moving air-current, the spiking activity of the neuron that innervates the hair changes and the combined spiking activity of all hairs is extracted by the cercal sensory system.

The hair has been experimentally studied by researchers though its characteristics are not fully understood. The socket structure has not been analyzed experimentally or theoretically from a mechanical standpoint, and the characterization that exists is mathematical in nature and only provides a very rudimentary approximation of the socket's spring nature. This study aims to understand and physically characterize the socket's behavior and interaction with the filiform hair by presenting and proving new hypotheses about the hair and socket behavior. The operating principles of the socket can be used for the design of highly responsive MEMS devices such as fluid flow sensors or micromanipulators.

A three dimensional computer aided design (CAD) model was first created using confocal microscopy images of the hair and socket structure of the cricket, and then finite element analyses based on the physical conditions the insect experiences were simulated. The results show that the socket acts like a spring but due to its constitutive non-standard geometric shapes, it deforms like a thin membrane at times or like a plate in bending at other instances. It was also determined that the socket provides far greater resistance to hair movement than what has been previously postulated and computed by researchers.

INTRODUCTION TO A FLOW SENSITIVE STRUCTURE

Background

Many insects and arachnids have a high density of flow sensitive hairs. Insects such as crickets have very sensitive thin hairs called filiform hairs that can respond to very minute external disturbances by deflecting from their resting positions. In crickets, the hair length is the determinant of the kind of stimulus it will best respond to. Shorter hairs (less than 500 microns in length) are acceleration sensitive, and hairs longer than 500 microns are velocity sensitive (1).

The sensory system examined for this study is the cercal system of the common house cricket, *Acheta domesticus*. The cercal system “functions as an extension of the insect’s auditory system and facilitates the detection, localization and identification of air current signals generated by predators and mates” (2). Two long antenna-like appendages, called cerci (singular cercus), are the receptor structures of the cercal sensory system. Each cercus is approximately 1 cm long in an adult cricket and is covered with 500 to 750 mechanosensory hairs. These hairs range from 50 microns to 2 mm in length (2). Figure 1 shows the location of the cerci of a cricket and the mechanosensory filiform hairs. Each filiform hair sits in a viscoelastic socket underneath the surface of the cercus.

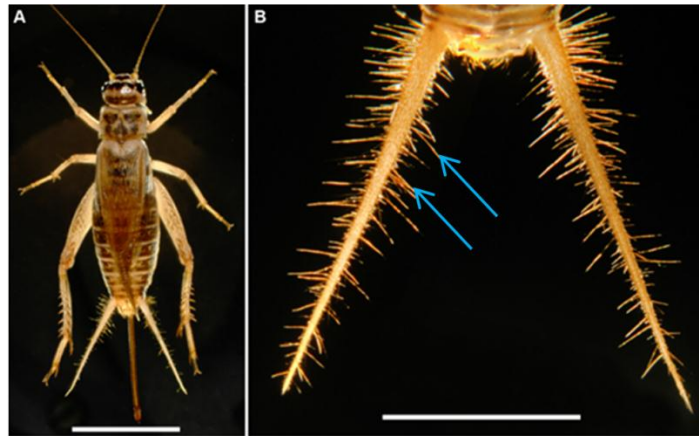


Figure 1: Panel A shows an adult female cricket with the ovipositor intact and the cerci. Panel B is a zoomed in view of the cerci (with the ovipositor removed) which are situated at the rear of the insect's abdomen. The filiform hairs can be clearly seen in panel B marked by the arrows. Scale bars- A: 1cm, B: 5 mm. Photo courtesy of Dr. John Miller.

The bottom of each hair has a wedge-like flange which impinges on the dendrite of a spike generating sensory neuron. When the hairs are stressed, they deflect causing a change in the spiking activity of their associated neurons. The information from the combined spiking activity of the hair array consisting of 1000 to 1500 hairs is extracted by interneurons in the cercal sensory system.

Each filiform hair is constrained at its base to move back and forth in the horizontal plane by a hinge-like support. Movement in one direction along a hair's movement axis excites the associated receptor neuron while movement in the other direction inhibits the neuron (2). Because the filiform hairs are extremely sensitive, even to air currents lesser than a mm/s, biomechanical studies to characterize the structural and sensing mechanism of the hair and socket assembly are necessary qualitatively and quantitatively. If the characterization is successful, then similar

principles might be adopted to design and fabricate ultra-sensitive flow meters, or highly responsive micro-manipulation devices.

History

The cricket filiform hairs have been studied extensively by researchers over the past few decades. One of the first major studies of flow sensitive insect hair was conducted by Tautz in 1977 (3) where eight filiform hairs of *Barathra brassicae* (cabbage moth caterpillar) were investigated for their motion patterns by vibrating them. While Tautz was able to come up with a mathematical model of the hair motion based on the his derived conclusions that the hairs acted as damped harmonic oscillators with respect to angular displacement and a time-varying forcing function, he did not completely solve the forcing function.

$$I\ddot{\theta}(t) + R\dot{\theta}(t) + S\theta(t) = \tau(t) \quad \text{Equation 1}$$

where $\theta(t)$ (rad), $\dot{\theta}(t)$ (rad/s), and $\ddot{\theta}(t)$ (rad/s²) are the angular displacement, velocity, and acceleration respectively; I (Nms²/rad) is the hair's moment of inertia, R (Nms/rad) and S (Nm/rad) are the damping constant and torsional restoring constant respectively due to the socket. $\tau(t)$, of course, is the time dependent forcing function-a torque. Equation 1 solves for the system shown below in Figure 2.

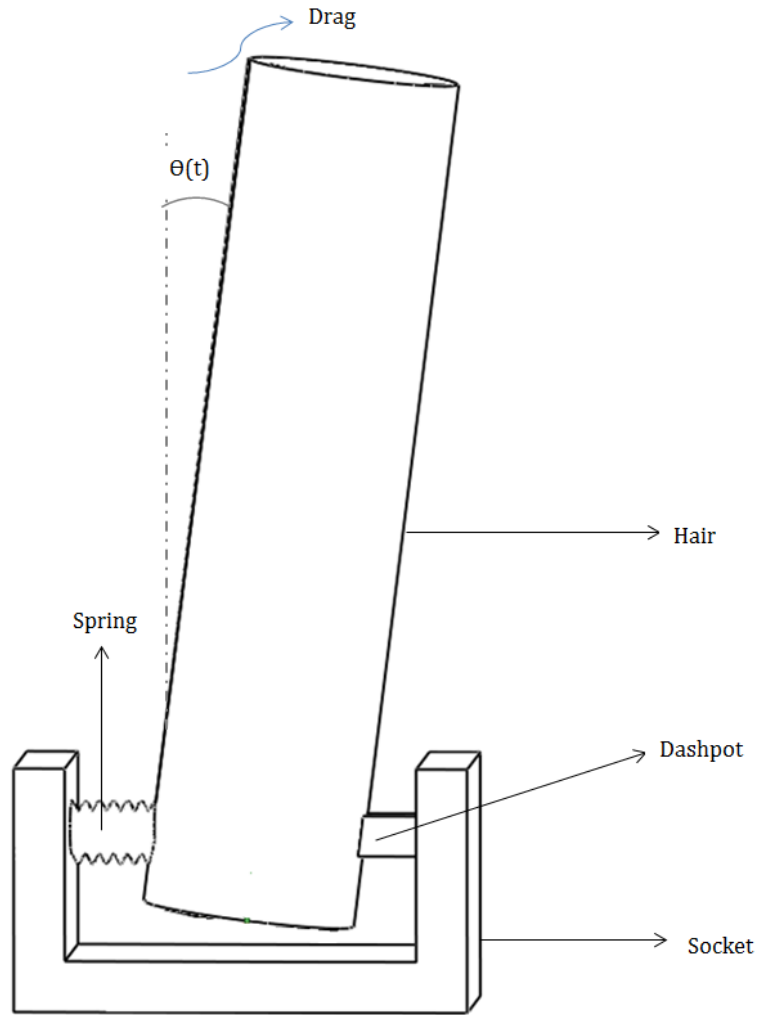


Figure 2: Schematic the differential Equation 1 represents. The spring provides the spring constant S while the dashpot provides the damping resistance R .

Shimozawa and Kanou (4) modeled filiform hairs of the field cricket, *Gryllus bimaculatus* and after making some approximations and a few assumptions, were able to calculate the form of $\tau(t)$. The approximations made were that the damping constant of the socket would be very small compared to other damping factors and could be ignored. Subsequent studies by Humphrey et al (5), Fletcher (6) , and Shimozawa (7) were able to curve fit experimental data and obtain values for R and

S. Interest in cricket hair sensing array has not been limited just to the theoretical realm; researchers at the University of Twente have fabricated several MEMS based cricket-hair inspired flow sensors. The “hair” is made of SU-8, and rests on a silicon nitride membrane (8). The membrane has electrodes deposited on its top surface, and a deflection of the “hair” results in the movement of the membrane, which changes the capacitance of the structure.

While the cricket’s mechanosensory hair array has been characterized well, and as mentioned, even flow sensors have been fabricated based on similar principles, all the previous work in the field primarily focuses on the hair’s characterization, and the socket simply becomes another mathematical constant. Hence, the socket’s characteristics are not well understood. In fact, there has been no work performed that mechanically characterizes the socket. This study focuses on characterizing the socket region by studying its deformation and stresses, and its interaction with the filiform hair, especially in a few areas of interest that are described later in this chapter.

Nomenclature

The nomenclature used throughout the paper for the various parts of the hair and socket structure will be clarified here to avoid any confusion. The images and descriptions presented below have the geometry parts labeled and the reader is encouraged to study them to get a good understanding between the names, purpose,

structural interaction and relationships, and the physical nature of the parts. Figure 3 shows a hair and socket schematic and the corresponding confocal images.

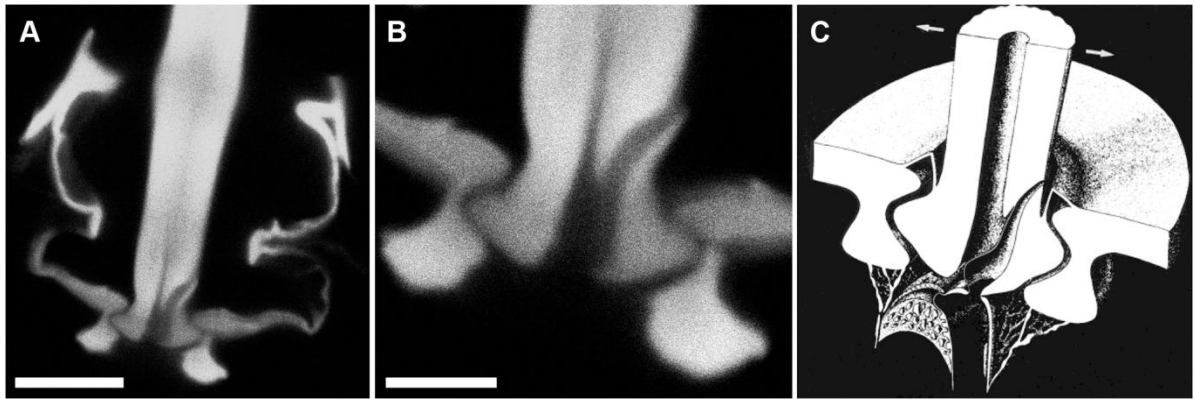


Figure 3: Panel A shows a confocal image of the hair in the socket along the short axis of the structure. Panel B is a magnification of the base region showing the ecdysial canal that extends from the hair base to the hair shaft. Panel C is a schematic of the hair and the bottom part of the socket (socket base). The ecdysial canal and its configuration can easily be seen. Scale bars: A: 5 microns, B: 2 microns. Data courtesy of Dr. John Miller.

The hair base (Figure 5 and Figure 6) fits in the socket base of the insect. There is a “bulge” on the hair shaft that is not visible in Figure 5 and Figure 6. The cross section of the hair is non-constant and elliptical from the base to this bulge and then transitions into circular and constant past the bulge. Also, the top part of the socket has a few extra features that are of importance to this study. Near the upper end of the top socket, the structure tapers in toward the center; the extra notch that pushes in toward the center is called the “iris” in this paper. Also, there is geometry on the upper part of the top socket that pushes upward diagonally and then comes back down. This is cuticular tissue material which when it sweeps back

down, connects to a sheet of some more cuticular tissue. These features are important because the hair bulge lines up with the iris of the socket (also, the hair is contained underneath the surface of the cercus below this bulge, and past it, the hair comes out of the skin), and when the hair is deflected enough, the hair bulge strikes the iris, which causes deformation in the cuticular tissue and the surrounding sheet (this sheet is called the “skirt”). Highly responsive sensors called campaniforms are embedded on the skirt and get activated based on deformation of the skirt. Another important feature to observe is the angled edge that connects the middle and top parts of the socket. This edge, in three dimensions, when swept along a path looks like a belt, and is called the “belt” in this study. Figure 4 below shows a confocal microscopy image of the hair sitting in the socket along the long-axis with all the parts labeled.

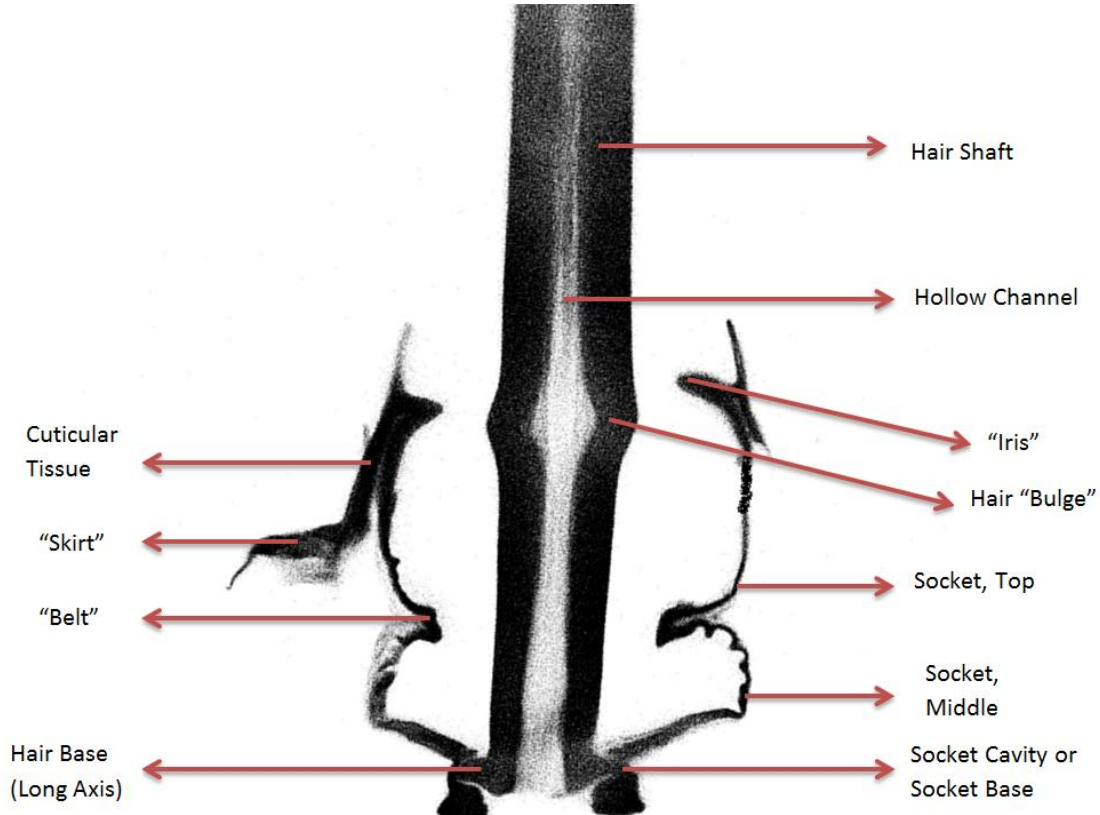


Figure 4: Vertical view of the hair-and-socket structure along the long axis with all the features labeled. The original confocal microscopy image was processed to remove most of the background pixels, and then the colors were changed to black and white. A small part of the image was manually reconstructed to include missing pixels. Data courtesy of Dr. John Miller.

Figure 5 and Figure 6 are magnified vertical sections of the hair bases along the major and semi-major axes of the structure's elliptical cross section. Figure 7 shows the hair base at the short axis again, but the ecdysial canal which contains the dendrite is now visible. This canal, when viewed from the long axis, ends up as a hole near the hair base. Figure 8 is a vertical section of the socket along its major axis.

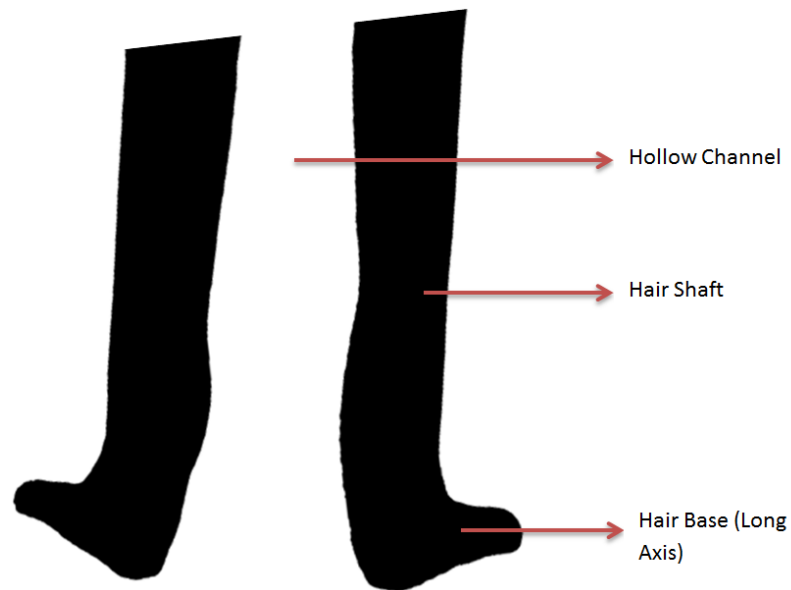


Figure 5: Hair base magnification along the long axis. The original confocal microscopy image was tuned into black and white, de-speckled to reduce background noise, and then the colors were inverted. Data courtesy of Dr. John Miller.

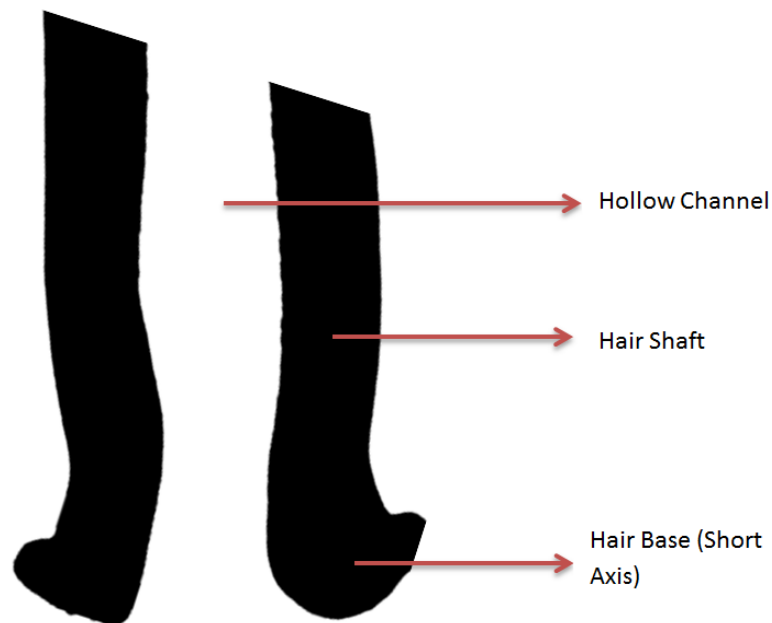


Figure 6: Hair base magnification along the short axis. The original confocal microscopy image was tuned into black and white, de-speckled to reduce background noise, and then the colors were inverted. Data courtesy of Dr. John Miller.

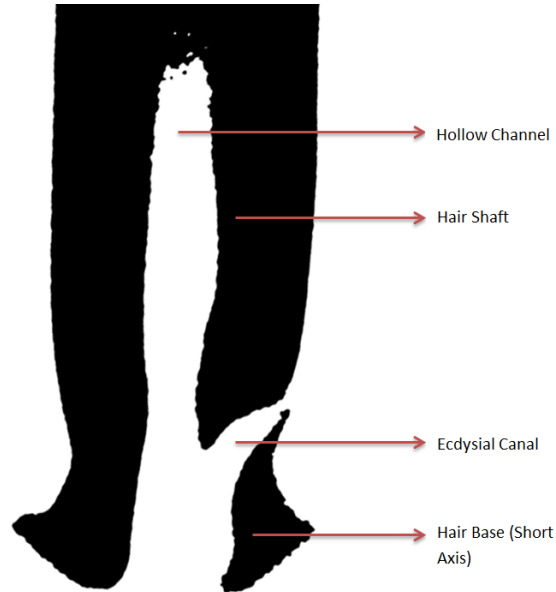


Figure 7: Hair base as seen along the short-axis direction. The ecdysial canal is visible in the image. Note that the hollow channel does not extend all the way up the shown hair length as this section view is not taken at the very center of the short axis. Data courtesy of Dr. John Miller.

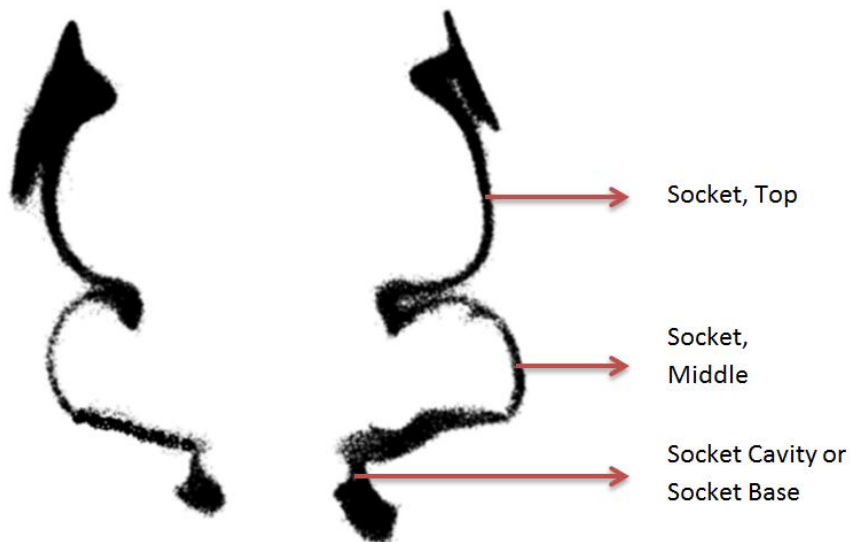


Figure 8: Socket along the long axis. The original confocal microscopy image was tuned into black and white, de-speckled to reduce background noise, and then the colors were inverted. A small part of the image was manually reconstructed to include missing pixels. The cuticular sheet or “skirt” feature is not visible in this image. Data courtesy of Dr. John Miller.

If Figure 4 is studied carefully, an arc pattern can be noticed around the circular part of the middle socket. These arcs are support cells and structurally speaking, they provide that region of the socket with some extra stiffness. Also, based on the description provided above, the campaniforms should be located near the area where the cuticular tissue and skirt feature meet. Figure 9, Figure 10, and Figure 11 show these features and give a more complete picture of the geometry.

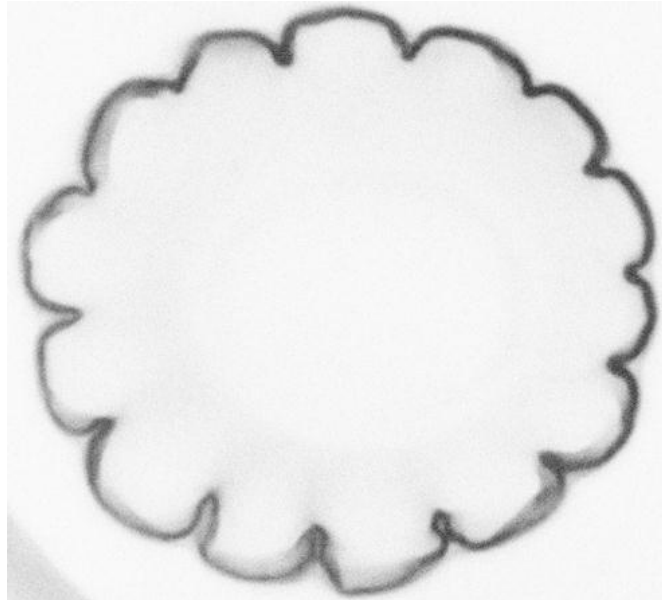


Figure 9: When the circular part of the middle socket is sectioned near its center and viewed from top, the arc pattern, or support cells become clearly visible. The wall thickness ranges from 0.5 to 1 micron. The meeting of the two arcs forms structural ribs and can add stiffness to the part. The original confocal image was processed to make the details more visible. Data courtesy of Dr. John Miller.

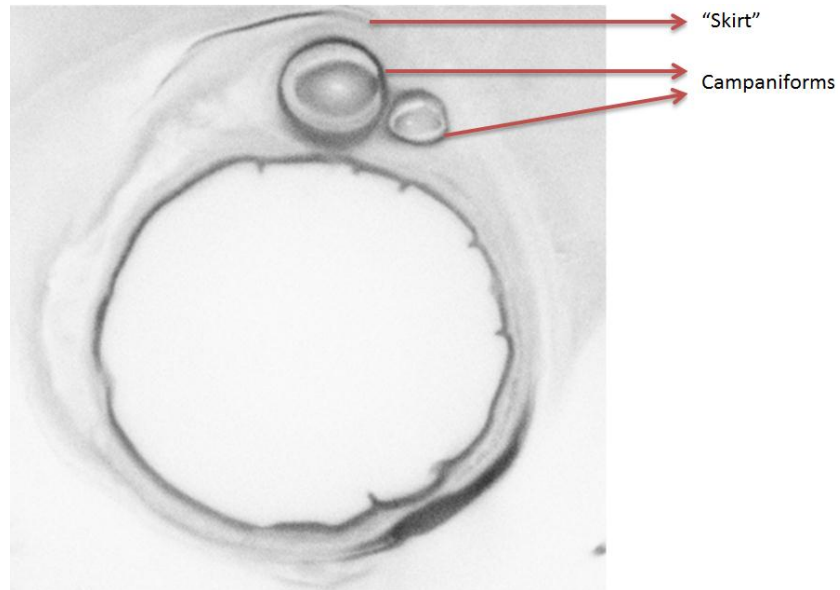


Figure 10: This is a top-view of the socket sectioned near the skirt feature. The campaniform sensilla and the sheet of tissue called the “skirt” on which they are embedded are clearly visible. The original confocal image was processed to make the details more visible. Data courtesy of Dr. John Miller.

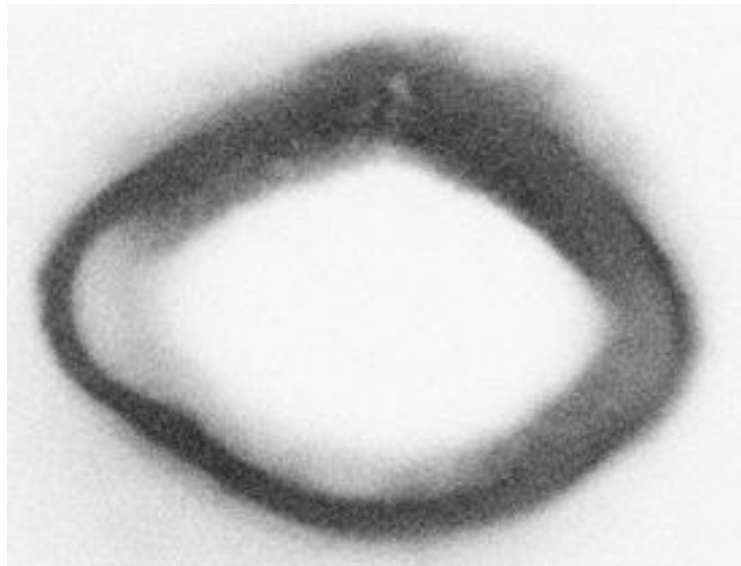


Figure 11: This is a top-view of the socket structure sectioned near the center of the socket cavity or base showing the elliptical cross section of the geometry. The original confocal image was processed to make the details more visible. Data courtesy of Dr. John Miller.

Physics of the Problem and Hypotheses

The filiform hair is constrained by a hinge-like support at the base which restricts the hair's movement to one plane of motion in the horizontal plane. It has been recently observed that the hair will always move perpendicular to its long axis, or along its short axis (2). While this does not mean that there's no motion along the long axis, the movement is so small that for the purpose of this study, it is ignored. The ecdysial canal runs in an arc, somewhat vertically, down the hair base when the hair is viewed from the short axis, the plane of motion. A dendrite is near the base flange of the hair which connects to a spike generating neuron below the socket. As mentioned before, movement along one direction of the short axis will activate the receptor neuron while hair movement in the other direction of the short axis will inhibit the neuron, and the information of the entire hair array is extracted by the cercal system. Figure 12 shows a schematic of this setup.

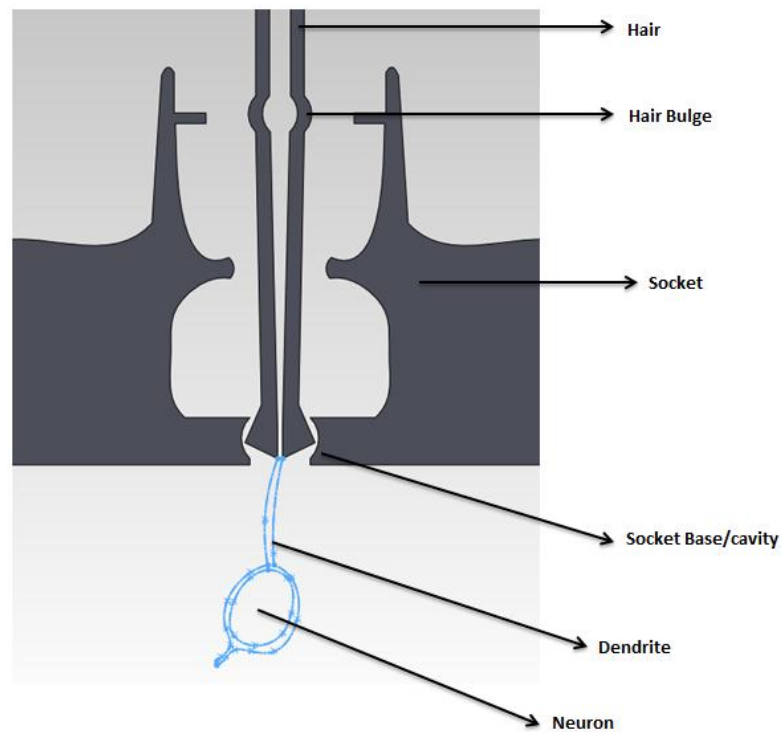


Figure 12: Schematic of hair and socket structure and the receptor neuron arrangement.

It is commonly accepted that the deflection of the hair causes a change of the spiking activity of the neuron by compressing the dendrite but the exact details of the compression, or even if the rotation of the hair base causes compression, as well as the hinge support are only hypothesized and not yet proven. According to the currently accepted hypothesis, there is some open space between the hair and socket bases, and the hair either rocks back and forth along the long axis, or moves left to right along the short axis without actually deforming the socket itself. In fact, a closer look at Figure 4 does indeed show some open space between the hair and socket bases.

However, this study presents and tests a new hypothesis: that the hair base fits tightly or rigidly around the socket base (and the gap that is seen in confocal microscopy images is an artifact of the various aspects of the microscopy sample preparation) and the socket itself is the “hinge” feature. A corollary to the previous statement is that the socket physically deforms as the hair is deflected and the elastic nature of the cuticle that forms the socket determines the “springiness” of the system.

What this also means is that the all features of the socket have to be examined carefully. The belt feature especially becomes a vital aspect to study well as at first glance, since the socket base is fit tightly with the hair base, any deflection of the hair would cause a deflection of the socket base and deformation of the middle socket giving rise to deformation of the belt. The upper socket should deflect a little if any at all, before the hair, or hair bulge to be exact, makes contact with the iris, but once the contact is made, the top socket will deform as well and in the process will transfer deformation to the belt feature. The belt therefore will act like a linear spring, and will not only absorb deformations but will also function as a type of displacement limit control as it separates the two socket parts, it can only compress so much before recoiling or collapsing (buckling failure). The recoil of the belt upon unloading of the socket may give the hair the damped oscillating patterns as observed by Tautz.

The other mechanism of interest is the contact of the hair bulge on the socket wall, or iris. As previously stated, highly receptive sensors called campaniform

sensilla are embedded on the cuticular skirt near the top socket. There are three campaniform sensilli on each socket: two on one of its sides as shown in Figure 10 above and one on the other side. Under extreme loading conditions, as during flight of the insect or a strong wind force, the filiform hairs deflect enough to strike the socket wall, and a secondary sensing mechanism controlled by the campaniform sensilla gets activated. This activation of the campaniforms is well known, but the deformation gradients of the skirt where the sensors are located, as well as the contact stresses of the hair bulge and iris have not been studied previously.

Another hypothesis made for this study is that once the contact occurs, the hair and socket will move together, but the hair bulge will also slide along the iris. From a structural perspective, the shear and out of plane stress transfers imparted by the hypothesized sliding may or may not be of biological relevance at this point, but for the sake of completion and further inquiry, this hypothesis will also be tested.

GEOMETRY DEVELOPMENT OF THE HAIR AND SOCKET STRUCTURE

Visualization

Several stacks of confocal microscopic sections through typical sockets were studied before the modeling process began. All microscopic data used in this study were obtained by Dr. John Miller. Stacks in which the hair was plucked out of the cercus were studied to visualize the hair geometry. These included hair sections along the short axis, long axis, and along then length (top view) near the hair base. Stacks of only sockets were studied where the socket had been sectioned along the long axis, and along its length. Sets of confocal images that helped the most with visualization of the structure were ones where the hair had been left in the socket, and the entire structure was sectioned along the long axis and along the length from the bulge/socket rim downward. However, given the elliptical nature of the cross-sections, it became very difficult to visualize how the model looked in three dimensions.

IMARIS, a Bitplane software, was utilized to form a solid rendering from the stacks of the confocal images available. The data files associated with each set of confocal images were scanned by the software to extract the relevant information while forming the 3D visualizations. Also, some data from the microscopy files, such as voxel depth and width had to be manually entered in the software from time to time.

IMARIS was also able to form a wire-mesh of the model it created from the confocal stacks of images. This model could have been saved and exported as a specific file type (VRML2) and then later used for running finite element simulations. Figure 13 and Figure 14 show the generated 3D image and model of the hair and socket structure.

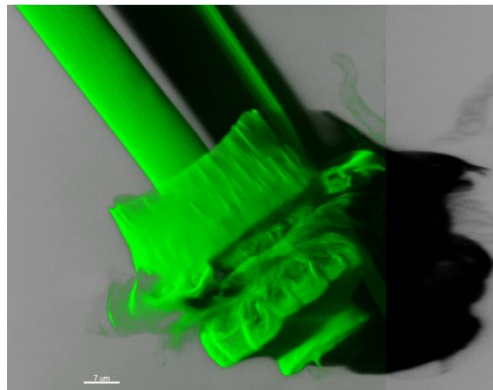


Figure 13: 3D structure generated by *IMARIS* from a stack of images sectioned vertically along the long axis with the filiform hair in the socket.

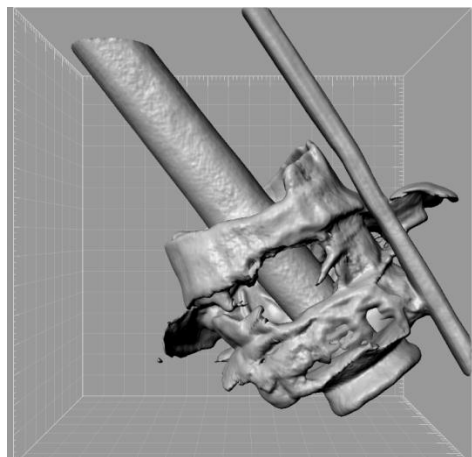


Figure 14: Solid model generated by *IMARIS* using one set of the many image stacks. This model was only used for visualization purposes and not for analytical applications.

However, *IMARIS* was only used to visualize the 3D geometry and not to create it. The model and wire mesh created by the software were not used for any analysis for reasons as follows: 1) *IMARIS* has a specific way of operating and it took many unwanted pixels from the confocal stacks and formed solids from them 2) The VRML2 file format which *IMARIS* saves the solid model and mesh as is a not a default CAD format for popular modeling packages as *Creo* and *SolidWorks* (however, VRML1 is a popular format, and it is quite easy to convert a VRML1 file to a VRML2 file, but going the other way is quite difficult), 3) the cricket cercus, at times, was not dissected along a horizontal or vertical plane, and this meant some features, or pixels from the images were missing or were not lined up, and the translation to *IMARIS* meant the model was missing some geometry here and there, and most importantly 3) by using the *IMARIS* generated model, all control over the geometry would be completely lost, and that was just not an acceptable option.

Measurement

Using *IMARIS* gave a clear idea of what the geometry in 3D would look like. The next step before modeling was to obtain the correct dimensions of the hair and socket structure. At first, *PDF-XChange Viewer* was used to take approximate measurements. Using the known scale bars of images, the scale was set and various dimensions were taken. An example of some of the dimensions can be seen in Figure 15, Figure 16, and Figure 17. This method turned out to be quite inexact and cumbersome, and allowed little flexibility with the type of measurements that could

be made. *ImageJ* measuring software was used to make the actual measurements later on. An example of measurements taken is shown in Figure 18.

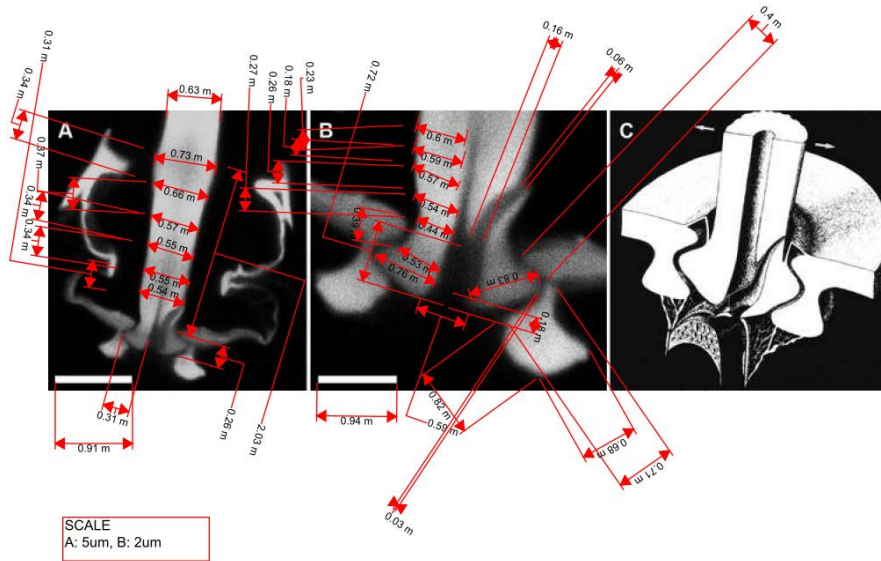


Figure 15: First set of approximate measurements taken using *PDF-XChange Viewer*. These images show the hair in the socket sectioned along the short axis. Figure modified from Miller et al (2).

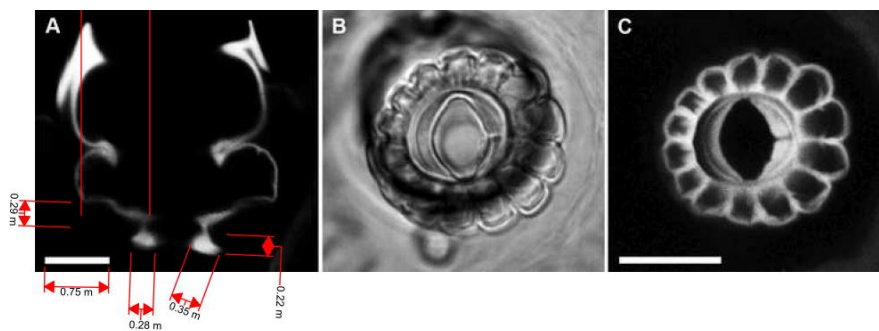


Figure 16: First set of approximate measurements taken using *PDF-XChange Viewer*. These images show the a vertical view of the section and then two top views near the middle of the socket (support cells visible). Figure modified from Miller et al (2).

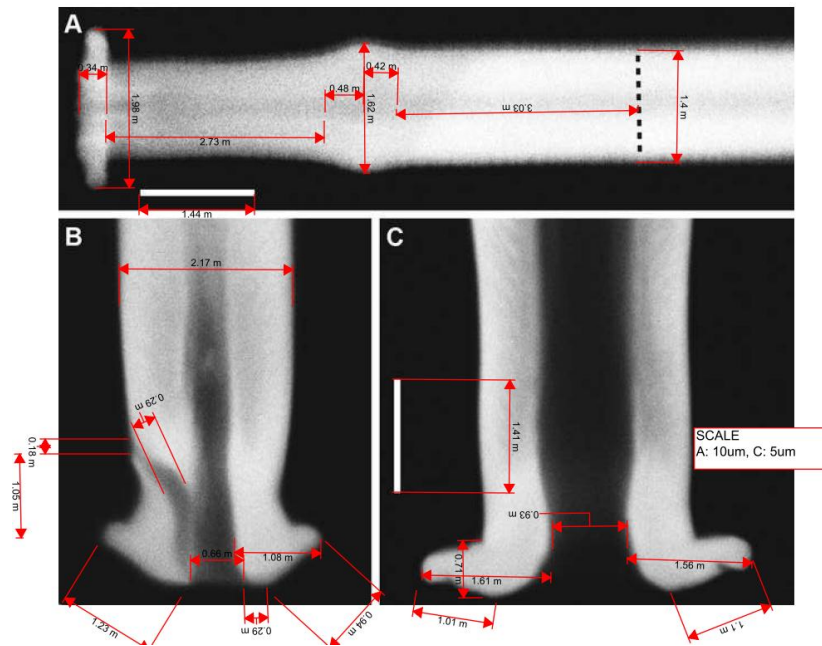


Figure 17: First set of approximate measurements taken using *PDF-XChange Viewer*. These images show the hair in the along its short and long axes. Figure modified from Miller et al (2).

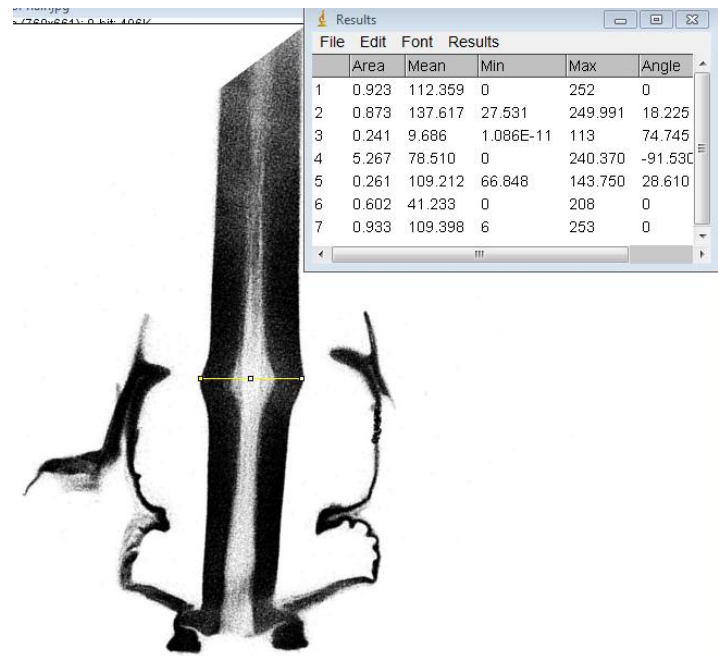


Figure 18: Sample measurements using *ImageJ*.

The data files associated with each microscopy image stack were used to set up the measurements. The pixels of each image were available in the data files, and so were the physical lengths of the image. Once this information was entered in *ImageJ* to set a scale, the necessary dimensions were obtained by using the measure feature of the software.

Three Dimensional Model Creation

All computer aided design (CAD) modeling that was used in the final analysis was done with *SolidWorks* 2012. Initially, a part of the geometry (support cells) was created with a professional *SolidWorks* 2012 version, and then imported into the educational *SolidWorks* version, but that specific part was not used in the final model. A few changes were made to the final model (not changes that altered the shape of the model but made certain parts more useable. For example, edges were split and adjacent faces were merged) in the finite element analysis package *ANSYS*'s modeling interface, but all the actual modeling was performed with *SolidWorks* 2011 educational version.

Hair

The first part created was the filiform hair. The various dimensions of the hair base and the length dimensions up to the hair bulge measured from *ImageJ* were used first to construct a base sketch. The hair base was drawn in great detail and no approximations were made to simplify the geometry. The same level of detail was also followed for the other length and angle dimensions till the hair bulge.

Figure 19 shows the cluster of dimensions used to create the base and shaft till the bulge. The figure shows how some non-standard dimensioning practices are employed. For example, the beginning of the hair shaft to the bulge is dimensioned with a total, in this case diagonal, length and an angle (27 microns and 87.50 degrees from the horizontal plane respectively). A usual way of defining such a line would be by defining the base and adjacent sides of the triangle that would correspond to the diagonal hair shaft line, however, because there was some noise in the confocal images, measuring a very small triangle base in *ImageJ* would have been difficult, and more importantly, a bit inaccurate as the start and end points would not be exact, and for a very small measurement, the error margin would have been high. Measuring an angle was a lot more straightforward and reduced the error margin significantly. The same reasoning was used to construct the other diagonal lines seen in the base sketch.

Once the base sketch was created, it was mirrored along the vertical plane to create a secondary sketch. This secondary sketch was then tweaked a bit more so that it matched the dimensions of the confocal microscopy vertical section as close as possible. It should be noted again that the reference confocal image that was measured was a vertical section with the hair cut along its long axis.

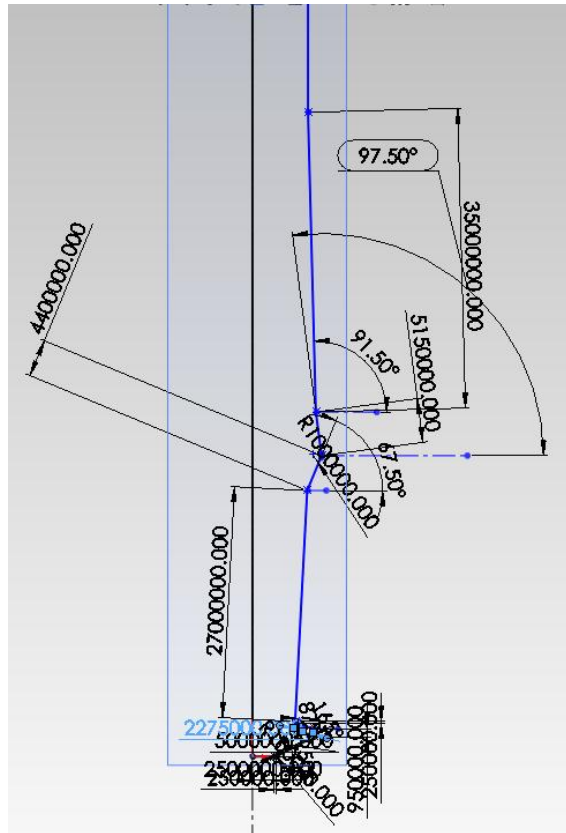


Figure 19: Dimension cluster used to create the base hair model. The dimensioning is a bit non-standard as the length of diagonal lines, for example, are define by magnitude and an angle instead of a horizontal and a vertical line. To ensure accuracy in values, when measurements were taken with ImageJ, the actual length and angles were measured. This reduced marginal errors due to noise in the confocal images.

An elliptical path was then created to sweep the secondary sketch along and create a solid. The ellipse had to have a particular ratio of the short to long diameters to match the physical hair. This ratio was found by measuring a few hair bases' axes and its magnitude was calculated to be 0.667. The elliptical sweep path was assigned this ratio before the sweep was executed. The first few tries of the sweep did not result in a solid as the geometry self-intersected at some time along

the path. Changing the dimensions of the elliptical path gave some better results with respect to reduction of intersection area, but not elimination of it. The diameters of the ellipse were changed many times but the geometry still self-intersected. Also, the major axis diameter could not be changed as at least one point in the path must intersect with at least one path in the profile when sweeping a body, and keeping one side of the long-axis fixed would mean changing the other side of the same axis. This results in a non-symmetric solid as one side of the ellipse is now further away from the center than the other.

Eventually, the path was changed so that now, the short axis intersected with the profile. This gave more physical control because now the profile started out at the narrowest point of the path, and as it would traverse the path, there would be no regions that were a shorter distance away from the center than the beginning point. This option did produce a solid after some minor adjustments were made to the path. Figure 20 shows some of the elliptical paths that were used for intersection with the profile sketch along the long axis. This was right before the path was switched such that the profile intersected the short axis. Figure 21 shows a magnification of the model tree of Figure 20. At that point, more than 80 paths had been tried. Figure 22 and Figure 23: show the solid that was created along the short and long axes respectively.

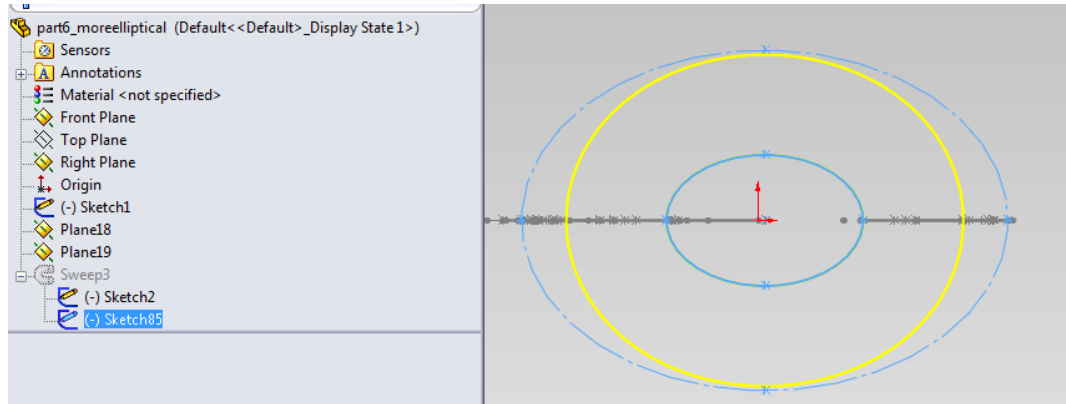


Figure 20: An example of some of the paths used to sweep the hair profile. The three elliptical paths seen in this image all intersect the hair base symmetrically about the vertical axis. Of course, because the path is elliptical, two different symmetry planes exist.

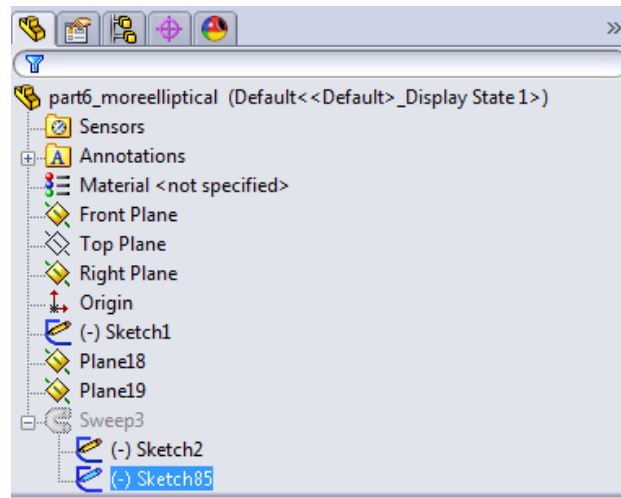


Figure 21: Close-up of model tree of Figure 20. By this point, many path sketches had been tried. This was the 83rd path sketch.

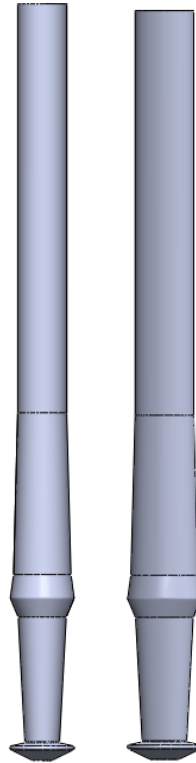


Figure 22 and Figure 23: Partial hair model when viewed along the short and long axes left to right respectively.

A horizontal plane that intersected the hair base at its widest part was then created (

Figure 24) and the model was sectioned at this plane and viewed from the top. Figure 25 shows the top-view and the dimensions of the major and minor radii of the base. The ratio of the radii was:

$$Ratio = \frac{66.571}{74.751} = 0.891$$

After the switch was made so that the profile/path intersection occurred on the short-axis of the path, a solid, as mentioned previously, was not created immediately and some tweaking of the path was required. This changed the path ratio a bit but

not enough for it to be more than 0.85. This exaggeration was probably a product of the sweep having to incorporate all the shaft geometry with its various dimensions as well. A line sketch was created that “divided” the hair base from the hair shaft. This sketch was then used to use a cut feature and the model was split into two parts-the hair base and the hair shaft. Figure 26 shows the sketch and the cut parts. This was done primarily to adjust the elliptical diameter ratio so that it represented the actual geometry. Other reasons to split the parts will be discussed toward the end of the modeling section.



Figure 24: The section plane created at the widest part of the hair base can be seen in blue.

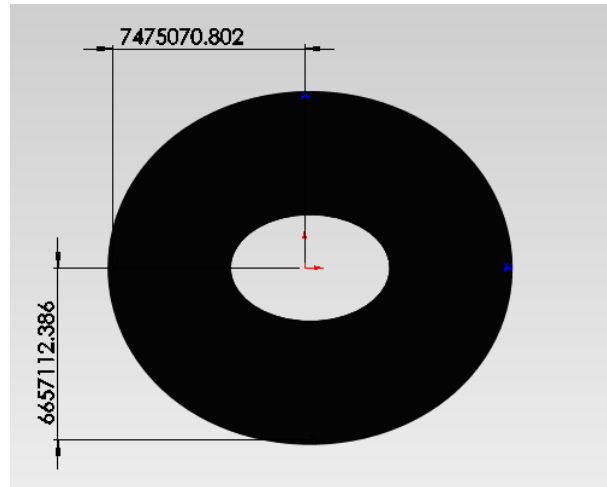


Figure 25: When sectioned at the plane seen in Figure 24, the ratio of the minor to major radii (hence diameter) was 0.891, even though elliptical the path used to sweep the geometry had the said ration at 0.667.



Figure 26: Hair body initially split into two parts-the hair base, and the shaft.

Next, a scale feature was used in the model. Because the confocal microscope image used for measurement and drafting was with the hair cut along the long axis, the correct diameter of the hair base was the longer-one and the hair base and the hair shaft were scaled along the short, or in reference to the model, the z-axis. Figure 27 shows this scaling feature. This was one of the first scaling features used. This number that appears on the “Z” axis field was modified later on. After the (final) scaling, the model was cut at the widest part of the hair base again on the same plane as before, and viewed from top as seen in

Figure 28. The ratio of the radii, and hence diameter now:

$$\text{Scaled Ratio} = \frac{5.237}{7.843} = 0.668$$

The created solid was then inserted in a new blank part. This was done to better keep track of the various sketches and planes in the geometry, because to complete the rest of the hair model, several other sketches and planes would have to be created. Confocal microscopy images have shown that past the hair bulge, the filiform hair’s cross section changes to circular and the diameter becomes constant. The exact location of this transition, however, was not known, and the relevant microscopy images were of the hair cut just past the bulge. Assuming that this transition occurred immediately after the bulge within a very short distance would mean irregular geometry and sharp edges, which would act as stress concentrators once a finite element analysis was run, so a longer transition distance close to the length of the hair shaft from the base to the beginning of the hair bulge was used. This was a safe assumption to make as the hair shaft length, past the bulge and

transition zone was roughly ten times the length to the transition zone from the base of the hair. In order to create this transition, a horizontal plane (that went in and out of the viewing screen) was created and offset the distance mentioned above. A circle of the correct dimension was sketched on this newly created plane. The other horizontal plane where the hair shaft had ended was used to convert the edge of the ellipse to a sketch. A loft was then created between the two sketches to create the transition zone. This zone can be seen in blue in Figure 29, which shows the hair along its long axis.

There is a hollow channel that runs along the length of the hair. Although this channel was created after completing the hair shaft length, the model at this stage had a hollow channel running from the base to the beginning of the transition zone. This was because of the nature of the profile employed to create the initial swept geometry. To ensure that short to long axis diameter of the hair base was 0.667, the path was modified several times before and after using the scale feature mentioned previously. After the scale was used for the first time, it had to be verified that the length of the triangular peg along the long axis of the hair base matched that of the *ImageJ* measurements. After scaling the model in the short axis direction, the model changed a bit in the long-axis direction to adjust for the various geometries. This was resolved by changing the path one more time so that the ratio of 0.667 was upheld. This change in the path led to the same self-intersecting case encountered before. To solve this, the base of the triangular peg in the profile sketch was not brought in all the way to the center vertical axis, but was stopped well before.

Therefore, when the model was swept after that, the gap between where the peg base stopped and the vertical symmetry axis began appeared as a hole in the model.

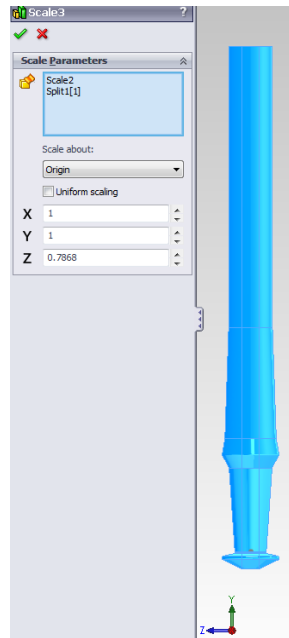


Figure 27: The hair base was scaled down along the short axis, since the long axis length was the correct one, to achieve the desired radii ratio.

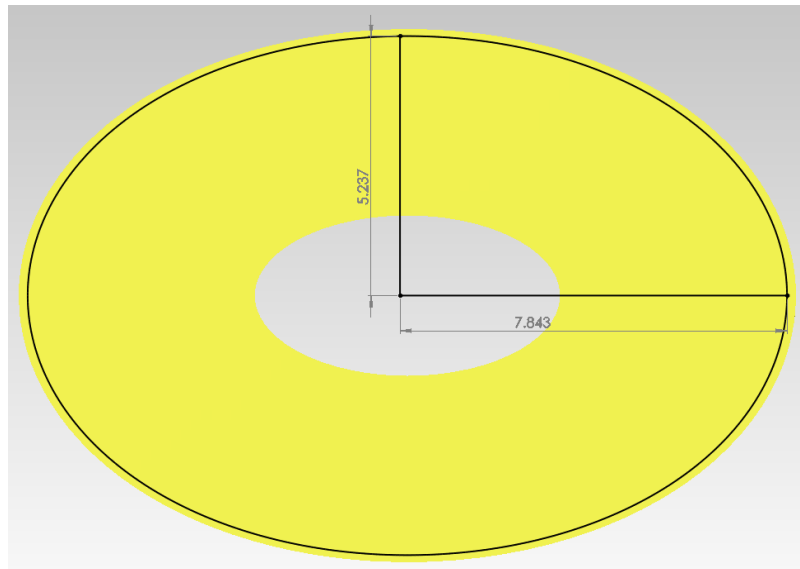


Figure 28: After the scaling, the ratio of the semi-major to major axis radii was 0.668.



Figure 29: Transition loft can be seen in blue

Before further completing the hair, this gap was filled. The edge of the gap was converted to a sketch right before the transition zone. This sketch was then extruded downward to the base of the model as seen in Figure 30. To complete the model, a constant diameter cylinder had to be created. The sketch used to define the circular end of the transition zone was extruded next to complete the length of the hair shaft. Figure 31 shows this extrude. Miller et al (2) have measured and characterized several hair and socket assemblies of an adult female house cricket and found a linear relationship between the base of the socket septum, the constant hair diameter, and the total hair length. Figure 32 shows a graphical representation of these relationships. Plot B in the figure shows the relationship between hair

length and the major axis of the base diameter. The data points in this relationship lie along the line:

$$l = 92m - 289 \quad \text{Equation 2}$$

where “l” is the total hair length in microns, and “m” is the long-axis diameter in microns. The R^2 value is 0.89. Using “m” from above (see Figure 28) as:

$$m = 2r = 2 * 7.843 \mu m = 15.668 \mu m$$

Now, to solve for the hair length:

$$l = (92 * 15.668) \mu m - 289 \mu m = 1154 \mu m$$

Plot A in Figure 32 shows the relationship between the hair length and the constant hair diameter, past the hair bulge. The data points lie along the line:

$$l = 124d - 219 \quad \text{Equation 3}$$

where “l” and “d” are the hair lengths and constant diameters in microns. The R^2 value of this relationship is 0.97. Equation 3 can be rearranged to solve for “d” as:

$$d = \frac{l + 219}{124}$$

Using the “l” obtained from Equation 2, Equation 3, d can be solved for:

$$d = \frac{1154 + 219}{124} \mu m = 11.1 \mu m$$

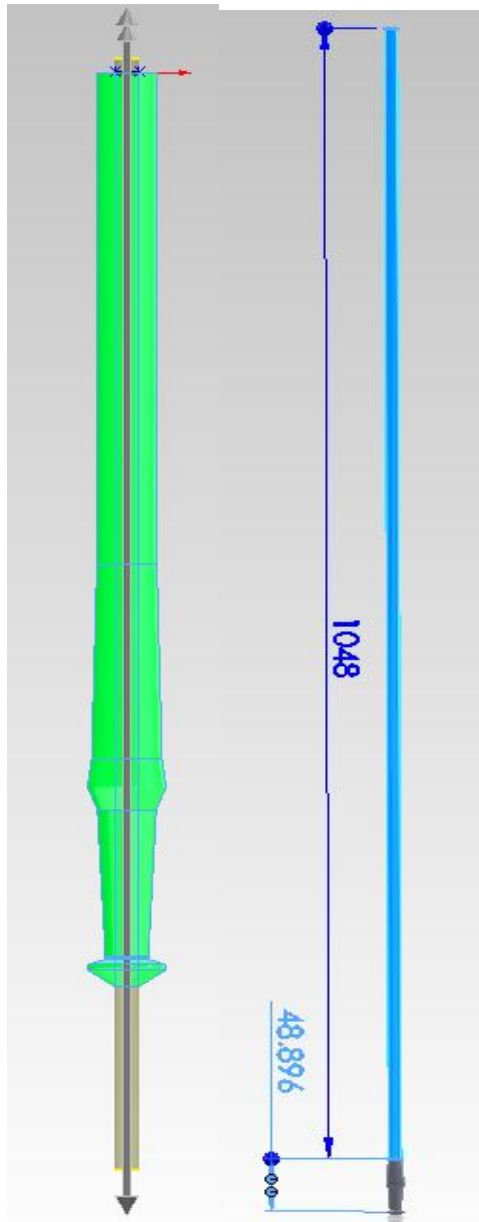


Figure 30 and Figure 31: An extrude feature was used to fill the gap created from the original sweep of the hair model (left). Note that this extrude is exaggerated and comes way below the hair base only for illustration purposes. Another extrude feature was used to complete the hair shaft length (right).

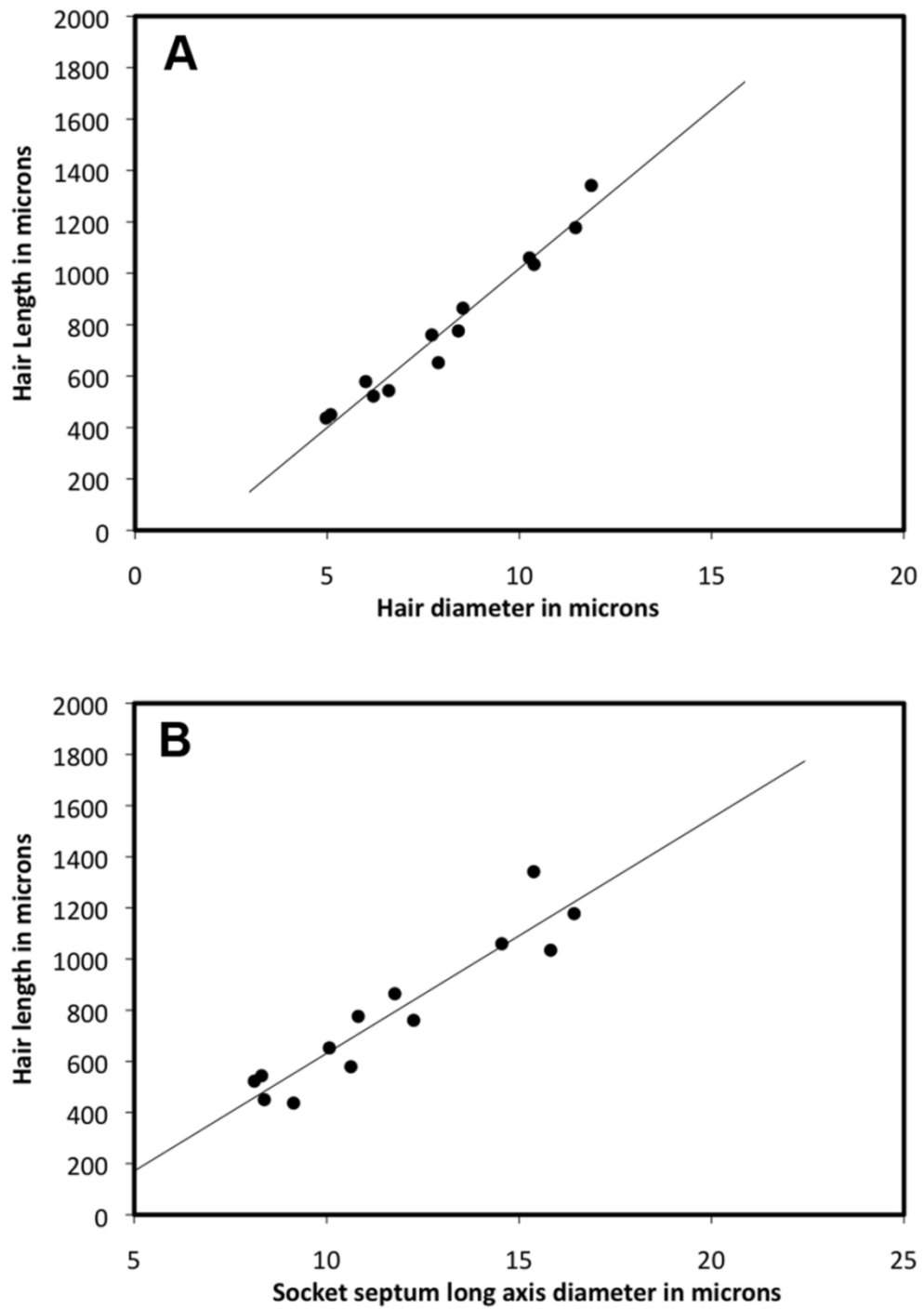


Figure 32: Scatter plots showing the relationship between hair length, hair diameter, and socket septum long axis diameter. Image courtesy Miller et al (2).

In fact, these calculations were carried out during the construction of the transition zone, as the constant hair diameter was required to sketch the circle that marked the end of the zone. Once the extrusion of the cylinder was complete, the hollow channel in the hair had to be created. The first hollow channel was “filled” because another channel where the previous one ended would have to be created. This meant less control over the geometry because if the channel were to be changed in the future, two sets of features would have to be modified. Two horizontal planes were created. The first one was created at the bottom most face of the model (bottom face of the hair base), and the second one at the top most face (face of the cylindrical extrude). An ellipse was sketched on the bottom plane. Using *ImageJ*, the “width” of the channel along the long axis was calculated previously, and that was then multiplied by 0.667 to obtain the short-axis diameter. Again, using a previous measurement taken at the top of the confocal microscopy reference image (before the hair it was sectioned off, a bit past the bulge where the constant cross-section began), a circle was sketched at the top plane. A lofted cut was employed next, between the two newly created sketches to construct the hollow channel in the hair. A vertical section view of the channel highlighted with the hair cut along its short-axis can be seen in Figure 33.

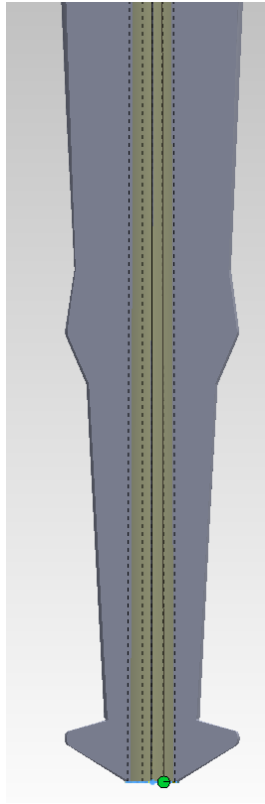


Figure 33: The hollow channel created can be seen in yellow.

Due to scaling the base hair model, and then inserting that model in a new part, and then further scaling the new model, the geometric planes were floating in space, and the model had no planes going through it, though it was still referenced from the original Front, Right, and Top planes. For greater control over the model, the three primary planes were offset to form new planes such that the new reference geometry now intersected the model through the center in all three dimensions. The new vertical planes were then used to create a reference axis. It should be mentioned that the hair shaft is actually not a straight cylinder but tapers to a point at its highest, but analyses conducted by Miller, Heys, and Gedeon suggest

that a straight cylinder approximation of the hair shaft is quite accurate (personal communication with Dr. John Miller).

Socket

The reference confocal microscopy image of the socket was a vertical section through the center of the socket's long-axis (Figure 8). However, several confocal stacks were studied earlier during the visualization stage. These stacks included sections of the socket from the top view. It was observed that as the socket was sectioned horizontally from the top and the middle bulge was approached, a flower like pattern began to emerge at the top of the middle part of the socket.

This pattern got more defined and reached its widest at the center of the middle part of the socket, and then transitioned back to the base. Throughout the middle part of the socket, the flower pattern maintained an elliptical cross section. Once the base, or socket cavity was approached, the pattern stopped. This, initially, was very difficult to visualize. However, using *IMARIS* to combine the top-view stacks, it turned out that the middle of the socket was in fact a bubble like structure, and the flower pattern showed support cells.

Figure 34 clearly shows this feature. The support-cells are postulated to enhance the socket's structural stiffness.



Figure 34: The support cells around the middle socket are clearly identifiable here. The campaniform sensilla can also be seen on either sides of the socket. Image generated using *IMARIS*.

The first socket model created was one with the support cells. This was a challenging task because the available *SolidWorks* 2012 features did not allow sketches to be patterned in an elliptical path by default. The standard choices available, to pattern a sketch, were linear and circular paths. An advanced professional version of the software, *SolidWorks* 2012, was used to create the middle part of the socket with the support cells. Because the available version of *SolidWorks* on campus was an earlier one, the newly created part had to be saved in a standard CAD format-IGES-and then opened and saved with *SolidWorks*. Because the part was complex geometrically, when it was saved in a different file format and then opened with *SolidWorks*, a lot of bad geometry was created. That is, necessary information, such as the wall thickness and the transition zone between the middle and top parts of the socket was lost. On top of that, the part imported as a shell, and random, irregular shaped self-intersecting geometry faces were created near the top

of the part. The original part was then saved as various other formats such as STEP and even a *Creo* part file and then opened with *SolidWorks* 2011, but the other formats did a worse job importing the part than the IGES format. Figure 35 and Figure 36 show the imported model, and the various holes in the feature.

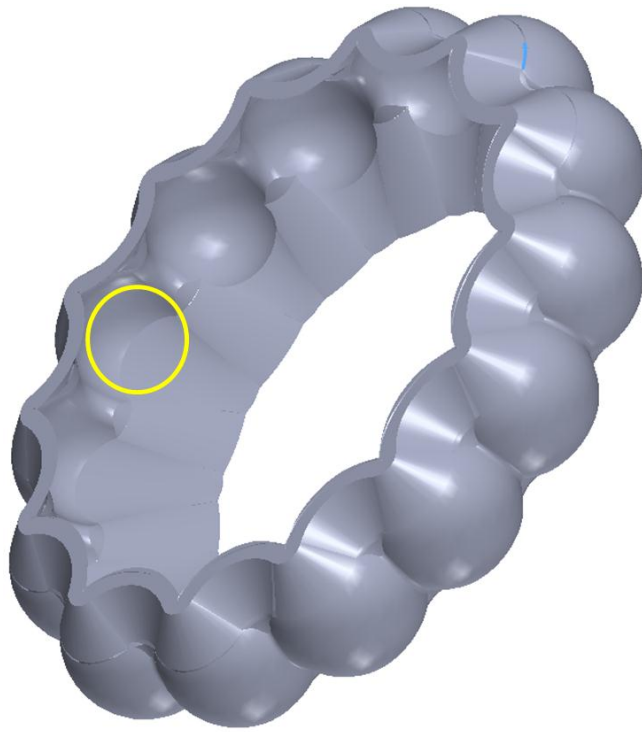


Figure 35: The imported model.

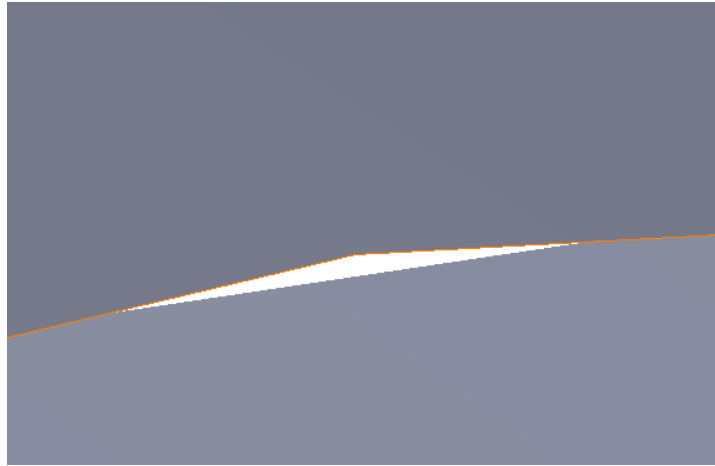


Figure 36: A zoomed in view of the area marked by the yellow circle in Figure 35, which looks good from a distance, but magnification shows many such holes in the model.

Using *SolidWorks'* Import Diagnostic tool, the irregular geometry was deleted. However, the deletion of the bad faces came at a cost: other parts of the geometry that referenced these faces now had holes. Though the holes were very small, the number of these discontinuities reached up to more than 100. These discontinuities were treated using various boundary and surface patch tools in *SolidWorks*, and the number of holes were brought down to 15.

The rest of the socket was then constructed using the imported middle part of the structure. The creation of these other parts was quite tricky. Since the middle part of the structure had zero thickness, and the other parts were assigned the thickness measured from Image], the connectivity between the top, middle, and bottom socket parts was poor. The connectivity and flow between the parts was not the only issue-because the imported part had lost some geometry information, it did not have flat faces at its top and bottom. Creating a swept, revolved, or lofted body

from a non-planar surface meant that several gaps now existed between the newly created part and the imported reference part. Once again, *SolidWorks*' boundary and surface treatment tools were employed to patch, fill, or knit these geometric gaps as required. The boundary and surface fill tools can work well for knitting and patching standard shaped gaps for regular geometries but are not an effective or elegant solution to fix irregular discontinuities in complex geometries. For example, many times, the best fill between a gap would not only fill that gap, but also extend the fill surface to beyond the required area. This was partly due to the nature of the geometry, but more importantly, the reference part was an imported one and its entities, such as edges and at times, even faces could not be picked to set certain boundary or directional limitations of the various fills, knits, and patches. Because over 85 holes were treated and fixed initially when the model was imported, and now, after modeling the other parts of the socket and treating the discontinuities that arose, there were many extra surfaces and faces in the model that served no purpose and only cluttered the model. At this point, even a fairly reasonable assumption stating that the middle part could be used without a thickness because the support cells would compensate for the extra stiffness as opposed to the other parts of the socket was not enough to continue with the model. The mediocre connections between parts, the lack of a definite belt feature, the various extra filled surfaces, and the fact that if the geometry had to be changed later on, all the various parts would need to be treated again-and not to mention the lack of geometric control over the middle part of the socket because it was imported led to discarding the

socket model and starting anew one from scratch. The new model was created without the ribs.

The new socket was initially created using a total of five sweeps: one for each of the three parts-top, center, and bottom-and two for other tertiary parts. Eventually, to ensure smooth geometric transitions between the various parts, as well as a greater global control option, the structure was completed with three sweeps. The greater control came into play because using one profile and one path for a sweep feature to construct most of the socket structure meant fewer geometric conditions had to be tracked and upheld at all times. So if a major part of the socket had to be changed, only one profile and one path sketch had to be edited instead of one profile and one path per part of the socket. The drawback, of course, was that if something was not modeled correctly, the entire sketch, and hence a major part of the geometry would have to be modified.

The confocal microscopy image of the socket that was used and the dimensions measured with *ImageJ* and which acted as the reference was presented in the previous section (recall Figure 8). Figure 37 shows the profile sketch and some of the dimensions used to construct the top and middle parts of the socket, along with the extra cuticular tissue that goes above the top of the socket and sweeps back down. Though this attached tissue is difficult to distinguish in the confocal images, and at first seems like it does not provide any structural relevance, it was still modeled. The importance of this cuticular tissue is explained later in the Finite Element Analysis section. This sketch was primarily made using many

construction points. These can be seen in Figure 37 as the floating blue crosses around the socket sketch. While some represent the center of the arcs used, a few were placed there relative to the origin based off *ImageJ* measurements to construct an accurately dimensioned structure.

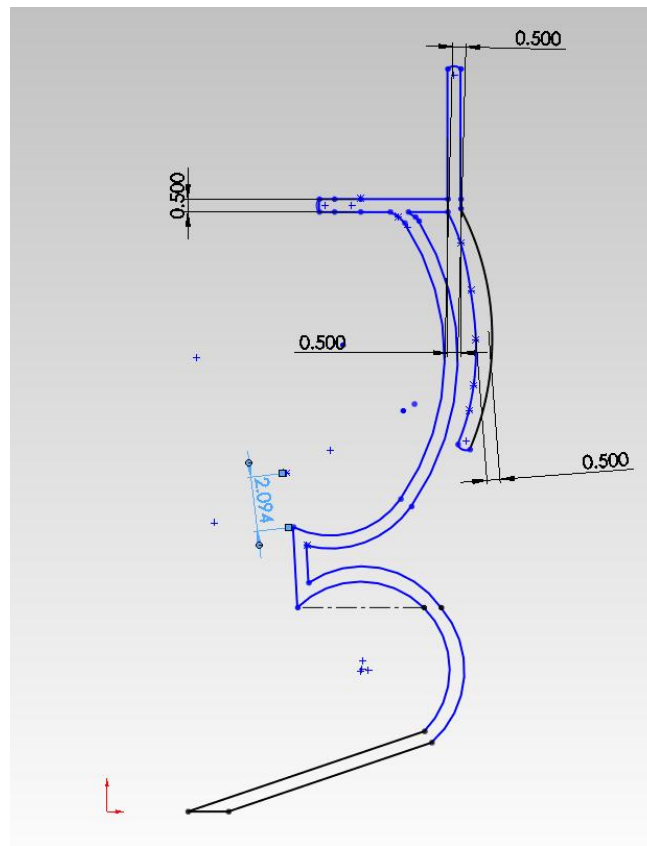


Figure 37: The profile sketch used to create the majority of the socket.

The base of the socket was not modeled fully until the hair and socket assembly was created. This was because of a couple of reasons: the hair had to fit tightly in the cavity, and so the hair base had to be used as reference. More

importantly, the socket cavity confocal microscopy images had some noise and were not sharp, so it was very difficult to get good measurements regarding angles, and curves. But given that most of the cavity followed the hair base contour made assembling the system first and then modifying the socket base once the hair base contour was visible in the same model the preferred choice of modeling. However, an approximate cavity was built at the bottom as a reference. The profile or vertical section of this approximate socket cavity is represented by the blue lines in Figure 38. Another important feature that was not very clear in the confocal socket image was some extra bit of skin that attached to the cuticular tissue's bottom geometry. This skin was modeled primarily for two reasons: first, the outside face of the sweep that would be created by this "skirt" sketch would be used as a fixed boundary condition while performing finite element analysis; second: highly responsive sensors called campaniforms are embedded on this skirt feature making the study of deformation and stresses of this feature important. This second reason is also why the previously mentioned cuticular tissue was included in the structural model. Figure 39 shows the profile sketch in blue of this feature and how it connects to the cuticular tissue.

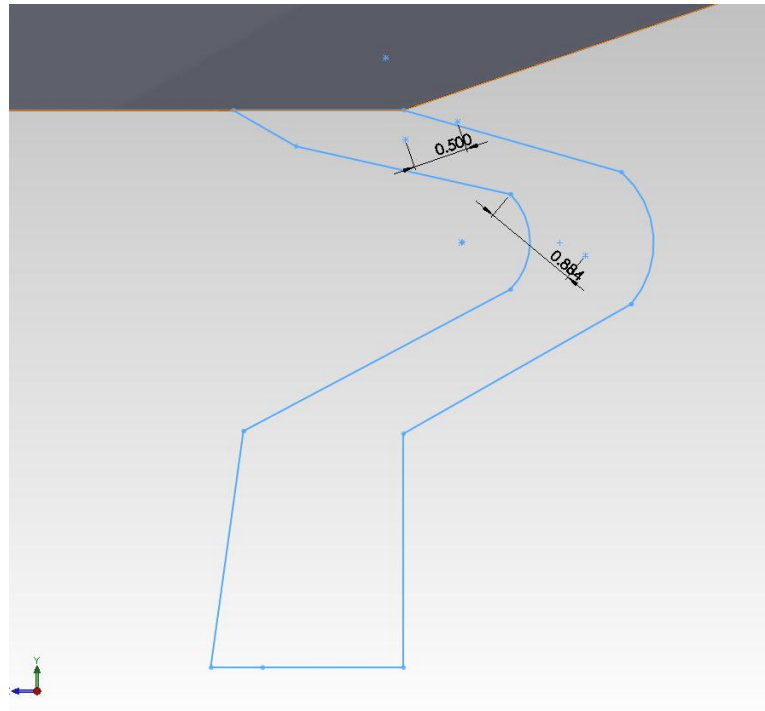


Figure 38: Initial profile sketch of the socket cavity

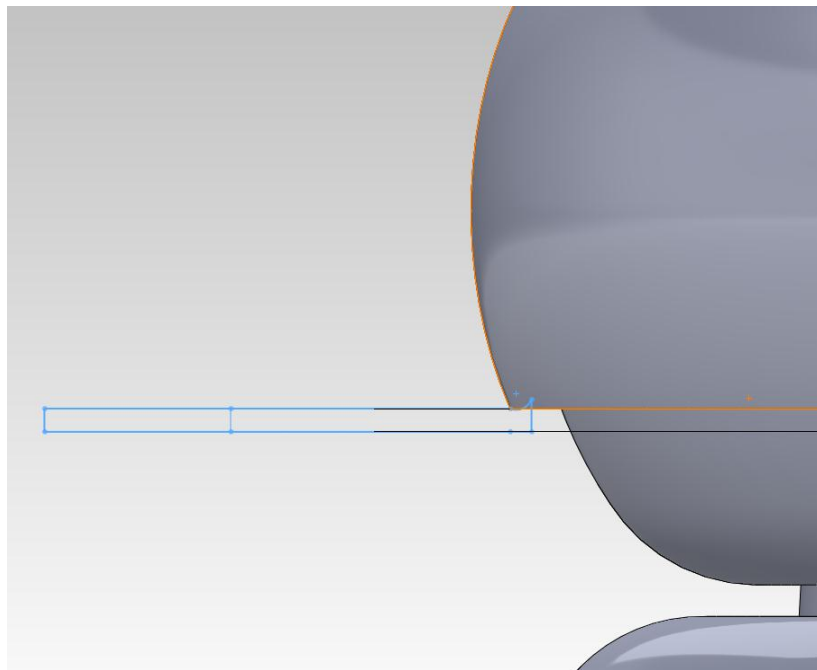


Figure 39: "Skirt" feature's profile sketch

Next, just like with the hair, the created socket was inserted in a new blank part. This was again for easier bookkeeping of the various sketches, annotations, and planes that were used up to this point in the socket model creation, and the ones that would be created in the new part. Once the new part file with the base socket model inserted was created, planes that intersected at the center of the part, or the center of all the elliptical geometries was created. These planes were used to insert a vertical axis. This axis would provide a simple way to assemble the socket with the hair.

Assembly

Once in assembly mode, the first part inserted was the socket. The hair was inserted next. The axes that were assigned to both models previously were then made coincident in the mate settings. This made the two models align vertically. To place the hair in the correct position relative to the hair, a distance mate had to be added. For the distance mate, two planar surfaces were required. The first planar surface picked was the bottom face of the socket cavity and the second planar face was the very top circular surface of the hair previously created by the extrude feature. The two planar surfaces selected were also the only planar surface combined in the two models. The initial distance set between the two faces to mate was a quantity greater than the depth of the extrude that was used to create the constant diameter hair shaft geometry. This brought the hair base quite close to the socket cavity. However, to see how exactly the hair base would fit in the socket base,

the model was sectioned vertically along the short axis. The mate distance was then modified until the top of the hair base lined up with the top of the socket cavity.

Since the socket cavity was an approximately dimensioned feature, the tight fit between the hair base and the socket cavity, as expected, did not occur. However, with the hair base visible, the cavity could now be modified such that it followed the hair base edges. The base cavity was formed by offsetting the hair base contours by a very small number (0.05 microns). Once this was accomplished, the bottom part of the cavity (looking at a vertical view) was completed according to measurements obtained previously from the *ImageJ* software.

After a lot of trial and error, the cavity was modified such that a snug fit with the hair base was established. The assembly was then sectioned along the long axis of the structure to ensure the same no-gap contact status between the hair base and socket cavity was achieved. This was not the case. There was some penetration of the socket base into the socket cavity in this sectioned orientation. The socket cavity was then further modified to achieve the desired fit. At first, the elliptical sweep path was changed until the fit was good. But this approach did not work well, because to compensate for the fit along the long axis and maintain the ratio of the minor to major axis diameter of 0.667, the geometry shifted and now penetrated the socket cavity along its short axis. The short axis section was then viewed and the elliptical path changed to ensure a fit, but of course, the penetration shifted back to the long-axis. After some time adjusting the path, it was determined that it would be very tedious and inefficient to continue with this approach. Instead, the path was

modified again so that a fit along the short axis was achieved, and then the socket part was opened and edited such that it now consisted of three different bodies-the top, middle, and bottom parts. Once this was done and the necessary fit obtained along one axis (short), the bottom part of the socket was scaled in the long axis until the required fit was achieved. This can be seen in Figure 40.

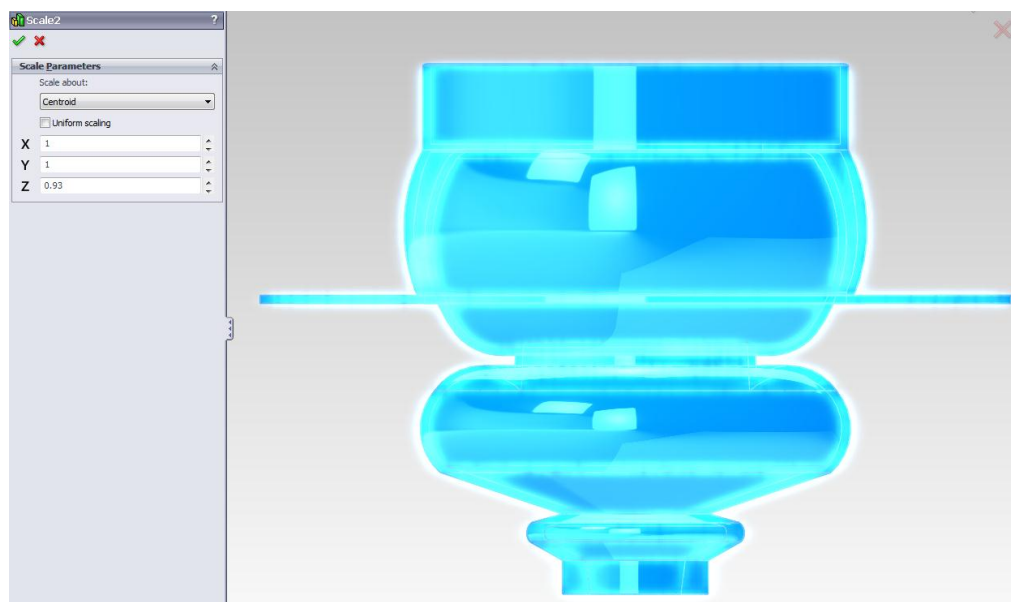


Figure 40: Socket cavity scaled down along the long axis. Changing the scale of the bottom part of the socket created some geometric inconsistencies.

The middle part of the socket was not scaled in any dimension, and it was initially in contact with the bottom part. Because of the scaling, the discontinuity arose, and to fix that, many sets of measurements of the model were taken and finally, when the right scaling parameters were obtained (such that the same geometry was upheld without discontinuities prior to the scaling of the base) the entire model was scaled. This can be seen in Figure 41. However, this two-fold

scaling at this stage created some undesirable geometry at the connection of the middle and bottom socket parts. This unwanted geometry was only visible once the model was sectioned vertically. This was an easy fix. A simple ellipse was created and the unrequired geometry was cut away. Figure 42 and Figure 43 show the irregular geometry and the cut employed to remove it. Figure 44 and Figure 45 show the final socket model sectioned along the short and long axes.

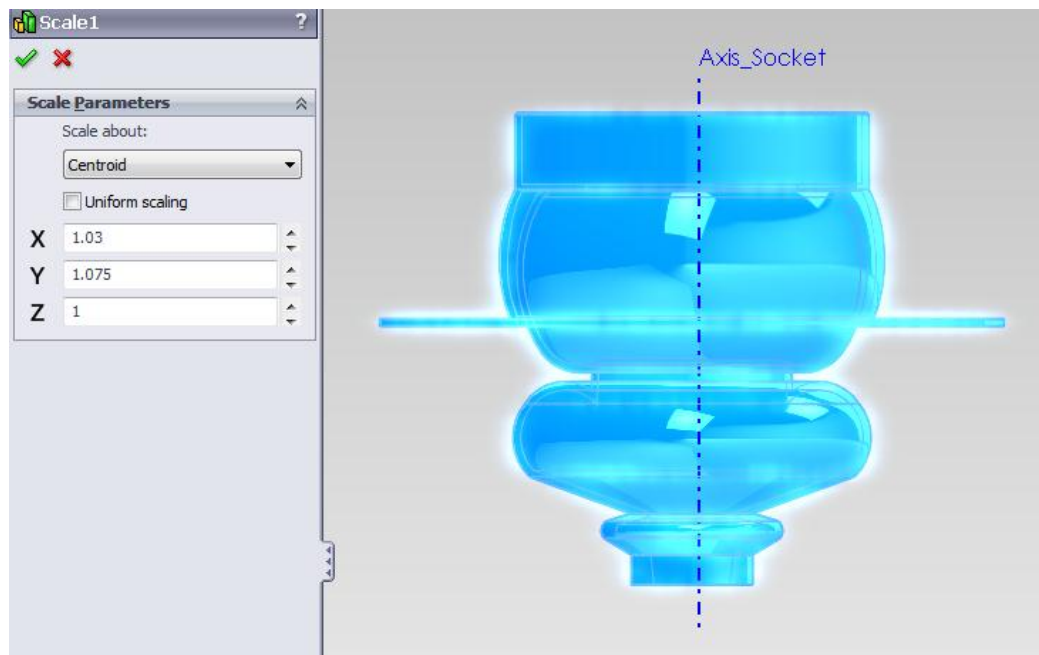


Figure 41: Scaling of the rest of the model to adjust for the previously scaled long axis of the socket cavity. Note that the “z” field is set to 1 as the desired fit is achieved in that direction.

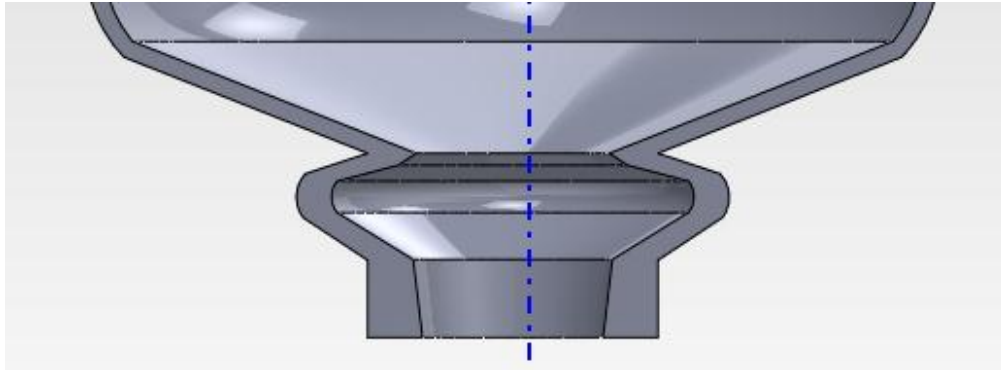


Figure 42: After scaling the entire body, the area where the socket cavity connects to the middle part of the socket had some extra geometry as can be seen, in this view, by the sharp edges at the connection point.

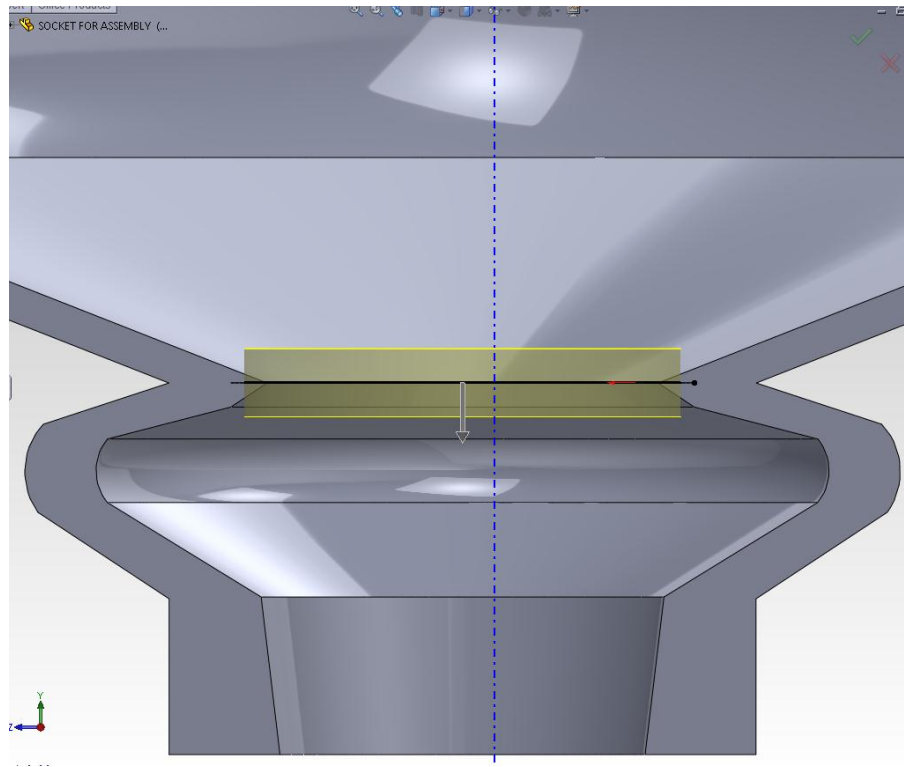


Figure 43: A cut was used such that not only would the extra geometry be deleted, but the socket cavity would retain its relative dimensions prior to scaling and after the cut.

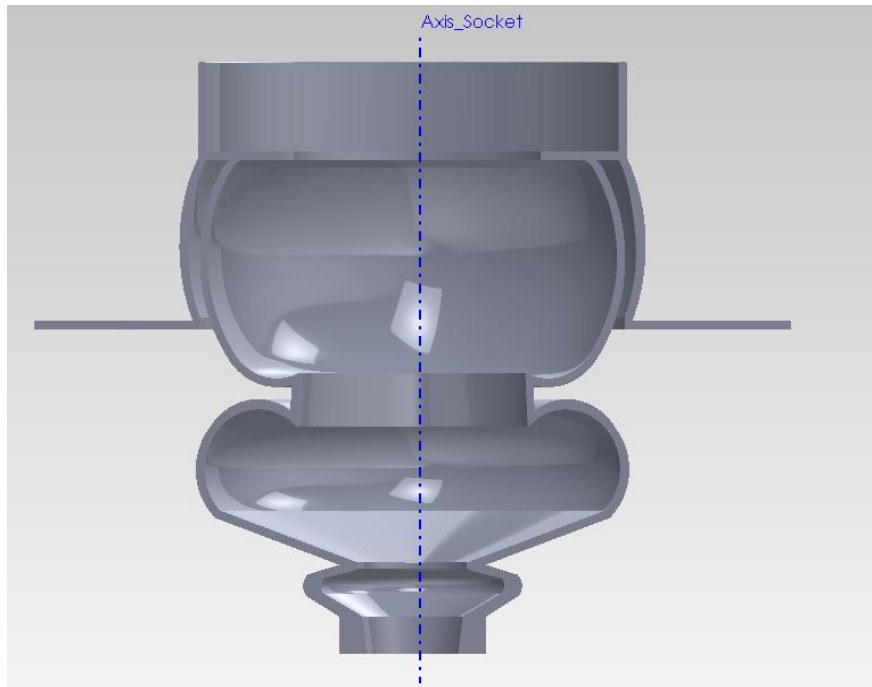


Figure 44: The completed socket sectioned along its short axis

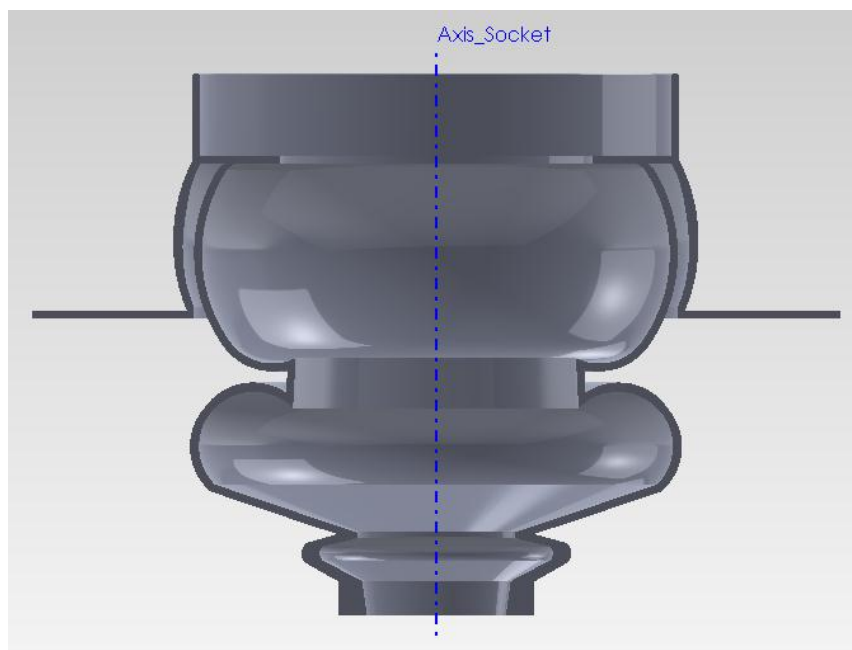


Figure 45: The completed socket sectioned along its long axis

Once back in assembly mode, a minor but crucial detail became evident. The hair bulge did not line up well with the top of the socket rim. This is a very important factor because as mentioned, many highly stimulus-responsive sensors called campaniforms are located near the cuticular skirt of crickets, and with a high enough excitation, as a high wind load, the hair will deflect enough so that the bulge in the hair strikes the socket rim, deforms the skirt feature, and the sensors activate.

This non-alignment occurred because two slightly different microscopy images were used to model the hair and the socket separately. This was done because the microscopy sections that showed the hair in the socket could not be used for accurate measurements as the aspect ratio of the cavity base and top bulge were very high (it was a zoomed out view to capture the entire socket) and the hair base details were very difficult to distinguish from the cavity in these images. So an image with close-up view of the hair was used to model the hair base, and based on data collected by Miller et al (2), the distance to the bulge and the total shaft length were modeled.

The hair was split into three parts-the base, the shaft from the base to the transition zone, and the shaft length with the constant cross section. The reason to do this was two-fold. First and most immediate was to manipulate the length of the middle part of the hair just a bit so that the bulge lined up with the socket rim. The second reason, as important and for future ease of operation, was for meshing purposes. Since the hair shaft length of the constant cross section is about ten times larger than the rest of the model, and since it is a very simple geometric entity, it

could be meshed with line elements or a very coarse mesh once in the finite element analysis package to save on the number of nodes and boost computation times.

The middle part of the hair was scaled in the vertical direction by a small factor of 1.07 so that the bulge lined up with the socket rim. An unneeded side effect of this scaling was that the middle part of the hair extended a bit into the hair base, and a very small amount into the top part of the hair shaft. The area of interest, the hair base, could not have the extra material as that would only add stiffness. To correct this, the extended part into the hair base was combined with the hair base to form one solid body. These details are visible in Figure 46 and Figure 46. Also, to ensure greater control during the meshing process, the socket was further split into more parts (bottom cavity, skin for boundary condition, middle and top bulges of the socket along with the tissue material).

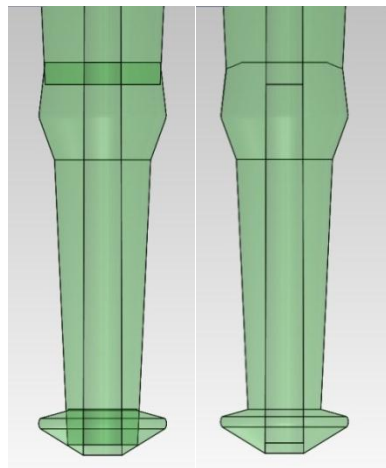


Figure 46 and Figure 47: The middle hair shaft extended into the hair base (left) when the length was scaled up so that the hair bulge lined up with the iris. The image on the right shows the correction achieved by combining the intersecting part with the hair base.

A quick note about scaling: the entire model was scaled up by a factor of 1000, so the units were millimeters instead of microns. This was done because it would be easier to make sense of slightly bigger forces and displacements while running analyses. All displacement and stress results should therefore be scaled down by a factor of 10^3 . After the finite element analysis was run for the first time, the force required to make contact was quite large. The confocal microscopy images were reexamined closely and it was determined that the ratio of the length between the two ends of the iris and the diameter of the top of the cuticular skin was fairly constant and was in the range of 0.6-0.65. The model was changed in *SolidWorks*, and the iris feature was brought in such that the said ratio was 0.61.

FINITE ELEMENT ANALYSIS

ANSYS Workbench 14.0 was used for all finite element analyses. First, a *Static Structural* module was opened.

Engineering Data (Material Properties)

The material behavior, as a first approximation, was assumed to be isotropic elastic and the mechanical properties of interest were the elastic modulus, Poisson's ratio, and mass density. For a static structural analysis, elastic modulus is the most important property of the three mentioned. The density does not really come into play unless a dynamic analysis is performed where the mass matrix also has to be incorporated to obey Newton's Second Law of Motion. All materials listed below were manually defined in the material library of *Workbench's* material library. This was the very first step, because the materials in *Workbench* cannot be defined once the finite element analyses setup is complete and a solution is iterated. Also, for the first few simulations, insufficient material properties were found in the available literature and the same material was assigned to both the hair and the socket. Once more in- depth research was conducted and new properties obtained, the hair was assigned a stiffer set of properties.

Cuticle

In arthropods, the cuticle is composed of two layers: a waxy water resistant outer layer and an underlying layer (9). The waxy layer is called the epicuticle and is

a thin surface layer. The inner layer is known as the procuticle and is further composed of two layers-exocuticle and endocuticle (9). Figure 48 shows a vertical section schematic of the layered cuticle of an insect.

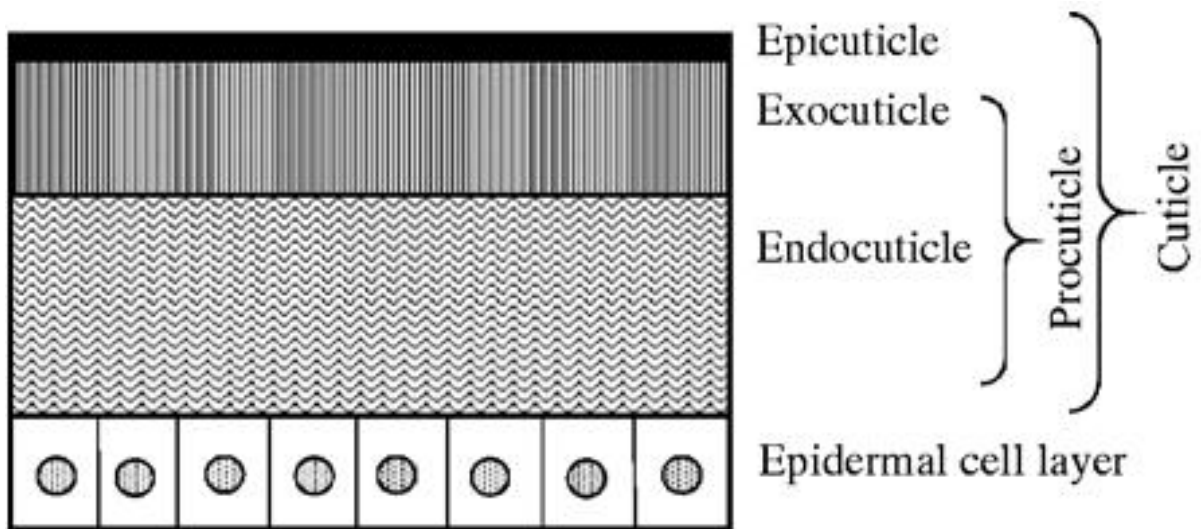


Figure 48: Schematic of insect cuticle and its components. Image from Barbakadze et al. (10)

Chitin is a long chain polymer of nitrogen-containing polysaccharide (11) and is found in many structures in the natural world such as exoskeletons of arthropods, and cell walls of fungi. Chitin, in its natural form is resilient and tough, but in arthropods, it usually gets embedded in a component of the cuticle called sclerotin. In most arthropods, chitin occurs mainly as a composite material component (12). The epicuticle does not contain chitin, however, the thicker procuticle does. The mechanical properties of the procuticle depend on the orientation and volume fraction of chitin nanofibers and the mechanical properties of an insect cuticle at the

microstructural level depend on the extent of interactions between protein and chitin (13).

Another way to look at cuticular properties is to characterize the purpose of the cuticle in the insect. Different joints and appendages have different properties. The cuticle serves a number of purposes ranging from acting as a sensory barrier to serving as a structural support for wings to forming various joints and attachment systems in the insect. For example, cuticle that surrounds and supports an insect's wings will have to have a very low modulus value and a high fatigue life. Cuticle around the leg joints of insects such as beetles has to have a low modulus value and high fracture toughness to aid in the springiness of their leg movements (13).

The cuticle can act as a sensory barrier for the insect and be a medium to transmit information between external stimulus and intrinsic responses (13). Campaniforms-the sensors of interest-for example are located on the outside of the socket. Their deformation determines their response to stimulus. What is important to note is how the material properties of the cuticle surrounding them would be different than the cuticle that's not very far from the area. That is, due to the campaniform sensilla's elliptical shape, the fibrous chitin is oriented in a specific way around the geometry, so that more deformation is experienced along one axis than the other (13).

When the cuticle is used for structural applications, such as joints, the properties are different. Cuticle of this kind must be able to undergo large deformation before failure, which means a high ratio of Young's modulus to tensile

strength (13). The storage of elastic energy is another function of the cuticle. Insects such as locusts and flea use this elastic storage capability of the cuticle to transfer energy while jumping, faster than the muscle (13). This kind of cuticle will again have different composition of chitin and resilin and will have different properties.

All this made selecting a specific set of mechanical properties for the cuticle very difficult. A second and a more significant issue was that properties of various insects were available in literature, but the cricket was not one of those insects. In the end, a range of general insect cuticle properties was chosen from Vincent et al (13), and that range was cross-referenced with specific properties of insects such as beetles (14), and spiders (15), and an average set was selected.

The cuticle properties used were:

$$Density = 1100 \frac{kg}{m^3}$$

$$Elastic Modulus = 5 GPa$$

$$Poisson's Ratio = 0.42$$

Hair

The mechanical properties of the hair were a bit more straightforward because the hair's shape, function and composition are not as varied as that of the cuticle. A range of values for the Elastic Modulus was obtained and then cross-referenced with the hair property of spiders, and an approximate value was established.

The density of the hair was close to that of the cuticle. However, the Poisson's ratio of insect hair was not available in literature. The elastic modulus of human hair was studied, and it was observed, generally, that human hair range of value was a bit higher than that of insects. The Poisson's ratio for human hair was available in literature. Because human hair was a bit stiffer, it was assumed that the Poisson's ratio of an insect hair should be a bit higher. The percentage amount by which the ratio should be higher was not known. Then, a study of treated human hair with conditioner was found, and the Poisson's ratio measured there was used for the Cricket's hair Poisson's ratio. It should also be noted at this point that the cuticle was assumed to have the same Poisson's ratio as that of the hair, so the value published above, was in fact, determined later. Also, two values for the hair's elastic modulus were used. One was assumed to be the same as that of the cuticle, and the second one was a slightly higher value.

The hair properties were:

$$\text{Density} = 1100 \frac{\text{kg}}{\text{m}^3}$$

$$\text{Low Elastic Modulus} = 6 \text{ GPa}$$

$$\text{High Elastic Modulus} = 9 \text{ GPa}$$

$$\text{Poisson's Ratio} = 0.38$$

Tissue

Once the first few analyses were performed, an area of soft tissue was modeled around the socket. This was done to simulate the actual environment of the

structure while it is stressed. The tissue acts as a damper. Again, properties of this specific type of tissue for a certain insect, Cricket, in this case, were very difficult to find. However, properties of soft insect cuticles were available in published journal articles. A range of properties for soft cuticles was found, and then the highest extreme of the range was selected for the Elastic Modulus. This was done because these properties were that of soft cuticle, not soft tissue, and “soft cuticle” can imply material with extremely low stiffness that does not fit the norm or range of tissue properties. Again, the property of most interest was the Elastic Modulus. The density and Poisson’s ratio were assumed to be the same as that of the cuticle and hair. The tissue properties obtained were as follows:

$$Density = 1100 \frac{kg}{m^3}$$

$$Range\ of\ Elastic\ Modulus = 1\ kPa - 50\ MPa$$

$$Elastic\ Modulus = 50\ MPa$$

$$Poisson's\ Ratio = 0.4$$

Design Modeler (Geometry Import)

The *SolidWorks* assembly was imported into the modeling interface of *Workbench*. The import, the first few times, went smooth. Next, a symmetry plane was applied to the entire assembly such that the short-axis of the structure now ran horizontally across the screen, while the long axis came out of the viewing plane. The application of the symmetry plane after the first few imports posed problems. This was because the default planes of *Design Modeler* (*Workbench*’s solid modeling

section) and that of the imported model did not align. The *SolidWorks*' part and assembly files had to be revisited again, and the assembly planes adjusted such that upon import, the geometric planes of the two software packages aligned.

A symmetry plane was applied to the model for a few reasons: first, to restrict the number of nodes and elements used while meshing. *ANSYS Workbench*'s educational license has a node limit of just over 200,000. Second, to enhance computation times, as not only was the model very complex, the deformation was predicted to be non-linear, which would add additional time; another factor that would make the simulation very computationally expensive were the various sliding contact regions. A third reason to apply the symmetry plane, of course, was to provide visibility so that the deformation nature and interaction of the hair base and socket could be observed.

Mechanical (Finite Element Set-Up)

After defining the necessary materials and their properties in *Engineering Data*, and importing the *SolidWorks*' assembly model in *Design Modeler* and applying a symmetry plane such that the structure was cut vertically along its short axis, the *Mechanical* application was opened. This application is the heart of *Workbench*'s *Static Structural* module and is essentially the pre-processor of the analysis.

Geometry

The first branch in the model tree was the processed geometry. A check was performed to ensure that all parts of the geometry were transferred well from

Design Modeler (DM). At times, due to overlapping surfaces or irregular geometry, the geometry files do not transfer as intended from the DM. For example, DM can import complex parts and to an extent, heal bad geometry like penetration of faces, or broken surfaces. However, the “healed” geometry does not always transfer well to Mechanical. The first few times, due to slight penetration of the hair base on the socket cavity on one side of the base, the geometry could not be imported successfully in DM. After reducing the mentioned small penetration, the geometry was successfully imported. But a symmetry plane could not be applied because according to DM’s default settings, sectioning the body at the symmetry plane would produce invalid geometry. This really meant that there were some intrinsic bad faces in the geometry. Again, the model was further modified in *SolidWorks* to repair these small faces.

A few times, after the successful geometry import, and a successful symmetry application, the model in DM seemed to have imported how it was designed in *SolidWorks* with not only the geometry intact, but the various parts transferred over as intended (for example, the hair model was split into three parts, and in some previous occasions, the hair model had imported as only a single body, or as two parts). However, when *Mechanical* was opened, the various “healed” parts by DM, or the splits in the imported geometry did not transfer over. Instead, many times, the parts were arbitrarily broken down into several smaller edges and faces, which were treated as solid bodies by *Mechanical*. This especially was a big problem when the damped model with the surrounding tissue was imported. Although, these

various faces could be suppressed and ignored from the analysis, doing so only led to either unconverged solutions or very inaccurate solutions. This was because wherever these small faces were suppressed, the mesh quality around them was extremely poor (this was difficult to see as these faces were internal ones, or near contact regions of bodies, and were well hidden) with the elements having very low aspect ratios. So, any load applied would deform these already skewed elements to a point where they would no longer be useful (degenerate) and the solution would stop. In cases, where convergence was achieved, these elements acted as stress concentrators and artificially increased maximum and minimum values of stress and deformations two, five, or even ten-fold. Figure 49 and Figure 50 show some of these bad faces and skewed elements in the damped model.

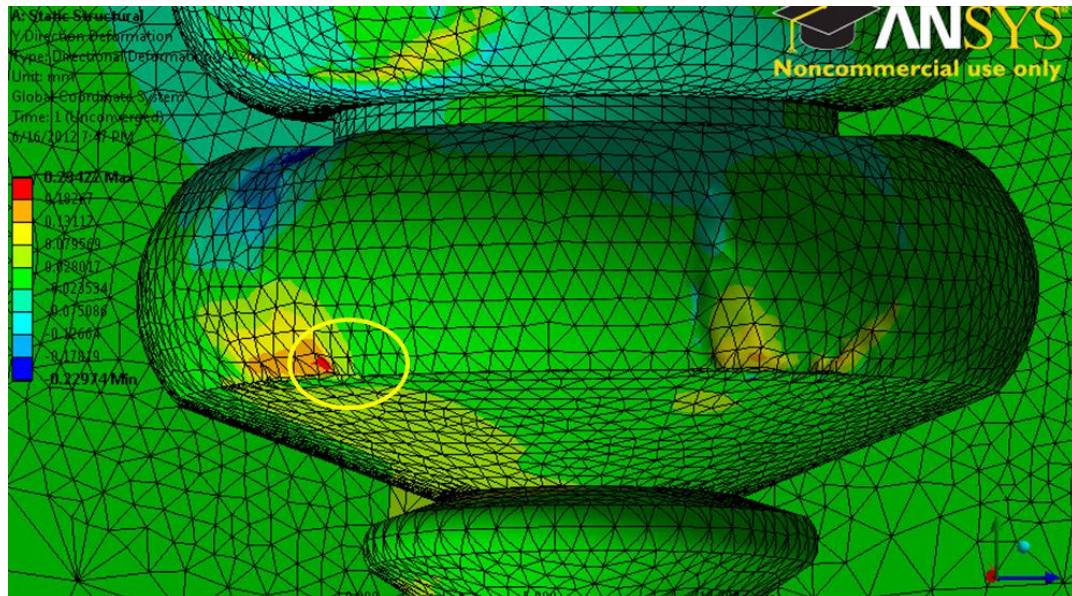


Figure 49: Due to slivered faces during the model import, bad elements formed.

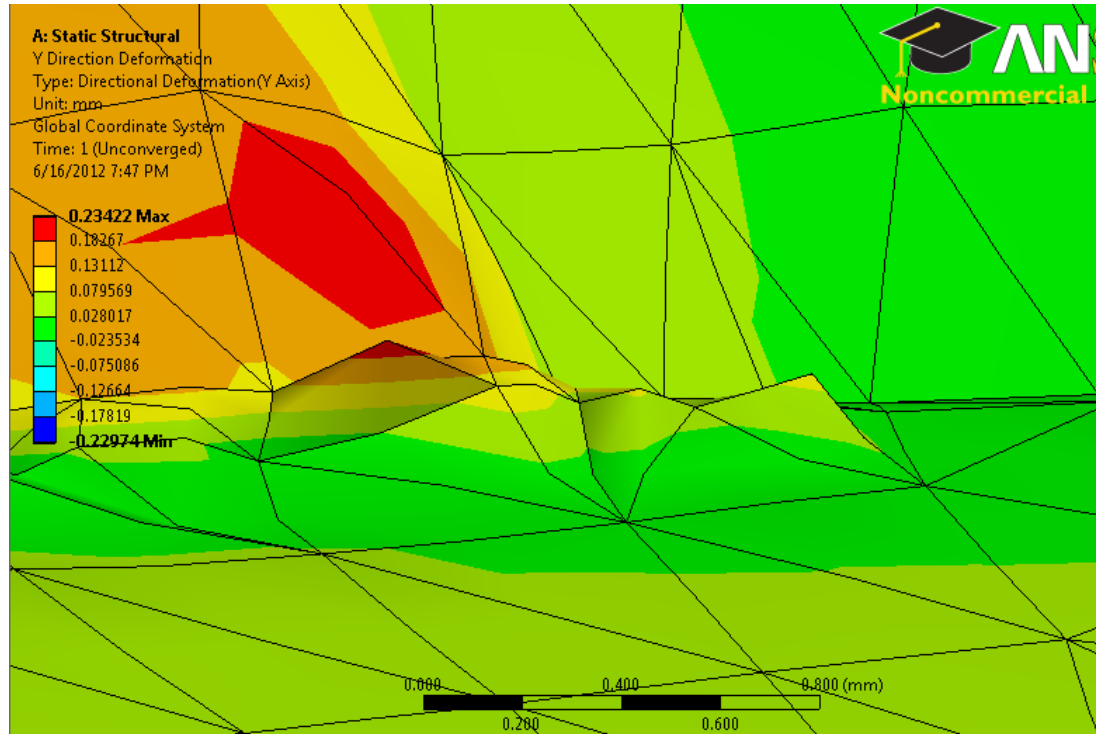


Figure 50: Zoomed in view of the marked yellow zone of Figure 49 showing some of the degenerate elements.

Once the geometry was imported into DM, and then successfully transferred to *Mechanical*, the material assignment was performed. *Workbench*, by default, assigns structural steel as the material to all geometries. From the previously defined materials in *Engineering Data*, the hair was assigned the hair material, the socket was assigned the cuticle material, and when the damped model was used, the surrounding tissue was assigned the tissue material.

Contacts

Workbench selects contact regions by default. This has to be checked thoroughly because the default setting has a low tolerance by which contact areas

are defined. So if two geometric areas are in close proximity, *Workbench* creates an automatic bonded contact region between the faces. Consider an arbitrary model shown below in Figure 51 and assume that the two bodies make contact at their respective bases. If you look at Figure 52 and Figure 53, it becomes apparent that the two faces in contact should be the red face of the upper body and the orange face of the lower body. However, when mated geometrically, *Workbench* will, at times, pick the yellow and green faces to be in contact as well, when they clearly are not as the base of the lower body is relatively wider than the base of the upper body. Therefore, to ensure that only the areas should be in contact, indeed are in contact, the contact region was thoroughly checked by hiding various bodies in the assembly so all contact and target faces could be identified clearly.



Figure 51: Two bodies that should make contact at the top body's bottom face and the bottom body's top face.

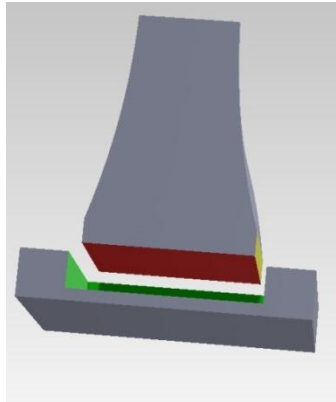


Figure 52: The red face of the top body should be the only contacting face, and not the yellow face to the bottom body's green faces.

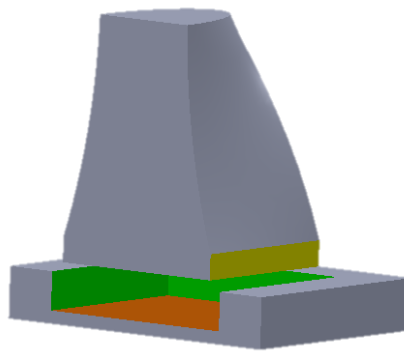


Figure 53: Again, the orange face of this body should be the only contacting face, and its green faces should not contact the upper body's yellow faces.

The actual structure should only have one contact region-that between the outside of the hair base and the inside of the socket base or cavity. This contact region selected by *Workbench* was kept while all the other ones were deleted. Figure 54 and Figure 55 show the contact and target faces below. This contact region was set to frictionless with the hair base faces as contact faces, and the socket base as target faces.

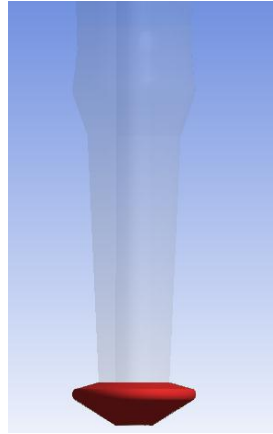


Figure 54: Contact faces on the hair body for the hair base/socket base contact region.

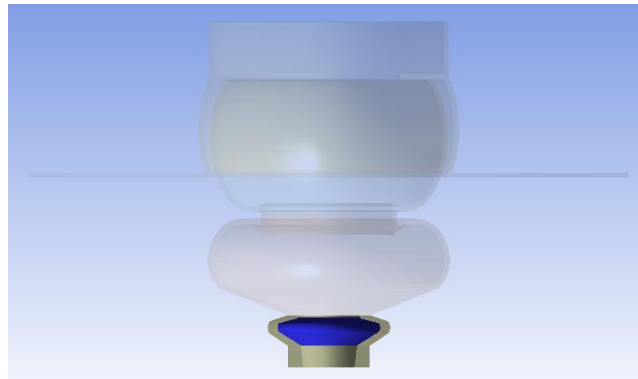


Figure 55: Target faces of the socket body for the hair base/socket base contact region.

In *ANSYS*, a frictionless contact region can only be applied to faces and as the name suggests, a zero coefficient of friction is set. Depending on the loading conditions, gaps can occur between contacting bodies. The separation occurs in the normal direction while sliding occurs in the tangential direction. Because sliding can occur, the solution is nonlinear as the contact area is subject to change for any given load application. Because the hair base and socket base have a tight fit, where they

are touching at all points of the restraining socket base, no separation could occur in any plane, so normal stress transferred between the two contacting bodies would be seen.

Under the “advanced” option, an “adjust to touch” interface treatment was applied to the contacting bodies. This option essentially overrides any slight penetration of bodies so that they are in contact, and also closes any small gaps, again, so the bodies touch. This option physically does not create or subtract geometry to induce touching, but manipulates the mesh in that area so common nodes are shared. Figure 56 shows two sets of contact pairs and how “adjust to touch” treats them.

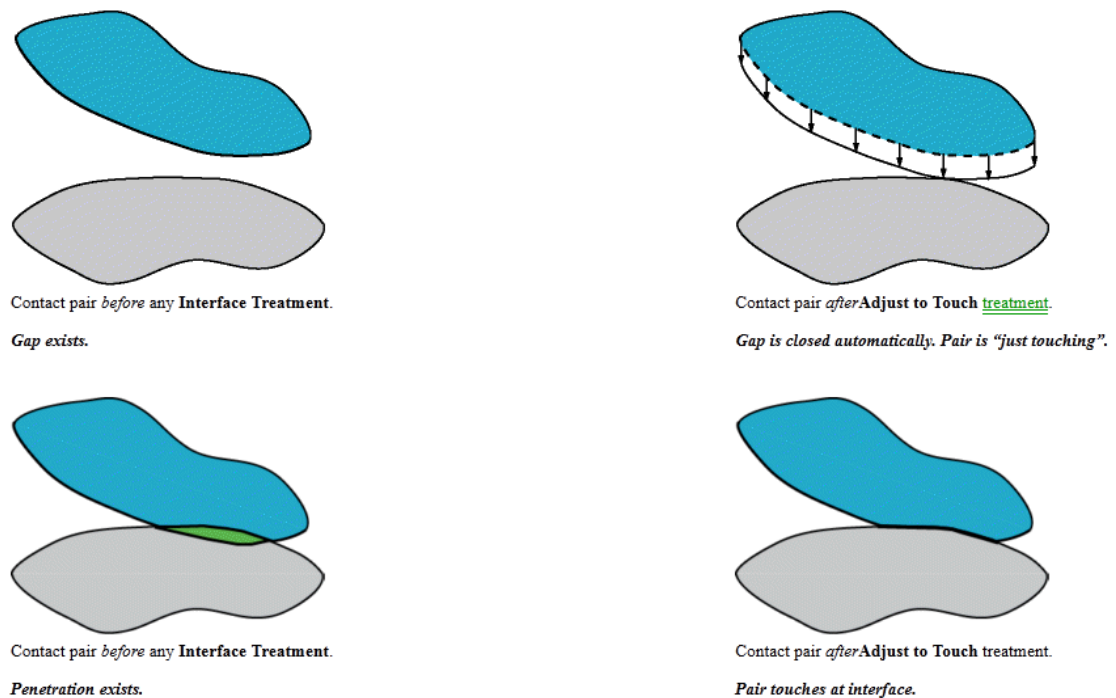


Figure 56: Interface treatment of bodies with small gaps and small penetrations. Image from ANSYS documentation. (16)

A second contact region also had to be defined. This one was not picked up by *Workbench* because initially, the two regions were quite far apart. But upon application of a high load, the two surfaces will contact. These surfaces were the bulge of the hair and the sweep of the socket's iris. The hair bulge was set as the contact body while the socket rim was the target. This contact region was also set to frictionless. These regions are visible in Figure 57 and Figure 58. To specify the contact search size, a spherical region called the pinball region was defined by a radius of 0.25 mm. Consider a contacting point approaching a target body-in such a case, the center of the pinball will be used as the contacting point for the nodes on the target face, and it is these nodes that are monitored by the solver (17). Nodes outside the pinball region are not. A pinball region was defined because initially, the bodies were nowhere near contact. Also, the mechanism of interest is the transfer of contact pressure and/or normal stresses between the hair and socket at contact but not penetration. To ensure control over the penetration, if any, the "Predict for Impact" setting was activated in the time step control option. This option simply reviews contact behavior at the end of each substep such as if the contact status has changed significantly or if any penetration has occurred (16). If any of the above has occurred, then the substep is reevaluated with the time step cut in half and the minimal time increment needed to discriminate change in contact behavior is also predicted. The contact stiffness was also set to be updated for each iteration based off of contact status and penetration along with underlying elemental stress at the end of each substep (16). By default, the contact stiffness is not changed at every

substep in *ANSYS* to optimize computing time; however, to enhance convergence, the stiffness of the pinball contact area was set to be updated for each substep based on the physics of the problem at that substep.

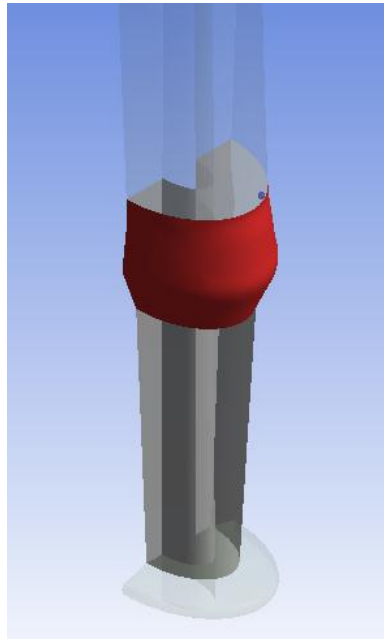


Figure 57: Contact faces on the hair body for the hair bulge/socket iris contact region. The pinball can actually be seen in blue near the top of the bulge on the right hand side.

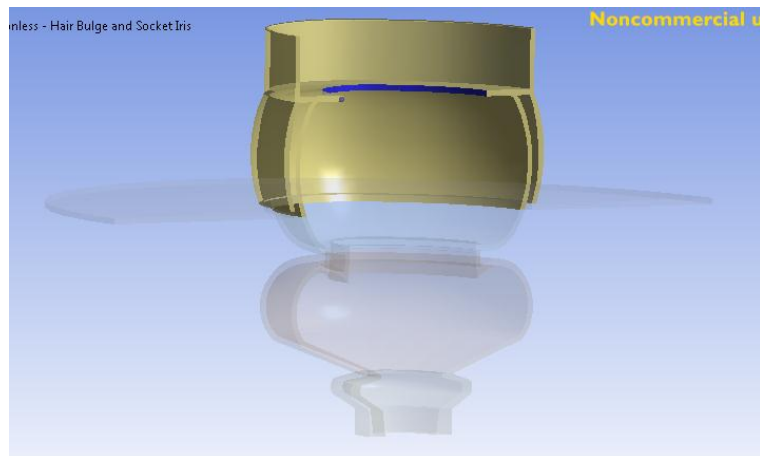


Figure 58: Target faces on the socket body for the hair bulge/socket iris contact region.

Mesh

To mesh with *ANSYS*, the order in which bodies or surfaces are meshed is crucial. The meshing in all applicable situations should be started with the smallest geometric area to the largest. This makes sense because it is easier for the mesh to expand from a smaller to a larger area, but going in reverse can cause collapsed vertices.

The assembly, before the import into DM, was split into eight parts in *SolidWorks*. The main reason to do that, as mentioned before, was to exert control over the meshing process. With the bodies split, the geometry could now be meshed accordingly. That is regions of interest could be meshed with great detail while other regions could be meshed with larger elements. Figure 59 below shows the split parts.

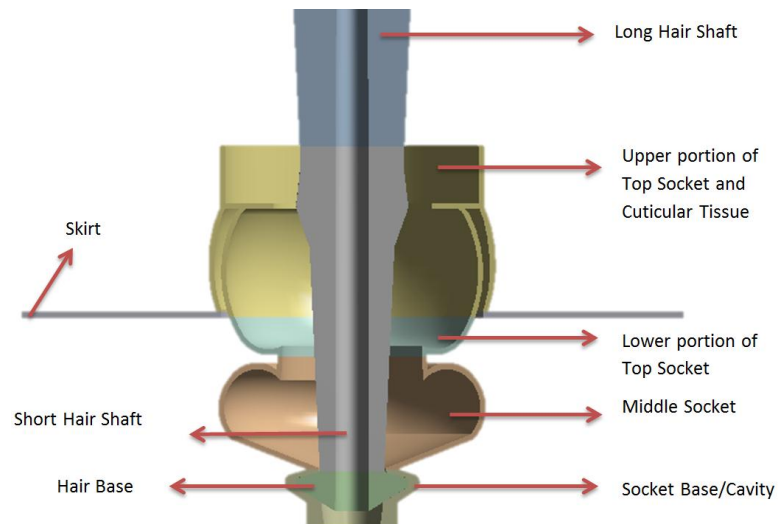


Figure 59: Total of eight split parts, three for the hair and five for the socket. Note that the various features as “iris” and “belt” are simply geometric entities in one or the other of these split parts.

Meshing is the first, and the most important part of a finite element simulation. Not only does the mesh have to be of superior quality, but also the appropriate element types have to be used. Furthermore, this superior mesh quality has to occur at the correct place in the model. The importance of the meshing process is further intensified when an analysis with topological, geometric, and even material non-linearities with large deformations is simulated. Before describing the meshing process, it is important to understand *Workbench's* meshing controls.

Global Mesh Controls: The default mesh setting is called *Physics*. This setting allows *Workbench* to control meshing parameters based on the physics of the problem. Following this field is the *Relevance* field. This option controls the *denseness* of the mesh, or how fine the mesh can be. A slider can be used to change this option from a minimum value of -100 to a maximum of 100. The three standard options for this field, if the slider is not used, are *Fine*, *Medium*, and *Coarse*, with relevance values of 100, 0, and -100 respectively. As expected, a finer mesh will, for all practical applications, give a more accurate solution than a coarser mesh, but the accuracy comes at a cost of additional computing time. Element Size is the next field in the global controls, and the name is self-explanatory. This option allows the user to specify an element size for the entire model that will be used for all geometric entities (edges, faces, bodies).

Shape checking is performed automatically by selecting the *Physics* default field. The criterion is as follows: the volume to the cube of the edge length ratio is compared for solid elements by a unitless metric in conjunction with the Jacobian

ratio (18). If the Jacobian ratio, which is computed at integration points, is greater than the mentioned metric or less than zero, shape failure will occur.

Initial Seed Sizing is another field that can be manipulated in the meshing process. This field controls the non-physical “bounding box” that the model is enclosed in, and understanding this field is not relevant in the current case (18).

The next field, *Smoothing*, aims to enhance mesh quality by moving node locations with respect to surrounding elements or nodes (18). The options for this field are Low, Medium, and High that control the smoothing iterations along a threshold metric. *Transition* controls the rate of growth of adjacent elements, and is the last field of importance in the global mesh controls (18). *Slow* and *Fast*, representing smooth and abrupt element growth transitions are the options that can be used in this field (18).

Local Mesh Controls: Assigning local controls to geometry usually overrides prior applied global controls. There are several fields that can be manipulated in this set of mesh controls, but the only ones that were relevant in the final meshing process are described.

Method control was the first branch. The default *Automatic* option was used for parts of the meshing. This option sweeps the selected bodies with elements if it can, otherwise options such as *Tetrahedrons* (an all tetrahedral mesh is created based on the choice of several sub-options such as *Patch Independent*, which again, has many local options that can be manipulated) are used (19).

The second option was called sizing control. This option, as the name suggests, controls the mesh sizing either by element size which allows a direct input of a positive value, or by sphere of influence which allows a mesh sizing to be applied within the boundaries of a sphere that is defined by

- A local coordinate system whose origin should be the center of the sphere
- Sphere center
- Sphere radius
- Element size

An alternative to entering an element size is choosing the number of divisions. This option only applies to edges however. If a vertex is elected, then the only Sizing Control option available is the sphere of influence where the vertex is the center of the sphere.

The edge behavior option for edges, faces, and bodies can be set to *Hard* or *Soft*, where the former means that the number of division cannot be changed by the meshing algorithm and is fixed, hence, the chances of mesh failure increases (19). The latter option allows changes to be made to the number of divisions by the algorithm.

Contact sizing was explored next. The sphere of influence is described above. Contact sizing generates these spheres internally to ensure that elements of similar size are created between contacting geometry such as face-to-face, or face-to-edge.

Mesh Generation: Exploration of the various mesh control options led to the setup described below. First, the contact region between the hair bulge and socket iris was assigned a contact sizing. The contacts size was defined by the element size option with a value of 0.5 mm. This contact area was also geometrically the smallest in the model. The second mesh control defined again was contact sizing through element size assignment of 0.5 mm. This contact region sizing was defined as the contact was frictionless and capturing the sliding was an important feature. Not much normal stress transfer was predicted initially when both the hair and socket were assigned the same material properties, but once the hair was assigned a stiffer material, a good distribution the normal stress transfer between the hair base and socket base in the plane of motion was predicted (and eventually captured) and a finer mesh near the contact became more important.

Next, bodies were meshed and a body sizing control was used. The first four selected body parts were the socket base, hair base, hair shaft to just past the bulge, and the middle part of the socket. These were chosen as one group because the deformations here were of interest, and also because they were connected at the base of the structure as one continuous body. Also, the second set of contacting faces that were assigned the contact sizing were parts of the hair and socket bases. The element size was set to 0.5 mm with the element behavior set as “soft.” Recall that this kind of element behavior means that the number of divisions per edge is not fixed and can be changed by a meshing algorithm employed by *Workbench* to accommodate for conditions of surrounding nodes and elements. Also, the element

size of 0.75 mm was chosen as it is small enough to capture and discriminate data and is small enough so that a smooth transition between some of its faces that were meshed with smaller contact elements and its remaining faces are smooth.

The next body meshed was the lower portion of the top of the socket and this was also meshed by defining an element size of 0.75 mm. This body could easily have been meshed with the previous set of bodies but was selected separately because of how it connected to the top part of the upper socket. That is, by meshing it separately, triangles could be used as the elements, since the previous four parts were meshed with triangles. If this part was meshed together with the other four parts, then it would still be meshed with triangles but the part that had to meshed next, the upper part of the top socket, would be “swept” by quadrilaterals by *Workbench*. This has to do with the meshing algorithm the software uses. For uniform element shapes throughout the socket, triangles in this case, the body was meshed as described above. The next body that was assigned an element size was the “skirt” and this was assigned an element size of 1.25 mm. The final body sizing defined was for the upper part of the top socket of which the iris feature is a part. This body was also assigned an element size of 1.25 mm, as it connected to the “skirt” which had the same element size. The only part for which no specific mesh control was assigned was the hair shaft past the hair bulge. The automatic default *ANSYS* mesh would be used for this part. For pictures of the mesh, refer to Figure 60, Figure 61, Figure 62, and Figure 63.

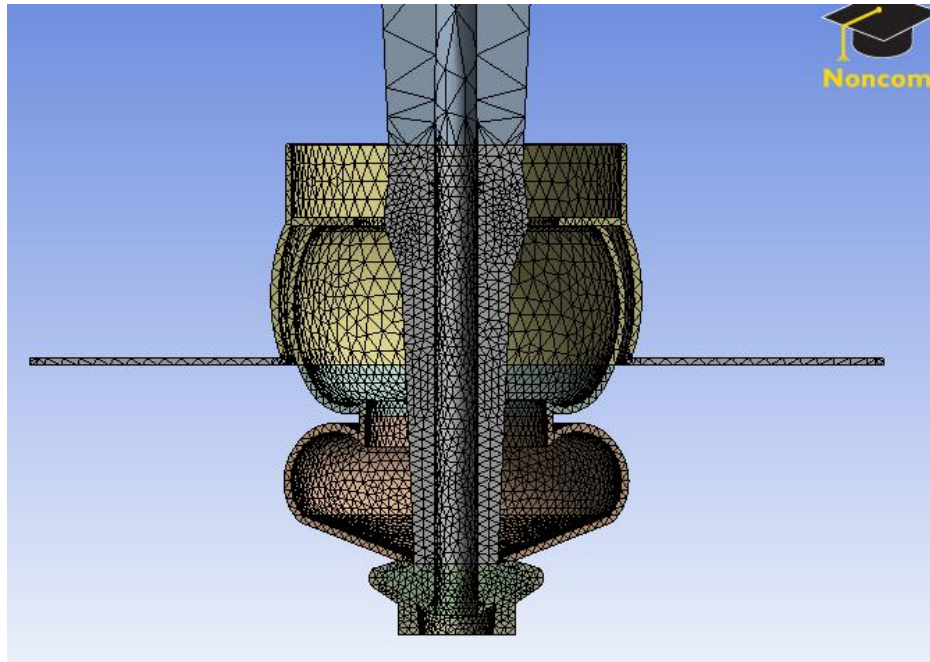


Figure 60: Mesh at the symmetry plane

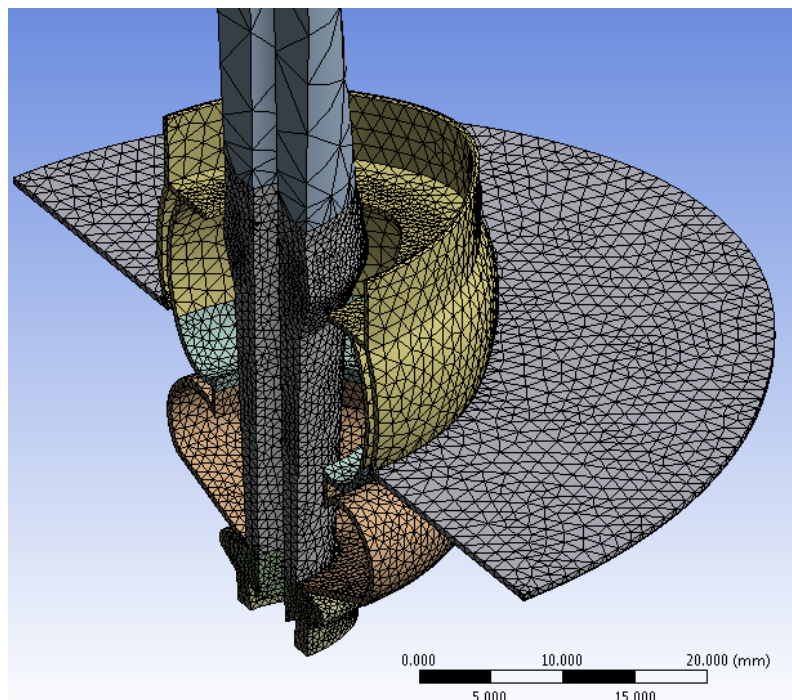


Figure 61: Mesh of the skirt feature. The finer mesh at the iris and hair bulge is also visible.

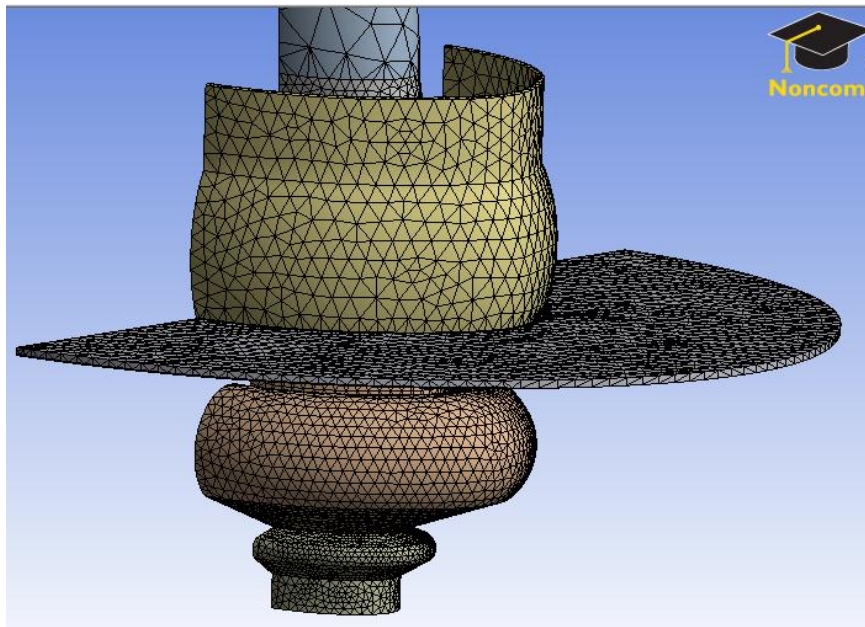


Figure 62: Mesh of the back faces

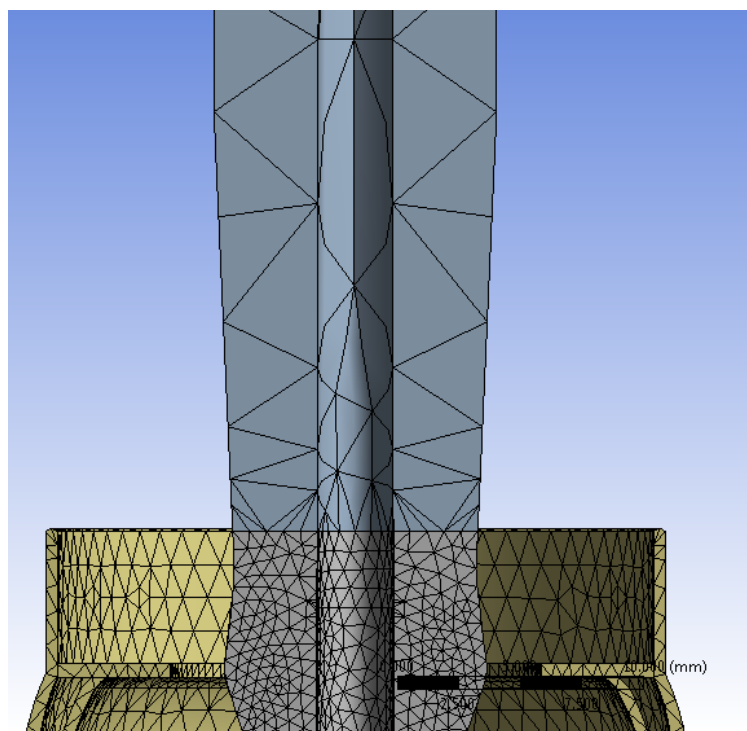


Figure 63: The hair was meshed using very coarse elements.

Mesh Quality: The educational license of *ANSYS Workbench* that was used has a node and element number limit. 200,000 is the node limit, so as soon as the mesh was generated successfully, the statistics were checked. Table 1 shows that the total number of nodes used was well below the limit.

Good mesh quality is paramount for any finite element analysis, especially a complex one with various non-linearities. To ensure that the mesh quality was good, the following steps were taken. First, a thorough visual inspection was performed and areas with poor mesh quality were identified. Once the obvious problem areas were identified, the geometry was reopened in the DM, and faces or edges were merged where applicable, or healed where appropriate to get rid of any visible slivers or collapsed edges in the geometry.

Next, the skewness of the mesh was determined. Skewness is a mesh metric that checks quality of the mesh. *ANSYS* documentation states that a maximum skewness value of below 0.75 indicates an acceptable mesh. There are two ways of calculating skewness.

1. Equilateral Volume Deviation

$$Skewness = \frac{Optimal\ Cell\ Size - Cell\ Size}{Optimal\ Cell\ Size} \quad \text{Equation 4}$$

This approach only applies to tetrahedrals and triangles. The optimal cell size is an equilateral cell with the same size as the circumradius. Figure 64 shows a schematic of the cell sizes.

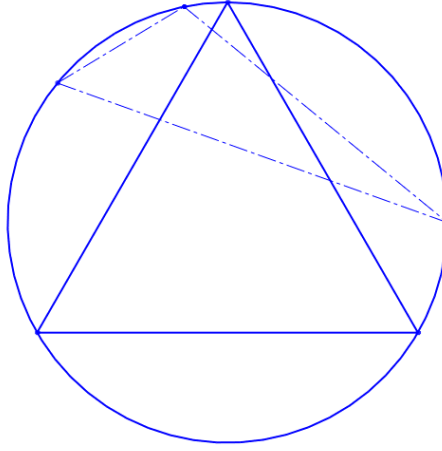


Figure 64: The triangle formed with the solid lines in an equilateral triangle and the optimal cell size. The dashed triangle is any given element.

2. Deviation from a normalized equilateral angle

$$Skewness = 1.0 - \max \left[\frac{\theta_{max} - \theta_e}{180 - \theta_e}, \frac{\theta_e - \theta_{min}}{\theta_e} \right] \quad \text{Equation 5}$$

where θ_{max} = largest angle in face or cell, θ_{min} = smallest angle in face or cell, θ_e = angle for an equiangular face or cell (so 60° for a triangle, 90° for a square). This approach applies to quad-based elements and is used for prisms and pyramid elements.

Table 2 2 shows the correlation between skewness and cell quality according to ANSYS.

Table 1: Mesh Statistics

Nodes	128798
Elements	72759
Mesh Metric	Skewness
Minimum	0.0015987
Maximum	0.9997641
Average	0.3810110
Standard Deviation	0.2318756

Table 2: Qualification of cell quality based on skewness values

Skewness Value	Cell Quality
1	Degenerate
0.9-<1	Bad (sliver)
0.75-0.9	Poor
0.5-0.75	Fair
0.25-0.5	Good
>0-0.25	Excellent
0	Equilateral

Table 1 shows that on average, the element quality was “good.” More importantly, it should be noted that elements with high skewness values were

relatively few in number. Figure 65 below shows the distribution of the elements and skewness values.

Also, Figure 66 and Figure 67 show that the elements where the quality was below acceptable were distributed in areas of little interest in the simulation, such as the hair shaft. During the import from *SolidWorks*, due to the complex geometry, there were some small faces on the “skirt” that imported as slivers, and they too contributed to some higher skewness values. Figure 68 shows elements with a skewness value of 0.2.

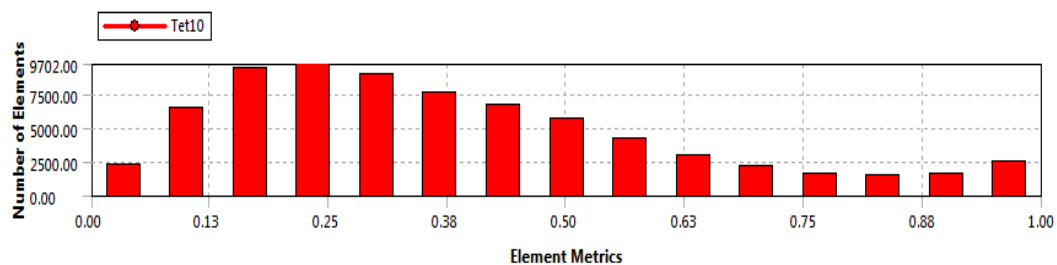


Figure 65: Number of elements plotted against the skewness.

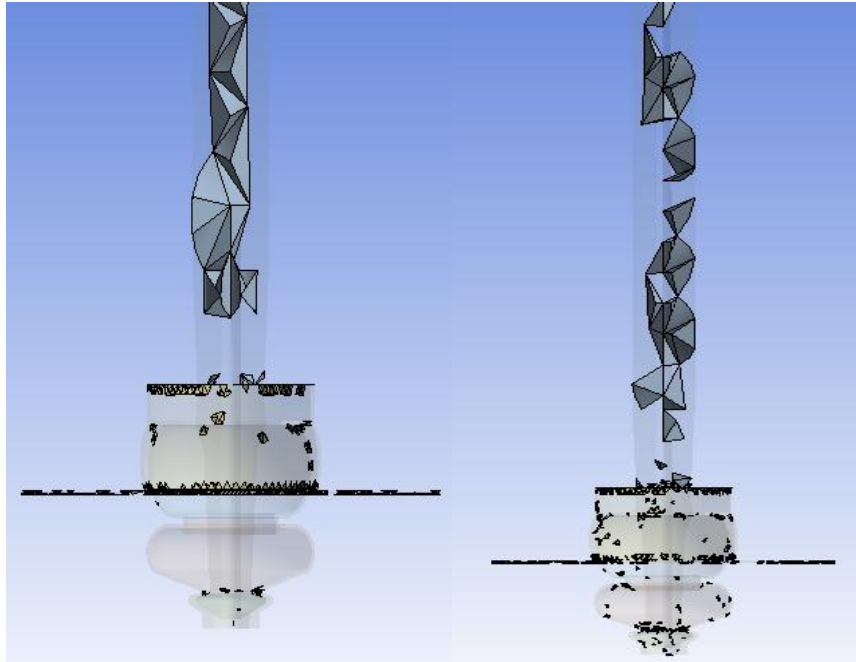


Figure 66 and Figure 67: Elements with skewness values of above 0.75 (left: values from 0.75 to 0.88 and right: values from 0.88 to 1.0). Very few elements have poor skewness numbers and they are distributed in areas that are not of interest to the study.

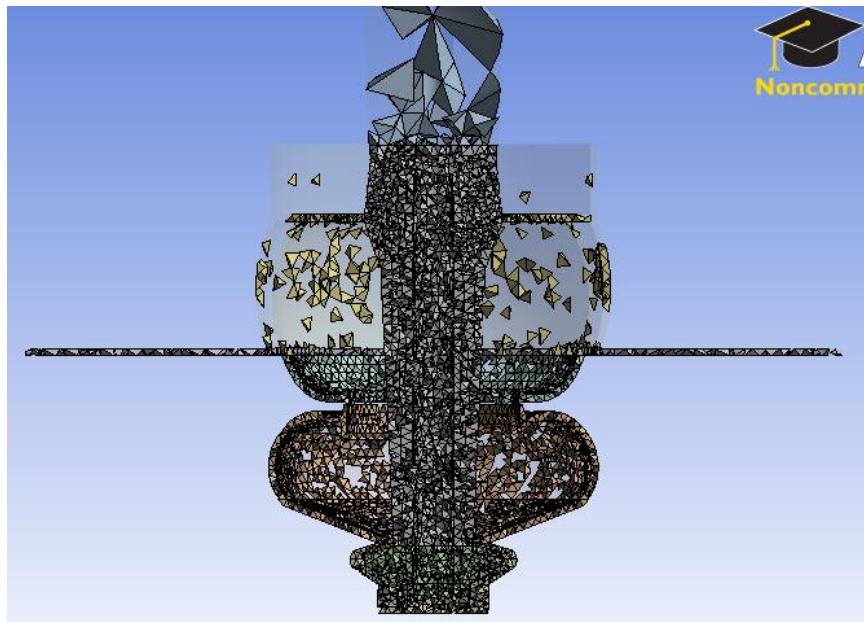


Figure 68: Elements with skewness value of 0.2.

Once the quality of the mesh was confirmed by checking the skewness values, a structural error sub-branch under the post-processor area of *Mechanical* was added. The stress contour plots produced by *Workbench* are by default “averaged.” A unique stress is calculated for an element at each node, and the default option simply averages the nodal stresses across the element and any geometric discontinuities (but not bodies). *Workbench* can also display the “unaveraged” or nodal stresses. The difference between these two types of stresses is called structural error and the value of this object can be used as an indicator of global as well as local mesh adequacy. In general, smaller values are desired, and the finer the mesh, the smaller these values will be because the nodes are closer to one another. Once the simulation was ran, the structural error turned out to be extremely small (Figure 108 in Appendix A), further affirming the quality of the mesh.

Element Type: The two main solid elements used for meshing were *SOLID186* and *SOLID187*. Both these elements are higher order 3-D elements that have quadratic displacement behavior and are well suited for non-uniform or irregular meshes. Each node has three degrees of freedom-translations in the nodal x, y, and z directions. Also, these elements are capable of handling large deformations, which was part of the analyses. *SOLID187* is a 10 node element while *SOLID186* is a 20 node element. Figure 69 and Figure 70 show the structure and options available of these two elements and Figure 71 shows the 3D nature of the elements in the mesh.

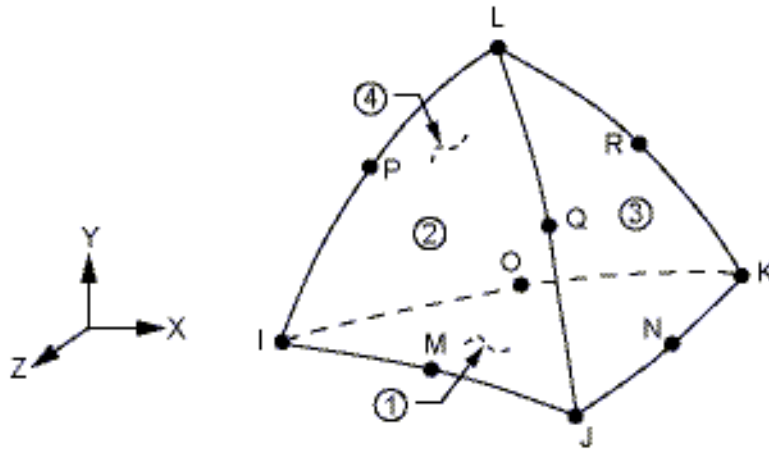


Figure 69: *SOLID187*-a 10 node element with three degrees of freedom at each node (displacement in the three coordinate directions). Image from *ANSYS* documentation. (16)

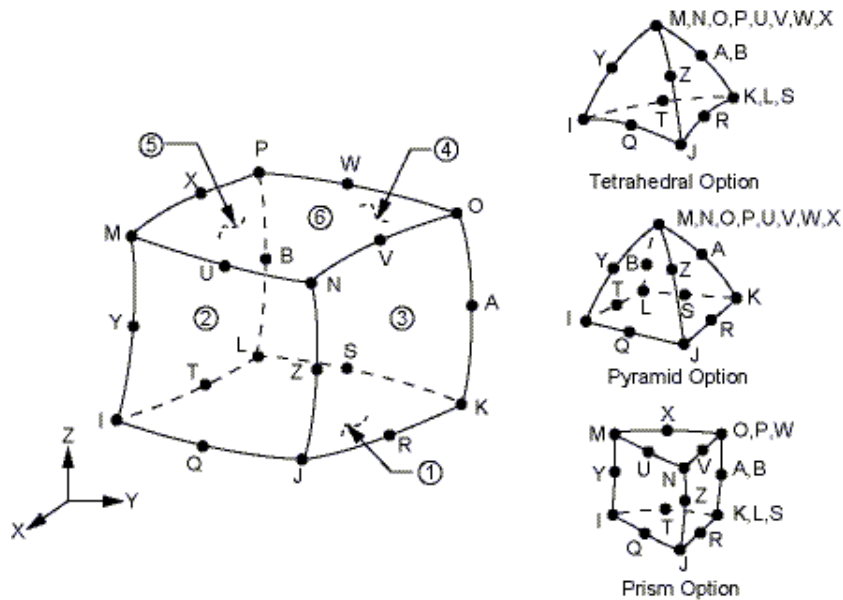


Figure 70: *SOLID186*-a 20 node element with three degrees of freedom at each node (displacement in the three coordinate directions). Image from *ANSYS* documentation. (16)

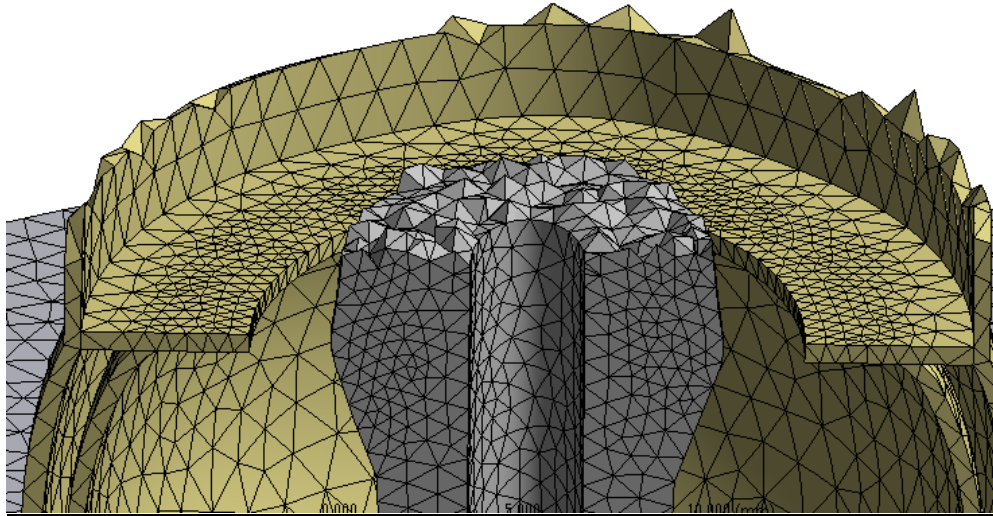


Figure 71: Cut plane employed to show the 3D nature of the elements.

Analysis Settings

Large Deflections: The first setting that was enabled was *Large Deflections*. Enabling this option changes the mathematical model of the solver a bit by adding extra terms in the strain equations. By default, the classic infinitesimal strain or small strain theory is used by *ANSYS*. An underlying assumption of the small strain theory is that the undeformed and deformed states of the body are identical. The finite strain theory deals with cases where large rotations and strains are present and the deformed and undeformed states of the body are considerably different. Small strain theories are suitable for many engineering applications where large bodies made of stiffer materials as concrete and metal alloys are concerned, such as bridges, or building columns. However, when “softer” or non-linear material as

elastomers, viscoelastic gels, or soft tissue are tested, the finite strain theory must be used.

The Lagrangian finite strain tensor can be written as:

$$E = \frac{1}{2} (\nabla_x \mathbf{u} + (\nabla_x \mathbf{u})^T + \nabla_x \mathbf{u} (\nabla_x \mathbf{u})^T) \quad \text{Equation 6}$$

Or in index form,

$$E_{KL} = \frac{1}{2} \left(\frac{\partial U_K}{\partial X_L} + \frac{\partial U_L}{\partial X_K} + \frac{\partial U_M}{\partial X_K} \frac{\partial U_M}{\partial X_L} \right) \quad \text{Equation 7}$$

The higher ordered terms are neglected in the small strain theory and the equations become:

$$E = \frac{1}{2} (\nabla_x \mathbf{u} + (\nabla_x \mathbf{u})^T + \nabla_x \mathbf{u} (\nabla_x \mathbf{u})^T) \approx \frac{1}{2} (\nabla_x \mathbf{u} + (\nabla_x \mathbf{u})^T) \quad \text{Equation 8}$$

$$E_{KL} = \frac{1}{2} \left(\frac{\partial U_K}{\partial X_L} + \frac{\partial U_L}{\partial X_K} + \frac{\partial U_M}{\partial X_K} \frac{\partial U_M}{\partial X_L} \right) \approx \frac{1}{2} \left(\frac{\partial U_K}{\partial X_L} + \frac{\partial U_L}{\partial X_K} \right) \quad \text{Equation 9}$$

The same simplification can be made to the Eulerian finite strain tensor.

Line Search: The *Line Search* option in the analysis settings was also enabled.

To satisfy the convergence criterion of any given solution, the solver employs, by default, the Newton-Raphson Method. Figure 72 shows a graphical illustration of this method, where the slopes of the straight lines represent a tangential stiffness and the goal is to drive the straight lines to the actual response curve by reducing

the force residual below an established threshold value, at which point, the solution is said to have converged (20).

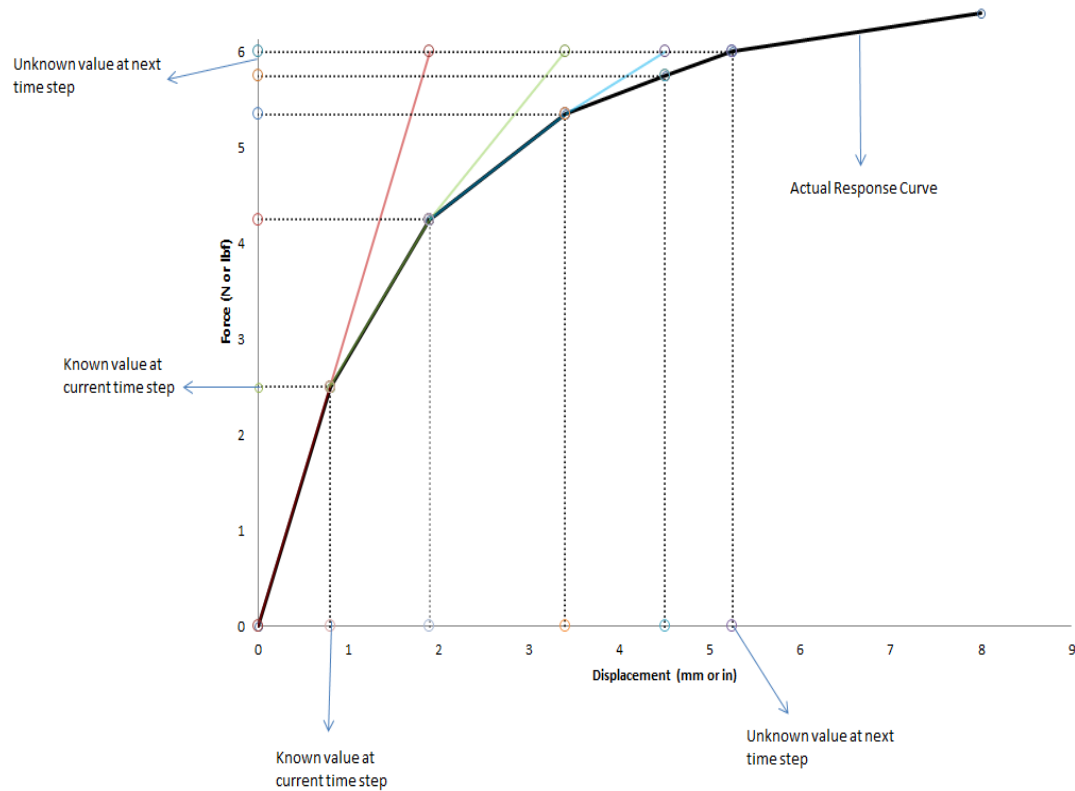


Figure 72: Newton-Raphson Method. Image inspired from Lee (20).

Now take a look at Figure 73, and notice that the response curve is “concave up”, and highly non-linear. The calculated displacement in one iteration can overshoot the goal quite a bit, and hence, a numerical technique—line search—that scales down the incremental displacement is enabled (20). Line searching can assist with convergence, but it is computationally expensive.

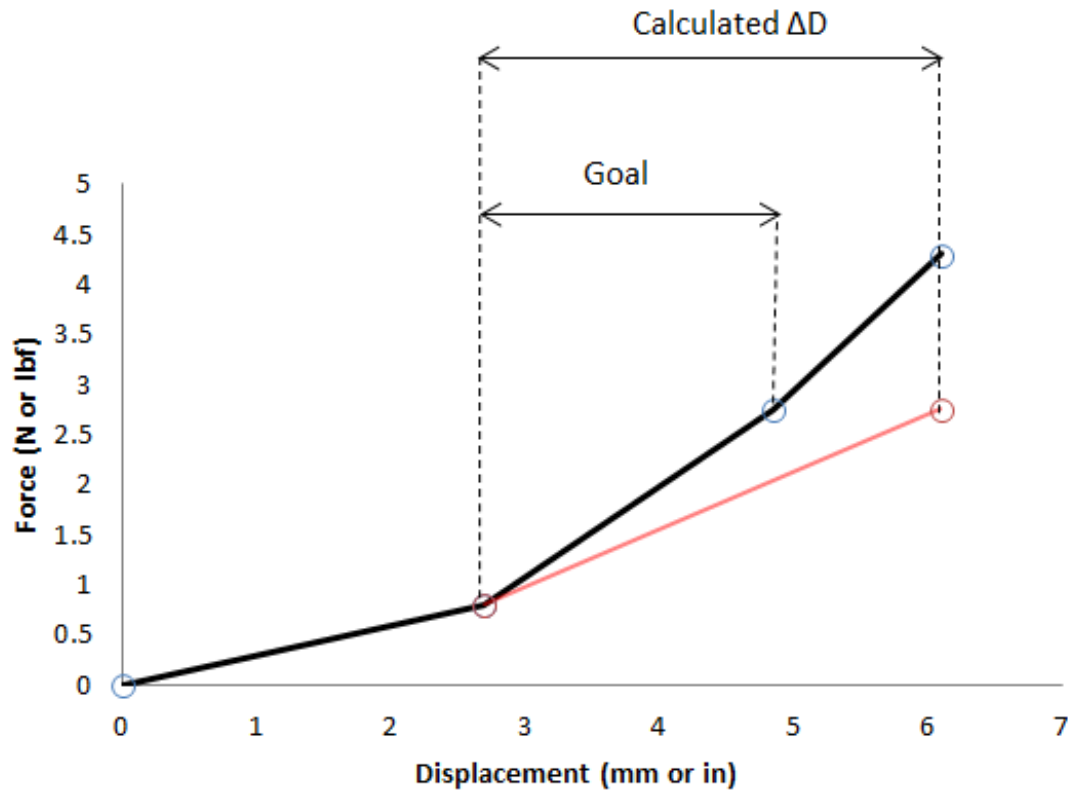


Figure 73: Line Search Method Schematic. Image inspired from Lee (20).

Substeps: A final setting changed to ensure convergence was that the number of loading steps was changed from the default 10 to 20. This meant that the same loading conditions would be applied over a greater number of steps; hence, a smaller load per step could now be achieved. This was primarily done to increase the resolution of the results set and also to ensure that no elements got too distorted by application of a large load in this non-linear simulation. This process again adds to the computation time significantly.

Boundary Conditions

A fixed support was added to the circumferential face of the skirt (Figure 74). A fixed support in *ANSYS* is a clamped support. This skirt feature is cuticular tissue that extends out and connects, eventually to the surrounding tissue of the adjacent hairs. The length of this tissue, in the insect is quite long as the distance between two hairs is anywhere from 100-300 microns. However, the length of the tissue in the model is about 20 mm, which is at least 5 times smaller than the actual 100 mm length (recall that the model is scaled up by a 1000 to begin with, and hence the actual length would be a 100 mm, and not 100 microns if the tissue were modeled with its real dimensions after scaling). A shorter length was used to conserve the number of nodes used. The stress and deformation results near the tissue are adjusted accordingly for discussion purposes.

The bottom faces of the hair base and socket base were constrained by a displacement condition (Figure 75). If the displacement is defined by the Cartesian components of a face, then a non-zero input for a given direction means that the face will retain its shape but move relative to its original location based on the magnitude and direction entered. The x-direction displacement (recall that in the model, the x-axis goes in and out of the viewing plane and represents the long axis of the structure) was set to zero, and the other two directions were left free to move, rotate, or deform. This represents the actual motion constraint in the insect, as the hair moves perpendicular to the long axis, and the displacement in along the long

axis direction is considered negligible (and set to zero in the finite element analysis setup).

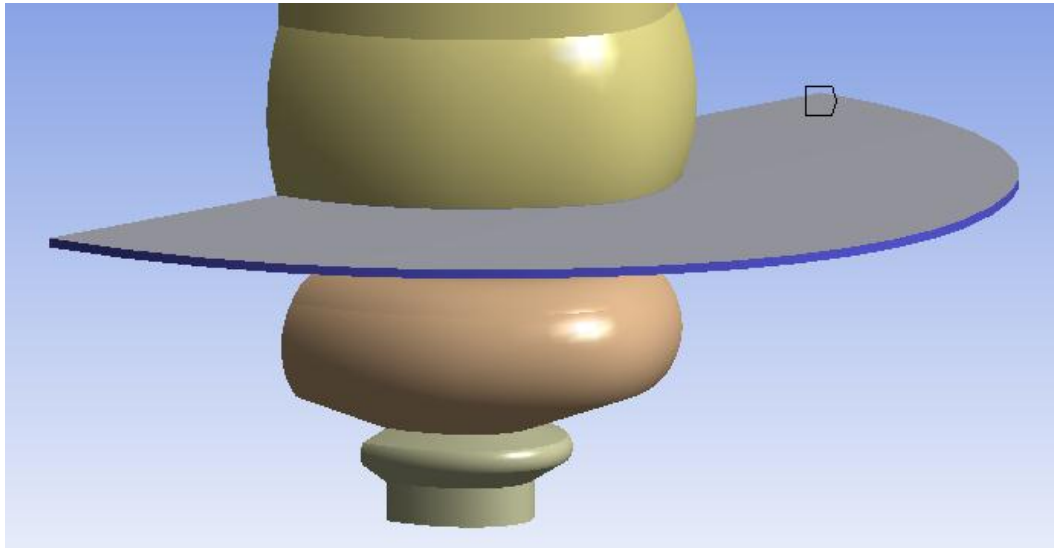


Figure 74: The outside face of the skirt was fixed or clamped. This can be seen in blue.

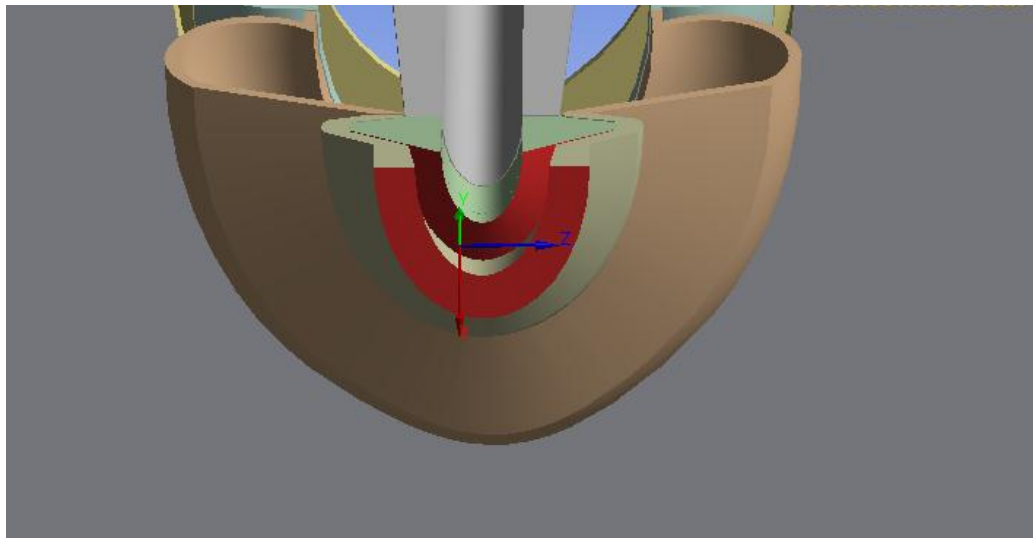


Figure 75: The bottom faces of the hair base and socket base seen in red here were constrained to not move along the short (x) axis only.

Loading

Eventually, two sets of loading conditions were used (not together). The first was a triangular line pressure distributed along the hair length. There were two small obstacles that had to be overcome for the load application: first, it was not possible to enter a triangular line pressure directly in *Workbench*, so it was decided to apply several unequal loads on the hair shaft symmetry edge, with the highest load at the top, and the smallest at the bottom of the hair near the cercus. This was because the velocity profiles of air currents over the hair length are not uniform, and are highest at the hair tip and go down to zero near the cercus. The second problem was the way the model was imported by *Workbench* did not allow the application of several loads. That is, the entire hair shaft was composed of two edges with the import, therefore only two loads could be applied at that point—one to each edge. The fix to this was very simple. DM was opened and the two edges were split to a total of 10 edges using DM's built in geometry tools. Once this was done, a total of 10 line pressures were applied to the model (Figure 76). The values were 1.6, 1.4, 1.2, 1.0, 0.8, 0.6, 0.4, 0.2, 0.05, and 0.025×10^{-3} N/mm. A line pressure, instead of a total force was applied because the theoretical force equations were normalized by the length, so for easier comparison, a line pressure was used. A second reason was that the model was scaled up by a factor of 1000, so the length was as well scaled up. Since the actual geometry was much smaller, the total force would be different for both cases, but the force per unit length would be the same and easier to compare.

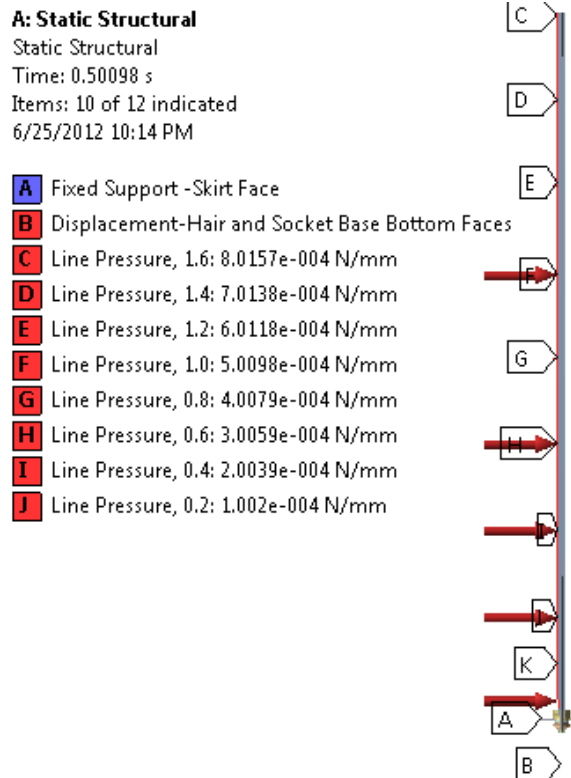


Figure 76: The line pressures were distributed triangularly with the highest being at the hair tip, and the lowest (close to zero) neat the cercus.

The second loading condition used was displacement control. A vertex on the edge of the hair shaft was picked and it was assigned a specific initial displacement (Figure 77). The results obtained were then compared to the load control setup. Since the primary goal of the study is to understand how the socket deforms and interacts with the hair, the actual force the hair experiences is a secondary concern. The magnitude of force required to deflect the hair enough such that it contacts the socket wall is a good number to have, and in fact, was used in the load control setup, but that is more of a check than a direct study. The primary area of concern is the striking of the hair against the socket wall, and also the hair-socket interaction. This

striking can be done indecently of an external load if a displacement is specified. This gives the analyses far greater control and un-biasness in results. Also, the results are more accurate in the displacement control method because the exact velocity profile along the hair shaft is only an approximation, and the line pressures are derived from the velocity distribution.

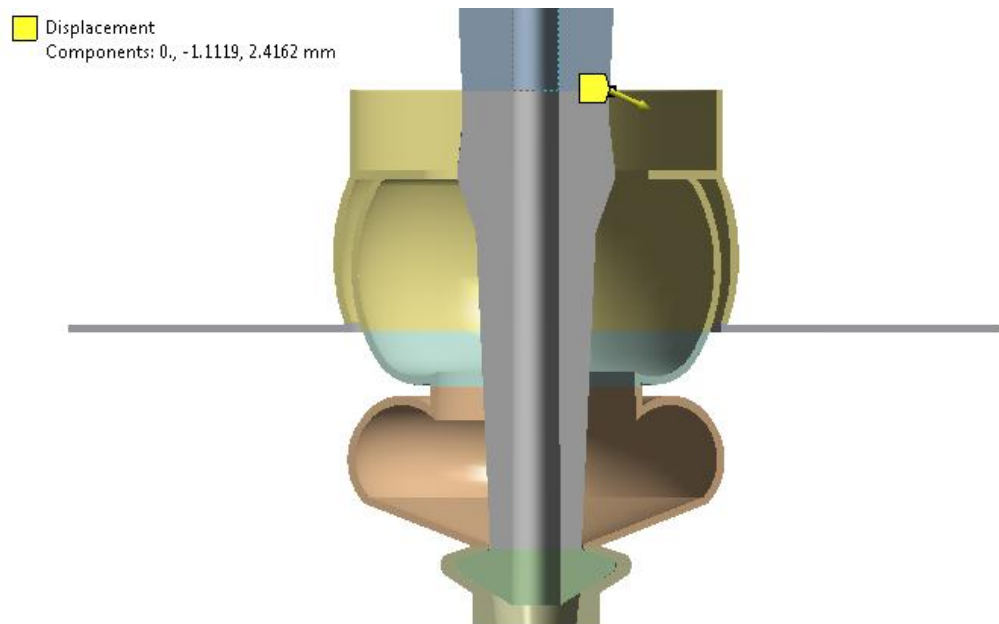


Figure 77: Displacement control method. The vertex to which an initial displacement was applied can be seen near the yellow tag.

RESULTS

Before beginning this section, the reader is notified that all contour plots created in the post-processing section (most of which are discussed in this chapter) are presented in Appendix A.

Solution in the Long Axis Direction

The first result set studied after the solution converged was the deformation. The deformations are the degree of freedom solution of the finite element analysis and are usually the most intuitive. Studying the deformation of the structure along the long-axis (x-axis of the model that goes in to the viewing plane) revealed that the socket acted like a balloon. The side of the socket where the hair had deflected was in compression as it had “come out” of the viewing plane while the other side of the socket got pushed further back in along the long axis. Until the contact of the hair bulge and the iris, the deformation on either side of the socket was symmetric, but after the contact, this changed a bit. For the middle part of the socket, after the contact, the socket deformed an order of magnitude less in the direction of hair deflection as compared to the other side. This at first seems counterintuitive as the normal force imparted by the hair would deform the socket more but it has to be noted that the middle part of the socket is not close to the contact area at all, and the contact primarily affects the top part of the socket, which it precisely did. Post contact, the top part of the socket in the direction of hair deflection deformed a bit more compared to the other side. To give the deformation numbers some more

context, the x-direction strains were studied. As mentioned, post-contact, there was asymmetry in the deformation, or in this case, strain values. This asymmetry while significant (factor of 2-4) was not as drastic as that seen in the middle socket where the difference between the values was 10-30 fold. The socket cavity does not really deflect or deform in the x-direction. This was the most expected result because 1) it is even further away from the contact region than the middle socket and the effects of that contact are barely felt, and 2) one of the displacements boundary conditions is such that the bottom face of the socket cavity is fixed along the long-axis of the structure, so not much deformation should have been seen in any case. While the socket cavity and its outer faces do not deform much, the inside faces of the cavity where the hair base fits do push outward (out of the screen direction) a bit. The “coming out” of the structure from the viewing plane was also evident looking at the x-direction normal stress contour plot where a majority of the structure had negative values (x-axis goes in the viewing plane) illustrating compressive stresses. One unexpected result was the formation of compressive stresses at the iris where the hair had contacted. The compressive stresses were expected to develop at the iris contact region in the z-axis or direction of hair shaft contact and a tensile stresses, due to Poisson’s ratio effect, were expected to occur in the x-direction. Also, just like with the deformation, the inside face that is in the direction of hair shaft movement compresses much more than what the other side of the inside belt face tenses. This effect is reversed when the outside belt face is observed.

The hair deformation along the long-axis is even more straightforward than the socket's movement. The hair simply deflects without deforming. The hair, as noted earlier, 1) is restricted to move along the short axis only and the very small movement along the long-axis is ignored in this analysis, and 2) cannot move along the long axis not only because its base is constrained such, but also the edge loading is applied only along the short-axis. However, one interesting feature was observed- when the back cylindrical surface of the hair shaft was observed, almost all along the hair length, there was a vertical partition where one side moved out of the viewing plane and on into the viewing plane. The socket also exhibited similar features. The magnitudes of these deflections were a 100 to 1000 times smaller than the average deflection values of the hair shaft. This "split" deflection where part of the hair shaft moved in and part moved out can only be attributed to rotation of the structure along the vertical axis. It should also be mentioned that this rotation was not a result of the contact because the hair shaft was displaying the same characteristics prior to contact. One explanation is that *ANSYS* adds weak springs where necessary in the model while solving to ensure no rigid body motion occurs. This rotation may have been a result of that (recall the *SOLID186* and *SOLID187* elements do not support rotation degrees of freedom).

Solution in the Vertical Direction

The y-axis deformation and strain values were the easiest results set to understand. Since the hair base and the socket base fit tightly with one another,

when the hair deflects, the socket base deflects and pushes the “non-deflected” side of the structure upward while the deflected side gets pushed downward. The further away any geometry is from the hair and socket base, which act as a pivot point, the more that geometry gets deflected. This is simply because the greater distance means a larger moment arm and therefore a greater moment. The skirt is the furthest geometry away horizontally from the pivot in the plane of motion but recall that the outer face of the skirt has a fixed boundary condition, so the maximum vertical or y-axis deflection is not seen at the outside of the skirt but somewhere near the center of the feature. Deflection of the skirt feature is of importance because of the campaniform sensilla embedded on it. Not considering any other factors at this point, the deflection of the skirt is significant and any sensors should easily be activated, especially given the fact that these sensors are very receptive.

The magnitude of deflection is not only based on the moment arm but also the force. The widest part of the middle socket defects the most in the socket structure as it is close enough to the pivot point vertically that the movement force can be transferred easily and far enough horizontally for a long moment arm to be formed. The greatest deflection of the entire structure occurs at the hair tip and this is expected. This is simply a result of the greatest moment arm in the structure. This deflection, while quite large for the structure, is not very much for the hair tip. The elastic y-axis strain at the hair tip can be assumed to be zero (it is about 10,000 times smaller than the average strain for the structure). This is again because the

hair deflects and does not deform. However the highest y-axis strain seen on the structure occurs where the cuticular tissue connects to the skirt but in the direction opposite of hair motion. This result is unexpected and quite rightly so. These maximum and minimum values the region experiences are artificial because of stress concentrators present in the geometry at the region. Recall from Chapter 3 how a few faces imported as slivers while using DM and could not be entirely repaired. As mentioned before, those faces were a small part of the merging geometry between the cuticular tissue and skirt feature. So, the next set of extreme values for y-axis normal strain was studied and they occurred on either side of the belt feature. This makes physical sense. The belt feature, as initially postulated, acts like a spring and separates the middle and top parts of the socket. In fact, it would be more accurate to think of the belt as a series of linear springs joined in an elliptical path. When the hair deflects, the inside of the spring in the direction of motion gets compressed and the corresponding side on the other side stretches. However, a very crucial detail became evident as the structure was studied from other angles. As the hair moves in one direction, and the belt (that separates the top and middle parts of the socket) gets compressed on the inside, a certain motion occurs of the middle socket. That is, when the hair shaft moves in a direction, the hair and socket bases move in the opposite direction; because the socket base moves in the opposite direction of hair movement, so does the middle part of the socket to which it is attached. So now there is a situation where the hair is moving in one direction and the belt area closest to the direction of movement compresses, but

at the same time, the same belt area has to stretch because the middle part of the socket moving away from it tenses it. So as the inside compresses on one side, the outside tenses, and the reverse of this combined phenomena occurs on the other side of the socket (the non-deflection side). It is helpful to think of the previous elliptical series of springs in parallel with another such spring series. Figure 78 below illustrates this mechanism.

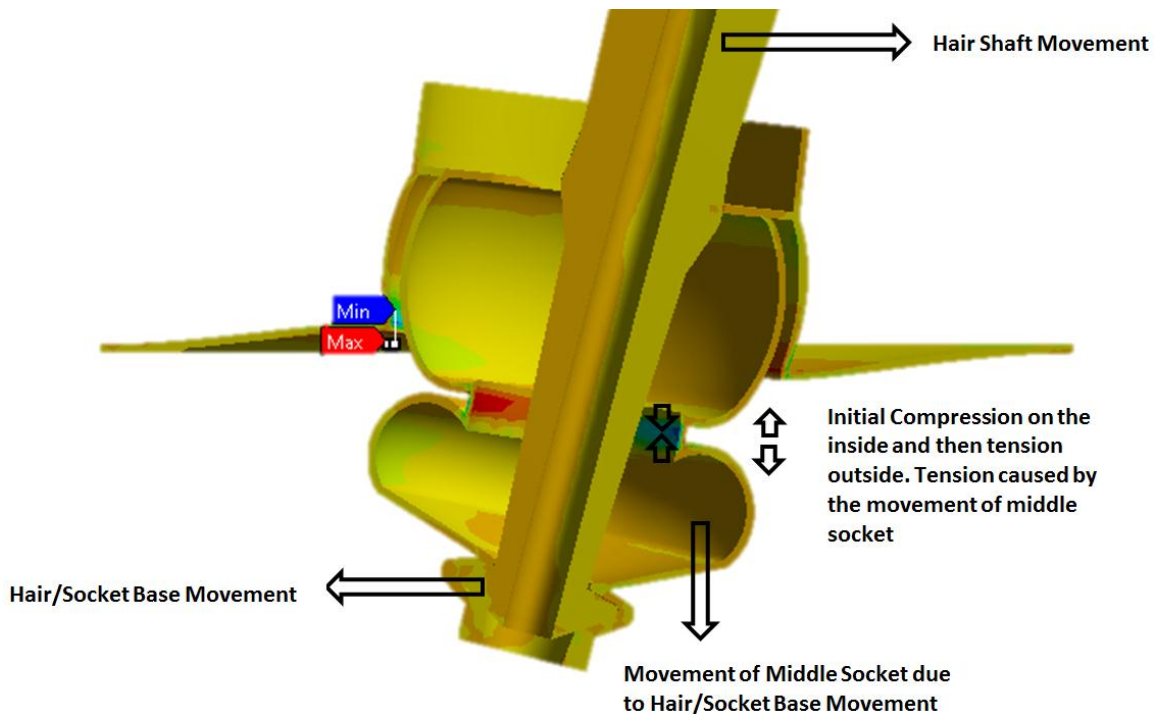


Figure 78: A schematic of the compression and tension of the belt feature in the direction of hair movement.

The normal stresses in the y-direction are also very easy to understand. The half of the hair model (quarter of total hair) that is moving toward the iris to make contact is in compression whereas the other half is in tension. This distribution is

not exact but from the hair base to near the hair tip act in this compressive-tensile manner. This can be compared to beam bending where the side half “away” from the transverse load is in tension and the side closest to the loading is in compression. The exception is the hair tip which is in pure tension in the y-direction (so moving upward). The socket stresses in the reverse manner of the hair, or at least the inside of the socket does. Because of the socket’s balloon-like shape, any deformations, strains, or stresses it experiences are not consistent with how they act on the inside versus the outside faces (that is one regime is in tension while the other in compression). The belt feature is a very good example of this where this tension-compression tandem is very consistent. Again if the normal y-direction stresses of the belt are studied, four zones immediately show up and a good way to divide these four areas is to think of the geometry in terms of two zones: the half of belt in the direction of hair shaft movement and the direction away from the movement. Now each belt half experiences both tension and compression depending on the above zones and which faces (inside or outside) of each of the zones are considered. If the inside face of a belt zone is compressed, then the corresponding outside or back part of the face will be in tension. Recall from Figure 78 that compression and tension are caused by socket movement in two different directions.

Solution in the Short Axis Direction

Looking at the deformations and strains along the short-axis of the structure (z-axis of the model and direction of hair deflection) made physical sense. The

bottom of the structure consisting of the hair and socket bases deflected in the opposite direction of the hair shaft motion. A gradual deflection gradient was observed throughout the structure with the bottom moving in the opposite direction of hair motion followed by the middle socket. The deflection changed direction towards the hair motion at the top surface of the skirt feature. After the hair bulge contacted the iris, the deflection changed directions again with the region below the skirt and above the belt moving opposite the hair shaft motion. At the final load step, the gradient had changed such that from the base to the middle of the belt, the structure moved in the opposite direction of the hair shaft, and from mid-belt above, the deflection and hair shaft motion were in the same direction. Studying the normal z-direction strain, again, gave a more accurate picture. While the middle of the socket was moving away from the direction the hair shaft was traveling in, it was stretching and compressing in the plane of motion. The half of the middle socket (and a quarter of the total as the simulation was being run on a half-model already) that was away from the hair shaft deflection was stretching as it moved away and the half that was deflecting in the direction of the hair shaft was actually compressing in the movement plane. The minimum strain (lowest negative, but highest magnitude) occurred on the outside edge of the belt in the direction of hair shaft motion while the highest positive strain magnitude was found near the inside edge of the skirt in the direction opposite of shaft motion. The normal stress the structure experiences along the short axis acts similar to the normal stress experienced along the vertical y-axis. The half of the structure that is closer to the

hair shaft movement direction compresses while the other half tenses. The difference between this behavior and the y-axis normal stress behavior is that in the current configuration, the hair and the socket experience the same kind (compressive or tensile) stress, and this normal stress direction is also consistent throughout the socket thickness (so both the inside and outside faces are either compressed or tensed). This applies to the entire socket but not the belt feature, which acts similar to previous cases where compression is seen in the hair movement direction and compression on the other end, and the reverse stress combination occurs on the outside belt face. The skirt area closest to the cuticular tissue in the hair movement direction compresses and a gradient is formed outward in the radial direction starting from this initial compression and going to tension. This other half of the skirt which is away from the hair movement experiences the reverse where the inside is in tension and a maximum compression occurs at the outer edge fixed boundary condition. Of course, at the contact area, a high compressive stress is seen at the iris and a slightly lower compressive stress on the hair bulge.

Combined Solution

The total deformation plot labels the maximum and minimum values of displacements at the expected areas. The hair tip moved the most while the fixed support of the skirt face did not move at all. What is of interest is the total socket deflection as the hair's deflection follows a consistently increasing gradient. The side

of the socket (especially the top) where the hair moves has a higher total deflection value than the other side. This higher number does represent deflection of the top socket till the contact, post which, the deformation effect gets added on.

The areas of interest of the equivalent elastic strain of the structure, ignoring any artificially enhanced values and numbers based on pure deflection, are the belt and skirt features both of which had higher strain values caused by deformation. Depending on which direction of normal stress was observed, different areas of the structure were experiencing extreme loading conditions, and to get a overall, normalized picture, the von-Mises or equivalent stress contour plot was studied. The von-Mises plot confirmed that the desirable areas of study of the structure-belt feature and surrounding geometry, skirt and surrounding geometry, and the hair bulge and iris features and the areas close to them-were indeed the most interesting to study as they experienced the greatest overall deformation and stress. All the other areas were very neutral and acted as support geometry.

There were two contact regions set up for the analysis as described in Chapter 3. The parameters that were monitored were the contact status, contact pressure, sliding distance, and penetration. When the contact status contour plot was observed, two important results came forth. First, the upper half of the hair base in the hair shaft direction slid out of contact with the corresponding socket base edge, and was able to transfer normal stress on the bottom edge of the socket base (Figure 79). A similar process occurred on the other side (opposite to the hair shaft deflection) but in reverse where the lower half of the hair base slid out of

contact, though the separation was small compared to the case described. This is probably because the lower part of the socket base past diagonal edge is thicker and provide more support. The second result observed was that there was some sliding of the hair base on the inside socket cavity wall along the long axis. This can explain why the rotation phenomenon that was originally attributed to the weak springs assigned by *ANSYS* earlier in this chapter occurred.

The second result set monitored with the contact regions was the contact pressure. Based on the observations from the contact status above, a high pressure value was expected between the contacts in the hair movement direction near the bottom of the socket cavity and a comparatively smaller pressure value opposite the hair movement direction near the top of the socket cavity (as the gap was smaller there). This is exactly what was seen, with the higher pressure value hovering around 40 kPa and the lower value on the other side around 12 kPa. Along the long axis where the sliding occurred, pressures of up to 22 kPa were seen. The rest of the hair and socket base contact region had negligible pressures. The 40 Pa pressure mentioned was a bit artificially enhanced as it occurred near an edge (Figure 80) but the surrounding ranges were 20-35 kPa.

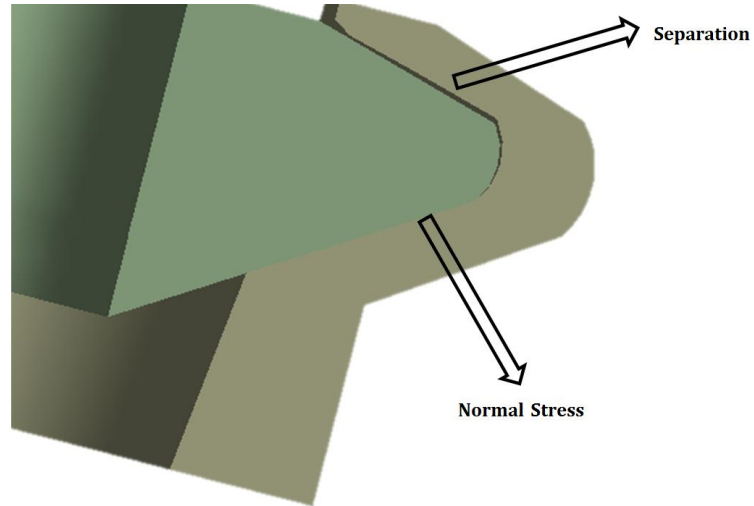


Figure 79: The hair base slides out of contact and cannot transfer a stress to the upper part of the socket base, but it does to the lower part.

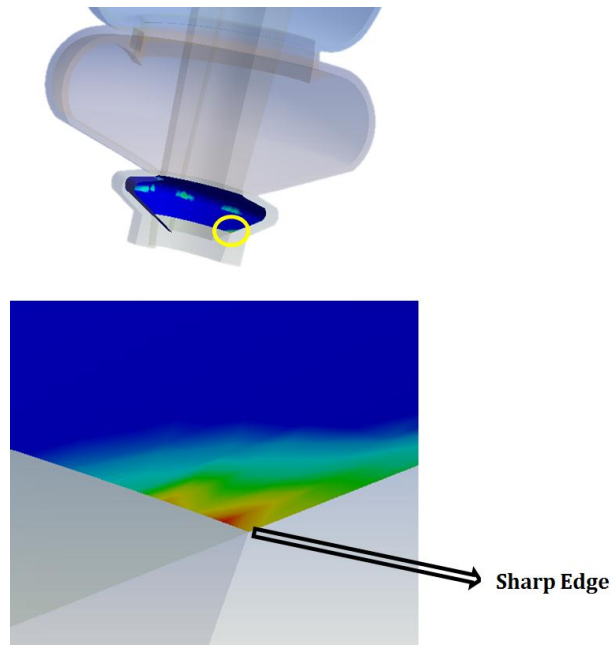


Figure 80: Top image shows the area where the highest pressure occurs at in the hair and socket base contact area. The bottom image is a magnification of the area marked by the yellow circle showing the sharp geometry that will enhance the pressure value artificially. The surrounding contours, however, do show that the pressure is in fact large, just not as large as 40 kPa.

Also of great interest was the pressure at the hair bulge and iris contact. The pressure value reached the maximum at the contact area (over 46 kPa). This pressure transfer is important, of course, because it is a derived result of the deformation of the iris, and the surrounding cuticular tissue, and eventually, the skirt. While deformation and stress results of the skirt are available from the previous result sets discussed, and even the von-Mises plot can be studied and these numbers can be backed out, this contact pressure plot discretizes the pressure gradient in great detail and is helpful for further detailed inquiry.

The third contact parameter recorded was the sliding distance. Recall that one of the hypotheses (and aim was to quantify) of the study was that once the hair contacts the iris, it will slide along the iris face. This is what was observed from the contour plot of this result set once the contact occurred. The maximum sliding distance of the hair on the iris, at the last load-step, was about 0.184 microns total. This distance is quite large as the thickness of the iris is only about 0.5 microns. Physically how the geometry is set, this sliding makes sense. The hair bulge is a smooth rounded face that makes the sliding easy. The iris is modeled as a rectangular notch but in reality, the edges are not sharp, but rounded as well. The significance of this sliding is not fully understood but a few explanations are provided in the conclusions section of this chapter.

The final contact set parameter that was tracked was the penetration (of the contact and target elements). This was done only to monitor the model from a finite element stand point and had no direct significance on the working mechanism of the

structure. If penetration occurred despite the contact and target elements set the way they were (refer to Chapter 3 for more details), then it would be evident that something was not correct with the setting. The maximum penetration occurred near at one of the contact areas of the hair bulge and iris contact, and the value was very small (0.0046 microns, which is more than a hundred times smaller than the contact element size of 0.5 microns as described in Chapter 3)) and would have no effect on any result set.

During post-processing the results, a path that ran down the hair base diagonally was defined. This can be seen in Figure 81 below. This path was constructed to approximate for the ecdysial canal. A new coordinate system was defined such that one axis (y-axis) was collinear with the path, another axis (z-axis) was normal to the path and hence the y-axis in the horizontal plane, and the third axis was, of course, orthogonal to the two created axes and went into the viewing plane. The stresses along the path in the newly defined coordinate system were calculated next. The conclusions section explains the reason for this path creation and computation of stresses.

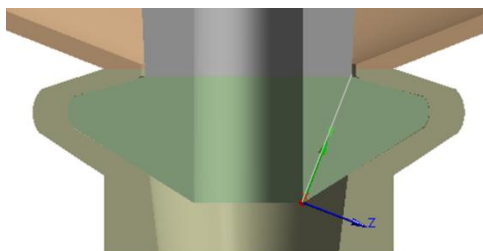


Figure 81: The path to represent the ecdysial canal can be seen by the light gray diagonal line running down the hair base.

DISCUSSIONS AND CONCLUSIONS

Hypothesis Evaluation: No Gap
Between Hair Base and Socket Base

Drag Force Calculation

All the experiments that have been performed on filiform hairs have had an air current as the forcing function. In the insect's physical environment, the hair deflection is caused by air currents. A line pressure was applied to the static finite element model as the external force. This force had to be approximated (a conversion of the velocity to a drag force it would project on the hair had to be performed. Refer to Appendix B and Appendix C for more details) because an input velocity cannot be applied as an external loading condition in *Workbench's* static structural module. According to Shimozawa et al (4), Imai in 1980 came up with an expression to calculate the drag force per unit length acting on a solid cylinder caused by a uniform air current perpendicular to the axis of the cylinder using Oseen's approximation of the Navier-Stokes's equation. This equation is:

$$F_D(V, D) = \frac{8\pi\mu V}{(2S + 1)} \quad \text{Equation 10}$$

where

$$S = \ln\left(\frac{8}{Re}\right) - \gamma \quad \text{Equation 11}$$

Re is the Reynolds number

$$Re = \frac{VD}{\nu} = \frac{\rho VD}{\mu} \quad \text{Equation 12}$$

γ is Euler's constant (0.577 here), ν is the kinematic fluid viscosity ($1.5 \times 10^{-5} \text{ m}^2/\text{s}$ at 20°C), μ is the dynamic fluid viscosity ($1.82 \times 10^{-5} \text{ Ns/m}^2$ at 20°C), ρ is the fluid density (1.213 kg/m^3), D is the cylinder diameter (5.75 micron), and V is the perpendicular air current velocity (85 mm/s). The fluid here is of course, air and the physical properties are obtained from ESSOM (21). Kämper and Kleindienst (22) stimulated a filiform hair 1050 microns in length of *Gryllus bimaculatus* (the field cricket) with oscillating air currents and found that at a velocity of 80 mm/s, the hair contacted the socket wall. The hair model used is 1100 microns in length (scaled up to 1100 mm), so a slightly higher air current value of 85 mm/s was assumed for the hair and socket contact. So if an 85 mm/s wind was perpendicular to the hair shaft's long axis, the drag force per unit length (approximate) using Equation 10 above would be $4.107 \times 10^{-9} \text{ N/mm}$ (Appendix C for the calculations).

To compare results, a common basis between the actual hair and the model had to be established. A direct comparison of quantities such as displacements, wind speeds, and stresses could not be directly compared as the model was scaled up by a factor of 1000. Many times, the actual quantities of interest such as force and displacement can simply be multiplied by the scaling factor to obtain the corresponding value for the model, but this direct scaling does not apply to fluids. Because a fluid domain in the form of air is one the primary means of actuation of the hair, the scaling of parameters had to be considered carefully.

In elementary fluid dynamics, non-dimensional analysis is employed to determine corresponding values of interest for a model or prototype, given

conditions for either one. The easiest way to perform a non-dimensional analysis is by using the Buckingham Pi Theorem, where dimensionless groups are created by choosing the desired repeating variable, and then the values are compared. Appendix B presents a quick overview of the Buckingham Pi Theorem (BPT) and outlines the relationships that are used below.

The velocity needed for the hair and socket contact in an actual hair is known (85 mm/s) and to calculate the corresponding velocity for the scaled up model, the pi group formed by using the Froude number has to be used:

$$V_{model} = V_{hair} \sqrt{\frac{L_{model}}{L_{hair}}} \quad \text{Equation 13}$$

which gives the required velocity for contact of the scaled up model as 2688 mm/s. The Froude number is a dimensionless number and is the ratio of inertial to gravitational forces a body experiences. At first thought, using inertial forces in a static analysis does not seem appropriate, but given the fact that the total force distributed on the hair shaft is a function of a time dependent quantity-velocity, the use of inertial forces to convert the velocity to an applied force makes sense. The pi group formed by the Reynolds's number could not be used as the Reynolds' numbers for the model and hair cannot be and are not the same. The hair experiences a very laminar flow with Reynolds number less than 1, while the model, using the scale, will experience very turbulent flow. The other factor that will change significantly is the boundary layer formed along the hair shaft.

Next the pi groups formed by the drag coefficient (Appendix B) have to be used to calculate the scaled up drag force the hair model will require for contact with the iris.

$$F_{D_{model}} = F_{D_{hair}} \frac{L_{model}}{L_{hair}} \frac{V_{model}^2}{V_{hair}^2} \quad \text{Equation 14}$$

where the drag force per unit length of the hair was calculated previously using Oseen's approximation ($4.107 \times 10^{-9} \text{ N/mm}$). The drag force per unit length that would be required for contact with the iris at the scale of the model turns out to be $4.107 \times 10^{-3} \text{ N/mm}$.

These above calculations were not performed before the finite element analysis. If the varying line loads applied to the model are totaled and multiplied by 0.35 (as that was the time-step where the hair bulge hit the socket iris) and then multiplied by 2 (as only the half-model was used for the simulations), the drag force comes out to be $5.1 \times 10^{-3} \text{ N/mm}$ (Appendix C for calculations). The error percentage of the drag force is around 25%. While the error may seem large, it actually is very acceptable for several reasons. First, the material properties of the hair and the socket were only approximates as the material data available was for similar insects or insect families, and even then, a range was provided. Sometimes, the material properties had to be approximated without much data (Poisson's ratio of cuticle for example) and this lack of accurate properties alone can account for the error margin. Another major error source regarding the mechanical properties was that the material model was a linear-elastic one with the material behavior set as

isotropic. In reality, the cuticle should really be modeled as a hyper-elastic material, or should have elastic-plastic behavior. It should also be noted that the properties of the cuticle are not completely isotropic, and change a bit depending on the orientation of the chitin fibers. But for all the corrections, other material parameters (various constants depending on the type of non-linear model used) or properties (yield strength, for example if the elastic-plastic model was to be used) would be needed and which were unavailable. Second, the exact velocity profile of the air along the hair shaft was not used. The data available for the velocity distribution was based on a model with a varying hair diameter along the length while the drag force equations used a cylinder of constant radius, and this contributes to the error percentage. Third, the equation (Equation 10) used to solve for the drag forces itself was an approximation and does not give exact numbers. Fourth, the actual hair has soft tissue surrounding the socket that provides some damping, and also the hollow channel in the hair shaft is filled with biological fluids which can change the forces required a bit. Granted though, that accounting for the damping would have made the error margin worse because a slightly greater force would have been required, but at the same time, all the previous explanations could account for the force by bringing it down significantly. Fifth, recall that the middle part of the socket had support cells and ribs that can provide that part of the structure with some added stiffness. To account for that stiffness, the middle part of the socket was set to a modulus value 20% higher than the rest of the socket, but the exact stiffness the ribs provide to the actual hair is unknown and the 20% adjustment may have been too

high, or too low. Sixth, the 80 mm/s air current speed tested by Kämper and Kleindienst was for the filiform hair of a field cricket, not a house cricket. This difference this would have made may be small, but still should be considered when talking about the accuracy of results. More importantly, several other non-material related factors could have contributed to the error source. For example, if the socket wall thickness measured was slightly off, say 10-20%, then that would change the deformation behavior. That is, a smaller or larger force would be required for iris contact to occur.

The hypothesis originally made that there is no gap between the socket and hair bases (and the gap seen in the confocal microscopy images is an artifact of sample preparation and studying the insect joint after it has been anesthetized) can now be given some context looking at the drag force numbers. If there indeed were a gap between the socket base and hair base, a much smaller drag force (and hence air current magnitude) would be required for the hair bulge to contact the socket iris feature as the resistance provided by the socket would only be a fraction of what it is with a tight fit. The drag force required to make this contact in the finite element model corresponded very well with what the actual drag force (actual air current tested by Kämper and Kleindienst) would be given a filiform hair of similar length. The model was created with no gaps and a tight fit with a frictionless contact that allowed sliding only. The stiffness offered by the socket, therefore, is much greater than what has been previously postulated. This also is largely due to the nature of

the analysis. Since no dashpot was included, the stiffness was higher to account for the damping a dashpot would have provided.

Ecdysial Canal Compression

The ecdysial canal runs through the hair base when the hair viewed along the short-axis. A quick study was performed to check if this gap-the canal-distorts the results obtained. After monitoring the stresses along the canal, it was determined that the gap in the structure does not have any noticeable effect and does not alter the validity of the results. A path to approximate the ecdysial canal was created as described in the previous section (Figure 81). The goal was to observe the kind of stresses the dendrite would experience. The path stress plots suggest that the channel is compressed entirely along its length (y-axis) at the final load step, but the stress distribution that is of importance here is at load-steps before the hair and socket contact, as at the contact point onwards, the campaniform sensilli get activated. Along the length of the canal, the compressive stresses increase rapidly and reach a maximum at the hair and iris contact, after which the compressive stresses decrease gradually. This same compressive stress pattern is observed in all three directions. The tensile stresses along the length decrease steadily and reach a lowest tensile value of about 0.13 Pa well before the contact point, and then become compressive. For the radial direction of the canal in the plane of motion (z-axis in Figure 81), the tensile stress is initially almost zero and then at a point before the contact, suddenly jumps up from about zero to 0.3 Pa, after which, it increases steadily and reaches a near constant value past the contact point. The compressive

stress distribution, as mentioned before, is the same in this radial direction as it was along the length of the canal. Along the x-axis of the local coordinate system (Figure 81), the tension in the canal increases initially, starts to decrease at a point well before the contact, and then eventually increases slowly much after the contact has occurred. The normal stress states at the final load-step of the canal can be seen in Figure 82, Figure 83, and Figure 84.

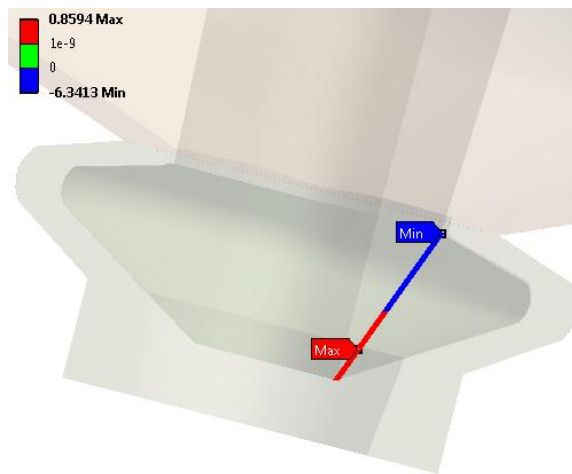


Figure 82: Local x-axis stress distribution at the final load-step. The blue region is in compression and the red region is in tension. Unit of the legend is Pa.

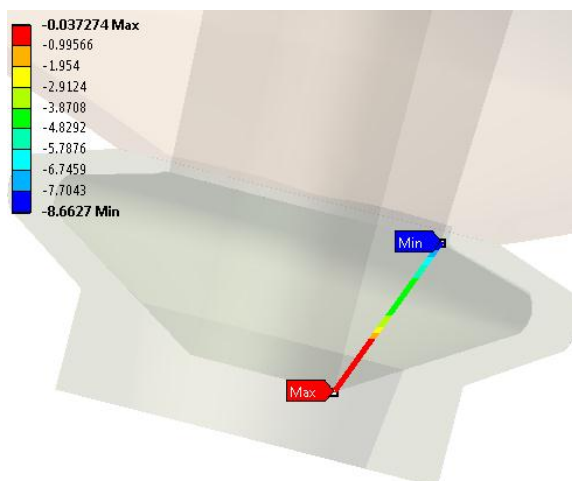


Figure 83: Local y-axis stress distribution at the final load-step where the entire channel is in compression. Unit of the legend is Pa.

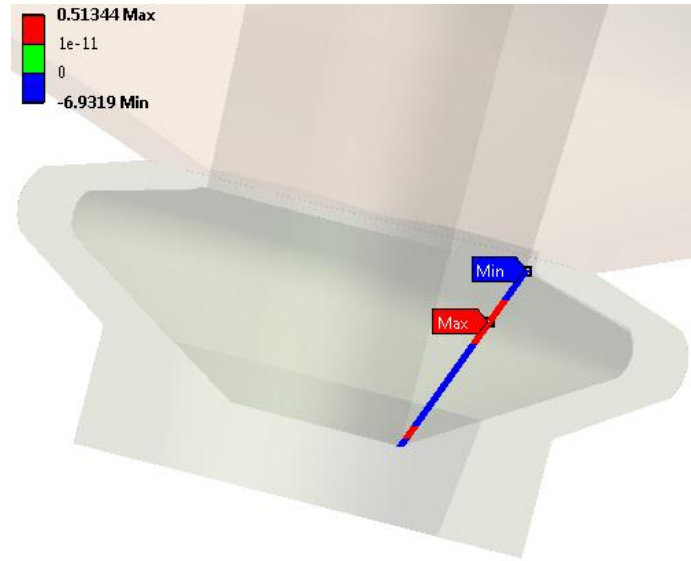


Figure 84: Local z-axis stress distribution at the final load-step. The blue region is in compression and the red region is in tension. Unit of the legend is Pa.

What was common among all the plots was that both the tension and compression values either switched signs (went from compression to tension or vice-versa) and jumped drastically in magnitude between load steps 4 and 5, both of which occur before the contact (which is between load steps 6 and 7). The undeformed wire-frame model was left on while displaying the deformed configuration of the model at load steps 4 and 5, and the hair deflection angle from the undeformed vertical hair shaft edge was measured in each case. At load step 4, the hair has deflected 7.06° and at load step 5, the deflection was 8.65° . On a side note, these numbers may seem a little high given the geometry of the structure. That is, given the distance between the hair bulge and socket iris, and the hair shaft length from the hair bulge to the hair base, the hair should only deflect about 4.44° before contacting the iris, but that assumes that the socket does not deform

physically as the hair begins to move, which is not the case. Before further inquiry regarding this response is made by anyone, it has to be understood that ecdysial canal's location is only approximated by the path to get a qualitative idea, and is by no means exact.

Dendrite Compression

The compression of the dendrite by the flange at the base of the hair shaft causes a change in the spiking activity of the receptor neuron that each filiform hair is innervated with. This change in the neural spiking activity by the compression mechanism is the primary sensory mechanism of the cercal system and is a well-known hypothesis.

To evaluate the hypothesis, a vertex at the base of the flange in the direction of hair movement was studied (Figure 85). This part of the flange pushes against a dendrite when the hair is deflected. To get a better understanding of this set-up, please refer back to panel C of Figure 3. The displacements of the vertex highlighted in green below were tracked over varying load-steps and this can be seen in Figure 86 and Figure 87 . The vertical gray lines show the time at which contact of the hair and socket iris occurs, at around 0.35 seconds. As can be seen in the Figure 86, the vertical displacement till about the contact point is high in magnitude (the negative signs on the plot simply show the direction of movement) and for a small period goes to zero and then starts climbing back up, once the contact occurs. So once the campaniform sensilla are activated, this primary sensory mechanism should not need to be employed exclusively and the point moves up releasing the compression

slowly. In Figure 87 it appears that the dendrite gets compressed horizontally as well till the contact point, past which the compression starts tapering down a bit.

If the hair base was not fixed with the socket base, the green point would keep compressing the dendrite it pushes against beyond the iris contact and activation of the campaniform sensilla, because the resistance that the socket base provides when the fit is tight would have pulled the hair base away quicker horizontally to the left. This result set agrees with the popular hypothesis of the primary sensing mechanism-compression of a dendrite by the base flange of the hair and also further provides some more context, but does not categorically prove the hypothesis presented in this study that no gap exists between the hair base and socket base.

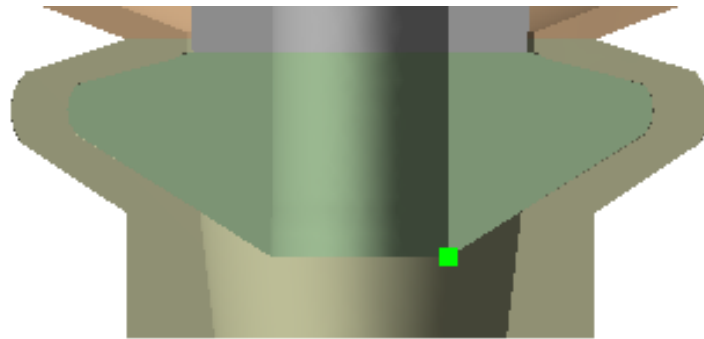


Figure 85: The vertex shown in bright green was picked and its vertical and horizontal movement at varying load-steps was tracked.

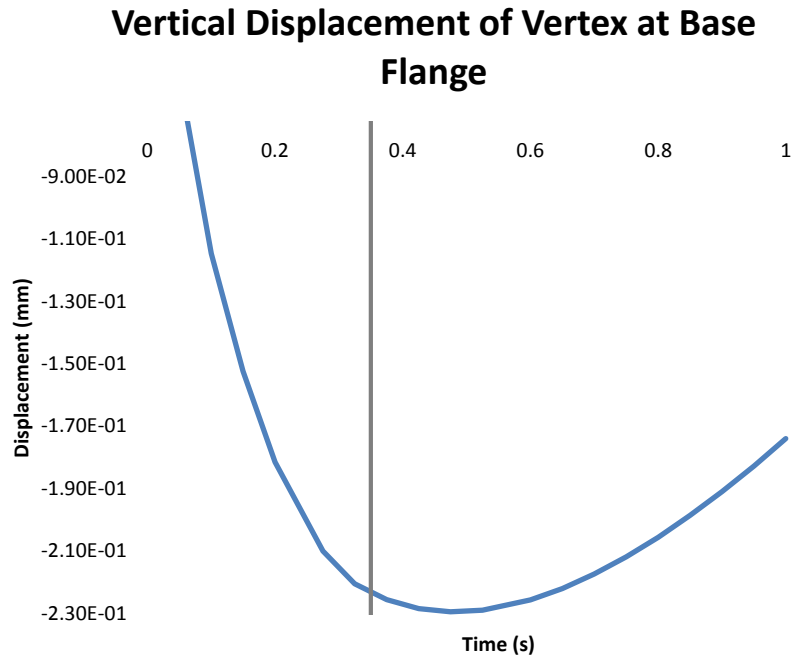


Figure 86: Displacement of the vertex at the base flange over time (load-steps). The gray vertical line shows where the hair and socket contact occurs.

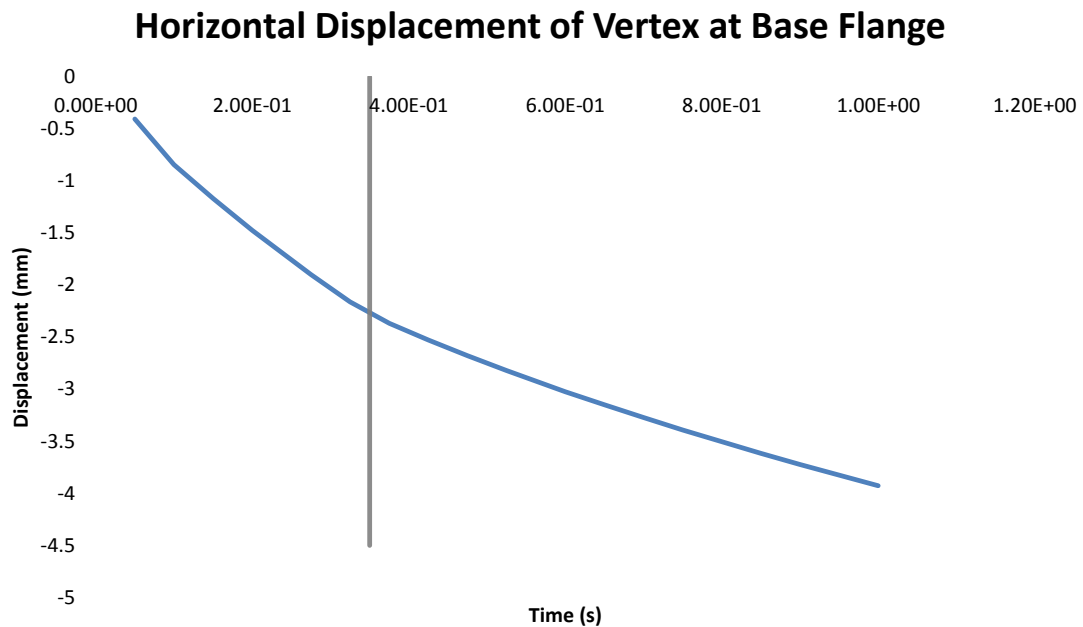


Figure 87: Displacement of the vertex at the base flange over time (load-steps). The gray vertical line shows where the hair and socket contact occurs.

Hypothesis Evaluation: Campaniform Sensilli and Hair Sliding

The sheet of cuticular tissue called the “skirt” has the very receptive campaniform sensors embedded in it. There are two sensors in the preferential direction, or side of movement and one on the other side. These sensors are located quite close to the inside edges of the skirt where deformation is the maximum.

The x-axis or long axis of the skirt does not deform much relative to the total deformation. Almost the entire half (or quarter of the total hair, half of the model) of the skirt that is away from the hair’s movement direction gets pulled out of the viewing plane when the hair shaft moves from left to right, while the half of the skirt in the movement direction mostly gets pushed back in the viewing plane. The deformation of the skirt side not close to the hair movement side (left side) is more than twice as large at least as the movement side (right side).

Along the z-axis (short axis), the right side of the skirt moves further right, but the left side of the skirt moves to the left a bit. This is an unexpected result as it makes sense for both sides to move in the same direction, but the left side moving further left has more to do with the middle part of the socket deflecting to the left and in the process pushing the top part partly to the left, and because the contact occurs on the right hand side, the left side’s deflection does not get compensated by the deformation caused by the hair contact.

What is of interest of course is the y-axis or vertical deformation of the skirt, which is anywhere from 10 times greater on average than the short axis

deformation and 20 times larger than the long axis deformation. The skirt behaves like a thin circular plate with the edges clamped when a transverse load acts on it. The right side deflects downwards and the left side upwards. In the insect, this cuticular sheet extends on to the next hair, which is typically 100-300 microns away (23), and the length modeled is about 20 microns, which means that the deformations should be scaled down by approximately a factor of 10. Another factor to consider is that the socket is surrounded by soft tissue that also provides some resistance, but the elastic modulus of this tissue is very low and the deformation should not be affected much. However, accounting for the above corrections, the deformation of the skirt is not quite so exaggerated in actuality. This does not change the hypothesis. If the structure of the campaniforms is observed closely (Figure 10), it becomes apparent that these sensors are thin elliptical features with a hole at the center. A discontinuity in a structure, or as previously discussed, sharp edges, act as stress concentrators, and a small input force can cause large deformations. So even though the deformation of the skirt is restricted in the real insect by the length of the skirt and the resistance provided by the tissue, not much deformation should be needed to activate the campaniforms. Of course, it should be noted that in the insect, a discontinuity in its structure will not artificially enhance the stress by the same factor it would in a finite element model (cracking around the hole becomes a point of concern in a finite element simulation). Also because of the elliptical nature of the feature, the hole's deformation will be

different in different directions for the same loading conditions. Figure 88 shows the magnitude and direction of the skirt's total deformation at the final load step.

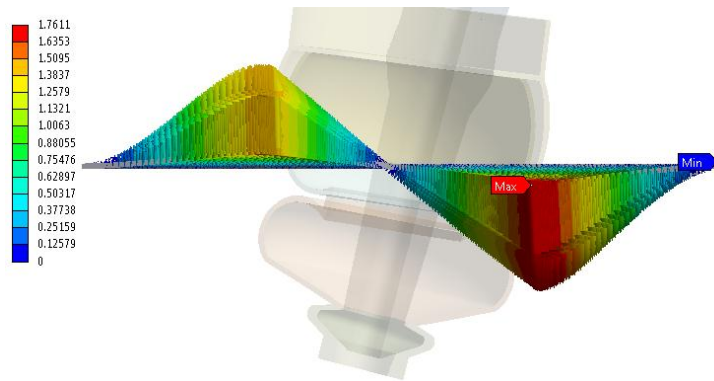


Figure 88: The direction of the arrow cluster illustrates the vector sum of deformation while the colors can be matched to the legend (units of microns). The arrow lengths are exaggerated to show the deformation shape. Note the red cluster where the maximum deformation occurs is actually the beginning of the skirt and everything to the left of the red cluster up to where the deformation tapers to zero is acting behind that (around the half circumference). The outside regions of the skirt faces do not experience deformation as the outside face is fixed.

Belt Analysis

The belt feature ended up being a very crucial aspect of the design. As discussed previously, this feature can be approximated as one set of springs where the springs in the set are parallel with one another and at the same time the set is in parallel to another similar spring set-up (that is out plane). Any displacement of the hair-before, during, or after contact with the iris-compresses or tenses the belt immediately. Again, this is because of how the structure is set up with the hair base fixed to the socket base, so hair movement causes movement of the socket from the socket cavity upwards, which engages the spring.

In the direction of hair shaft movement, the inside and outside edges of the belt were selected (Figure 89) and their displacements were tracked over various loads transferred from the hair shaft. The belt's spring behavior can be split in two distinct parts-before and after contact with the iris. The belt deforms linearly with load up to the contact point, after which the behavior becomes non-linear. The stiffness also changes substantially after the contact. At the very least (depending on the edge and direction), the spring constant post contact is over 140% of pre-contact, and the most, the change is about 235%. Table 3 and Figure 90 show the data and force-displacement plot. Using a linear spring model, the spring constant of the belt edges is around 0.4 N/m before contact and 0.845 N/m after contact. Also, because the belt separates two parts of the socket, its compression limit serves as the maximum distance the hair can deflect from its resting position (and compress the belt in the direction of travel).

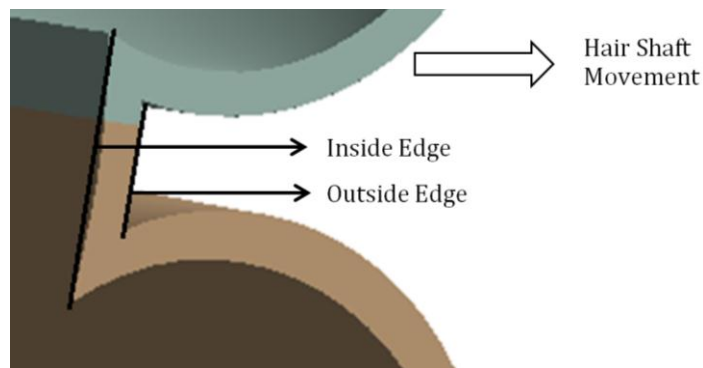


Figure 89: Belt edges used for calculating spring constant.

Table 3: Deformation in various axes of the two belt edges. Note: x-deformation was very small and ignored. Deformation in mm, Load in N, Slope in N/mm.

	INSIDE	OUTSIDE	INSIDE	OUTSIDE	INSIDE	OUTSIDE	
	Def. Y	Def. Y	Def. Z	Def. Z	Def. Total	Def. Total	Load
	0.11184	0.11911	4.26E-02	5.09E-02	0.15484	0.14631	4.72E-02
	0.24002	0.25582	8.92E-02	1.06E-01	0.32702	0.31078	9.44E-02
	0.33573	0.35843	1.24E-01	1.46E-01	0.45452	0.43319	1.42E-01
	0.42211	0.45173	1.55E-01	1.83E-01	0.57011	0.54435	1.89E-01
	0.53539	0.57601	1.97E-01	2.31E-01	0.7242	0.69267	2.60E-01
	0.60184	0.65006	2.23E-01	2.60E-01	0.81618	0.78127	3.07E-01
	0.66144	0.71625	2.50E-01	2.91E-01	0.89988	0.86213	3.54E-01
	0.71511	0.77551	2.78E-01	3.23E-01	0.97638	0.93617	4.01E-01
	0.76438	0.83023	3.05E-01	3.54E-01	1.0476	1.005	4.48E-01
	0.80991	0.8811	3.30E-01	3.83E-01	1.1142	1.0694	4.96E-01
	0.87246	0.95147	3.66E-01	4.24E-01	1.2072	1.1592	5.66E-01
	0.91087	0.99498	3.89E-01	4.50E-01	1.2652	1.2151	6.14E-01
	0.94705	1.0362	4.12E-01	4.75E-01	1.3204	1.2684	6.61E-01
	0.98125	1.0754	4.33E-01	4.99E-01	1.3732	1.3193	7.08E-01
	1.0137	1.1128	4.54E-01	5.23E-01	1.4239	1.3681	7.55E-01
	1.0446	1.1485	4.74E-01	5.45E-01	1.4726	1.415	8.02E-01
	1.074	1.1828	4.94E-01	5.67E-01	1.5196	1.4602	8.50E-01
	1.1022	1.2158	5.13E-01	5.89E-01	1.5649	1.5039	8.97E-01
	1.1292	1.2475	5.32E-01	6.10E-01	1.6089	1.5462	9.44E-01
SlopeBeforeContact	0.534002651	0.493425	1.455299	1.254365	0.396425	0.412835	
SlopeAfterContact	1.264644971	1.114166	2.097168	1.85573	0.835116	0.865604	
Ratio_After/Before	2.368237254	2.258025	1.441056	1.479417	2.106617	2.096733	

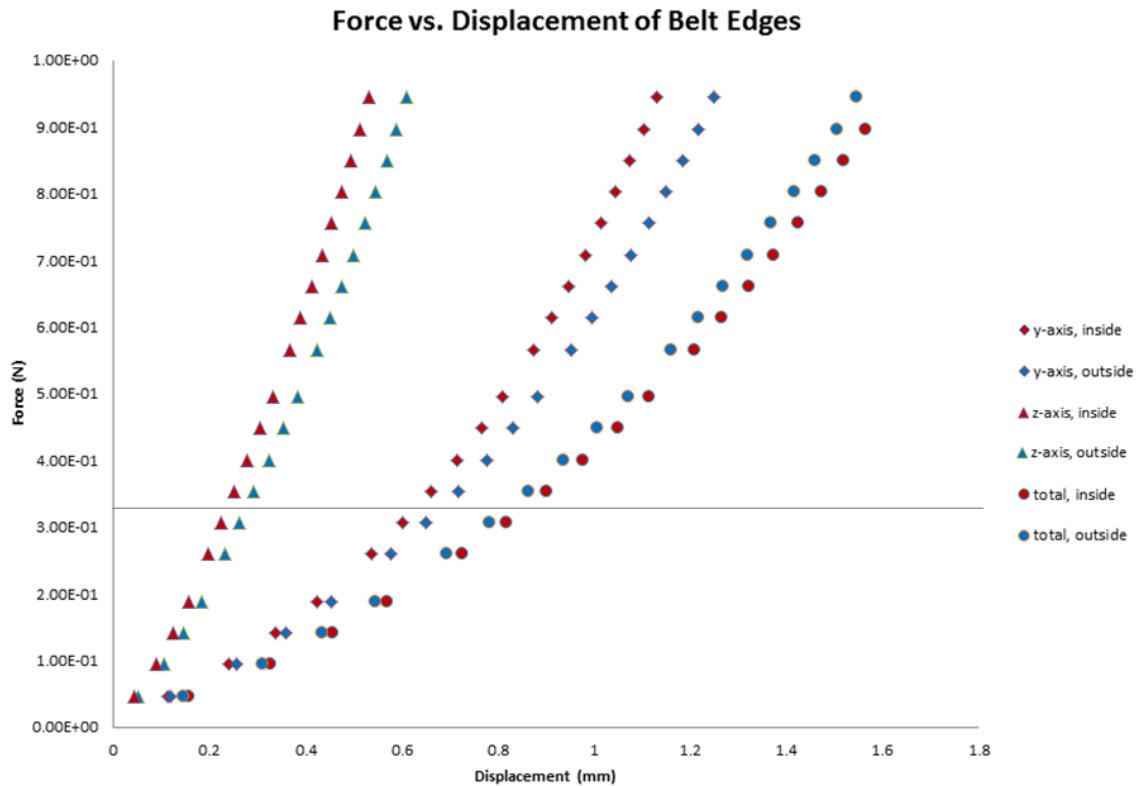


Figure 90: The horizontal line above $F = 0.3\text{N}$ is where the contact occurs, and the changes in the slopes are clearly visible past that point.

Sliding

The sliding mechanism was hypothesized, and monitoring the sliding of the hair bulge on the socket iris after contact revealed that the hair bulge slides quite a bit after contact is made. A maximum sliding distance of almost 0.185 microns was observed. This is significantly large as the thickness of the iris is only 0.5 microns. Once the socket is deformed enough so that the hair makes contact with the socket iris, more socket deformation is unlikely, because the hair begins to transfer force on the socket by other means such as shear forces. Figure 91 and Figure 92 below show the normal z-direction stress and the yz plane shear stress of the inside iris wall. The

contact occurs around 0.35 seconds, and the change in z-normal stress is drastic, but after that, it tapers off and around the same time, the yz-shear stress picks up. The biological significance of the hair sliding is not known but it may simply be another displacement limit as mentioned. That is, the socket and the skirt do not need to deform much beyond once the campaniform sensilla are activated, so the hair begins to slide to distribute the stresses more evenly through the structure.

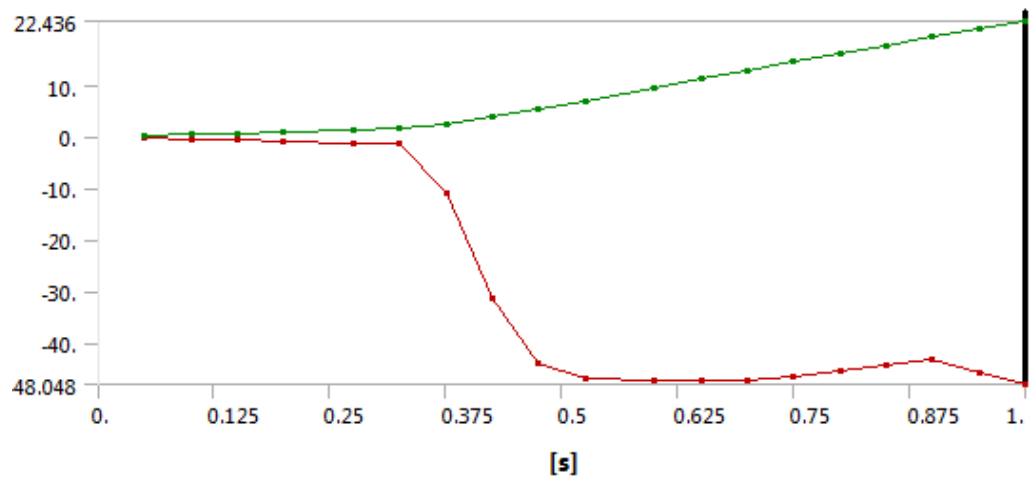


Figure 91: Normal Z-axis stress vs, time plot. Stress units of kPa.

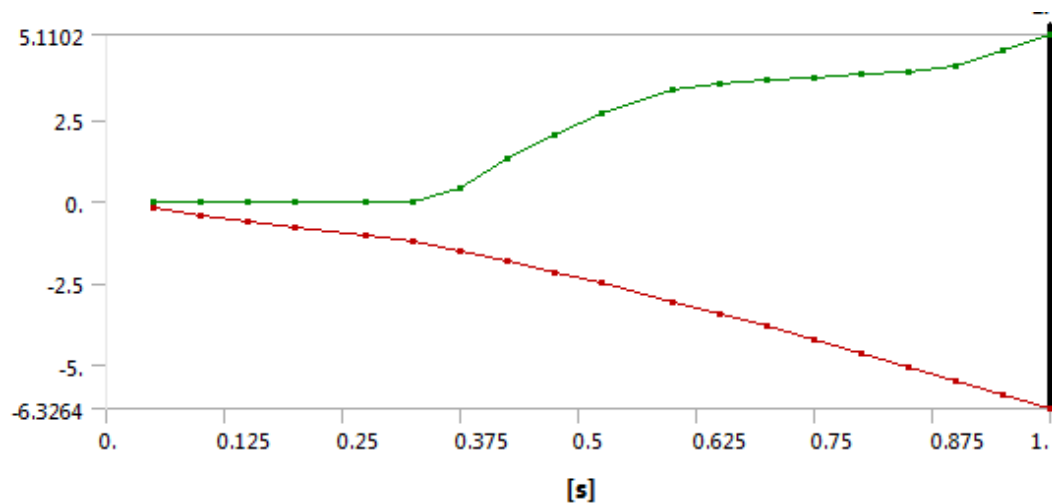


Figure 92: YZ shear stress vs, time plot. Stress units of kPa.

Socket Spring Constant

Recall that Equation 1, where the inverted pendulum model was used to set up a solution for the hair motion, included angular velocity and angular acceleration terms. Since this model created and simulated was a static one, the equation reduces to:

$$S\theta(t) = \tau(t) \quad \text{Equation 15}$$

where θ is the angular displacement of the hair, τ is the applied torque on the hair shaft, and S is the spring constant of the base.

To find the torque, the center of rotation had to be determined. This was calculated very easily by studying the z-direction deformation plot (Figure 98, Appendix A) and matching the contour bands on the plot to the legend colors. The center of rotation of the hair occurs at 29.3 mm from the bottom of the hair base. This point also exactly lines up with the top edge of the belt. This makes sense because the belt compresses on one side and tenses on the other, and its tension/compression pulls the hair with it (of course, the socket base still mediates the hair movement). The spring constant, like other parameters calculated for the model, can be grouped into before and after iris contact zones. If the torque-angular displacement data is plotted, it becomes evident that the relationship is linear in both zones but the slope changes by a factor of about 3.5 post contact. This can be seen below in Table 4 and Figure 93. Figure 94 shows the spring constant tracked over various load steps in terms of time; that is, at time 0.1 second, the torque is one-tenth of the total applied torque, and at time 0.2 seconds, the torque is one-fifth

the total torque and so on. The average spring constant before contact is about 1.2×10^{-9} Nm/rad and after contact is 4.24×10^{-9} Nm/rad (calculations in Appendix C). Published values of the spring constant for a hair length of about 1000 microns range from 8×10^{-12} to 2.5×10^{-10} Nm/rad (24). This puts the calculated value anywhere from 5 to 150 times greater than the published values. The same error sources (lack of correct material properties, use of approximate forces and velocity distributions, measuring errors of wall thickness of socket) that applied to the drag force values also apply to the spring constant numbers and can adjust the calculated values significantly to match the published values. It should also be noted that the published values have a large range they vary across (more than an order of magnitude) and this affects the error range substantially.

Table 4: Angular displacement and torque data. The slope value is the spring stiffness.

	Theta (rad)	Torque (Nm/rad)
	9.54E-06	0
	0.0352	3.30E-11
	0.0727	6.60E-11
	0.101	9.90E-11
	0.1277	1.32E-10
	0.1653	1.82E-10
	0.189	2.15E-10
	0.2053	2.48E-10
	0.2155	2.81E-10
	0.225	3.14E-10
	0.2341	3.47E-10
	0.247	3.96E-10
	0.2551	4.29E-10
	0.263	4.62E-10
	0.2706	4.95E-10
	0.2779	5.28E-10
	0.285	5.61E-10
	0.2919	5.94E-10
	0.2986	6.27E-10
	0.3051	6.60E-10
SlopeBeforeContact	1.19277E-09	
SlopeAfterContact	4.24127E-09	
Ratio_After/Before	3.555797362	

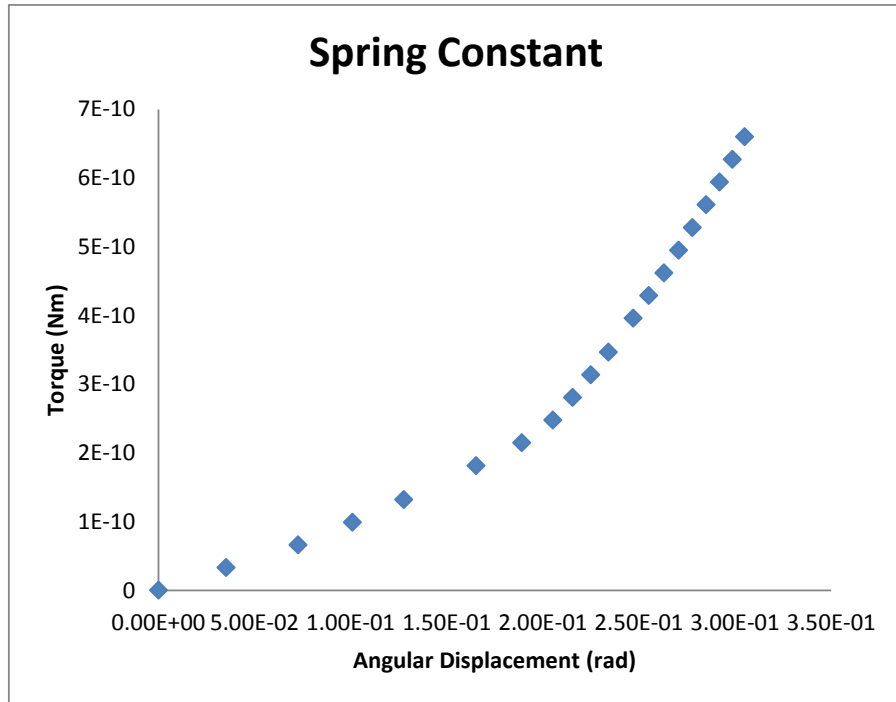


Figure 93: The two slopes are easily identifiable. The hair-bulge and socket iris contact occurs just before 0.2 radians.

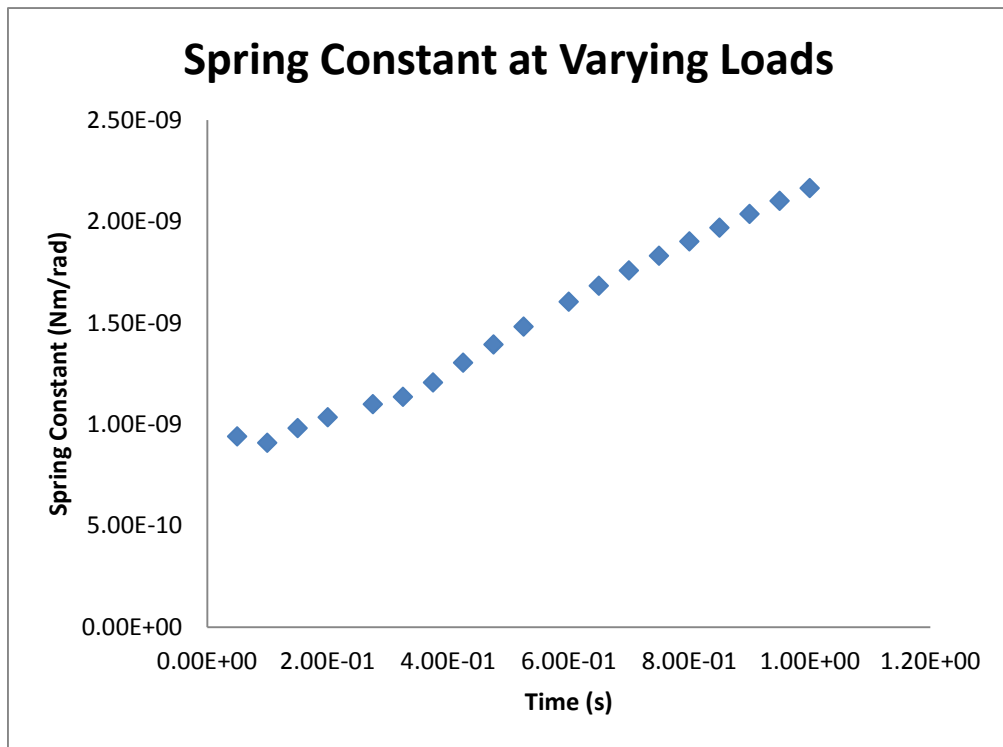


Figure 94: Spring constant is plotted at different load-steps.

Future Work

There is a lot of scope for future work and addition to the work presented here. First, a scaled down version of the model (equal to the actual hair scale) would simplify the analysis and can help a great deal in validating the results. More importantly, other hypotheses should also be tested with different fits around the hair and socket bases to see if the gap is actually artifactual. This study analyzed one scenario of a tight fit and based on the numbers obtained and comparisons made to experimental data, the tight fit hypothesis seems plausible, but one good way to prove or to dismiss the hypothesis would require testing the socket and comparing results with various gaps modeled in.

Because the hair acts like a damped oscillator, a transient or fully dynamic analysis will yield a lot more insight in characterizing the socket and in getting more accurate spring constant values. In a dynamic analysis, a dashpot will be modeled in and the spring may not have to be stiffer to compensate for the lack of a dashpot, as it is in a static analysis, and not only can the damping numbers then be compared to experimental data, but the spring constants can also be compared more fairly because the experimental and FEA framework now would be the same (transient instead of static). The deformations seen in this study were crucial in defining the socket behavior but the stresses and solutions of “unloading” can be of great use, especially if damping is considered.

As far as material properties go, actual filiform hairs and socket should be tested by atomic force microscopy or micro indentation to obtain properties in axial

and bending tests. If the relevant material properties are extracted, then a material model can be created to define the socket (maybe a Neo-Hookean material model that is popular while modeling soft biological tissue).

Another way to obtain more detail about the socket would be to model in the campaniform sensilla and extend the skirt feature out much further. The campaniform sensilla have to be modeled as holes, and care should be taken while running a finite element simulation to account for artificially enhanced stresses near the discontinuity. The hair shaft past the cercus can be completely left out of the model if the socket is being studied and the load required can be added remotely at a point or edge. The hair, of course, should be included if an oscillatory load is applied.

The work presented in this thesis provides a starting point for any kind of finite element analysis of the cricket's socket and hair. The model created can be saved and opened with various meshing and finite element packages. More than that, the actual finite element simulation was able to shed new light into the working of the socket and hair base, and many previous assumptions made in this field can now be given context, one way or another.

From an engineering stand point, the aim was not to mimic the structure but gain understanding about its highly responsive nature to fluid flow. The work presented in this thesis can be used to first theoretically account for a sensing mechanism or control in the form of piezo-resistive devices, and the sensitivity can be gauged. The theoretical work should also focus on comparing sensitivities of

other materials in various configurations (say a strain gage oriented along an axis of a composite beam) to the structure of the socket and extract the relevant design properties.

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APPENDICES

APPENDIX A:

CONTOUR PLOTS

A quick note about the contour plots: the units for all deformation plots are microns, strain plots are microns/microns, and stress plots are kilo-Pascal (kN/m^2). Recall that the model is scaled up by a factor of 10^3 , so all deformations and stresses have to be scaled down by a factor of 10^3 . The actual units that *ANSYS* gives out for deformations are mm, and for stresses are MPa, but they are interpreted as stated above. Also, unless otherwise show in the plot, the orientation of the coordinate system is as shown in Figure 95 below.

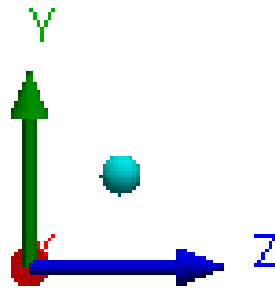


Figure 95: Orientation of the coordinate system of the contour plots that follow. The z-axis is the short axis and the hair shaft moves from left to right (towards positive z-axis). The axis going in the page, x-axis is the long axis of the structure, and y is the vertical axis.

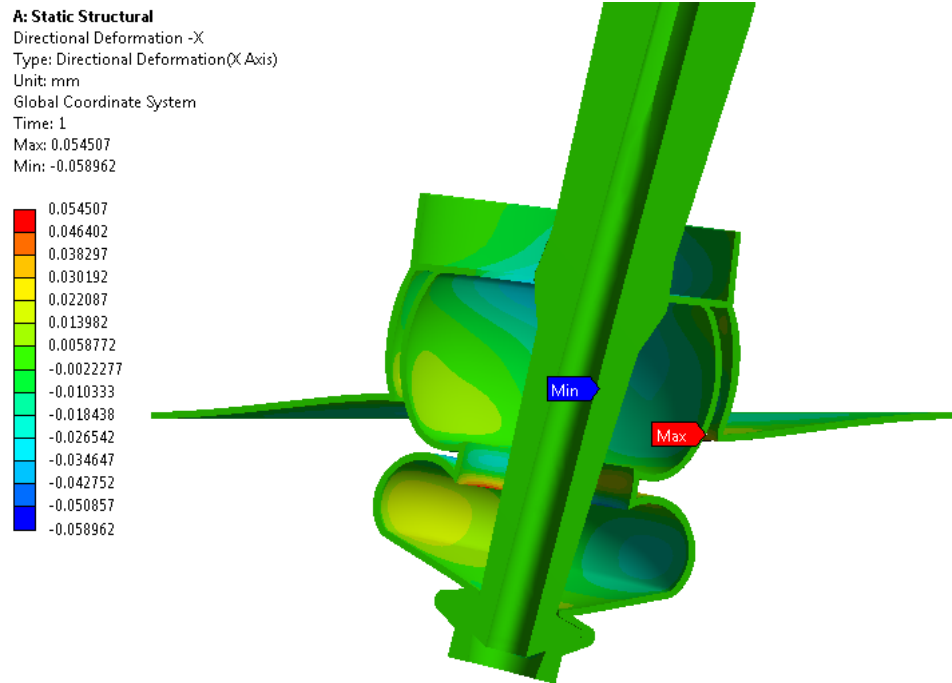


Figure 96: x-direction deformation at the final load step.

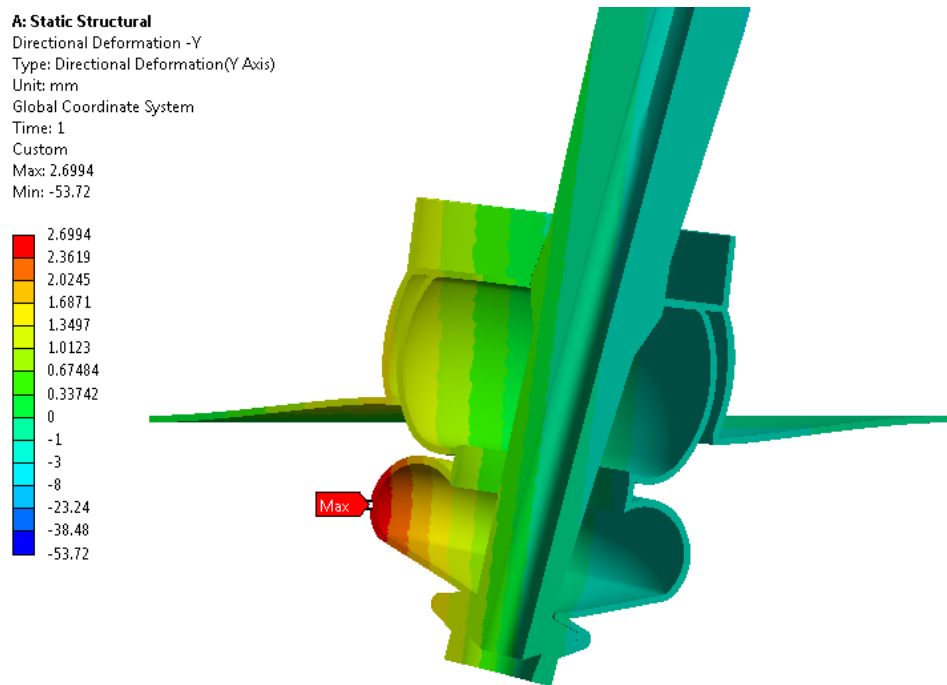


Figure 97: y-direction deformation at the final load step.

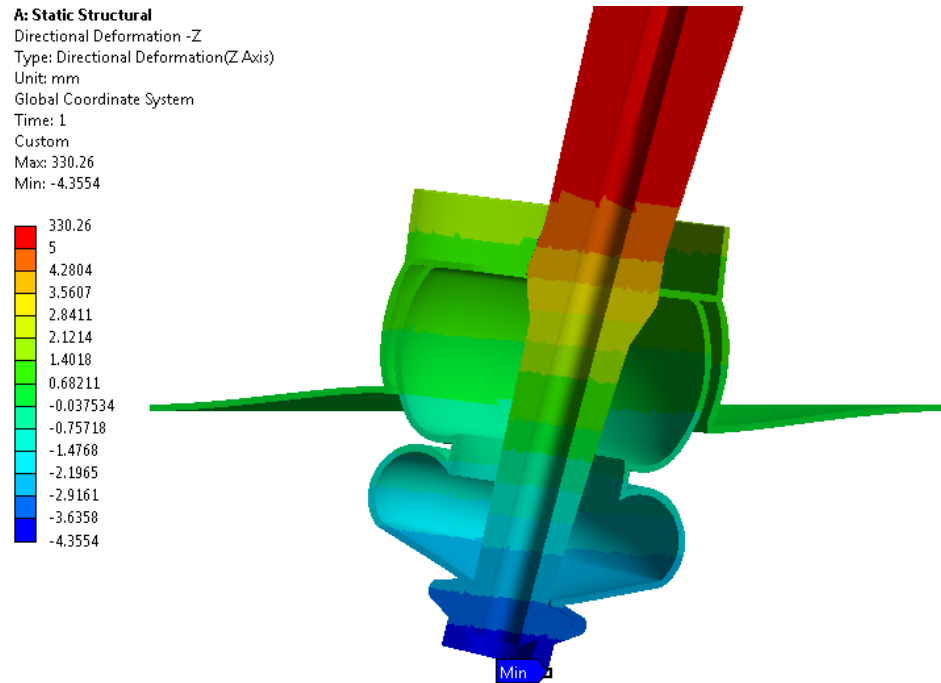


Figure 98: z-direction deformation at the final load step.

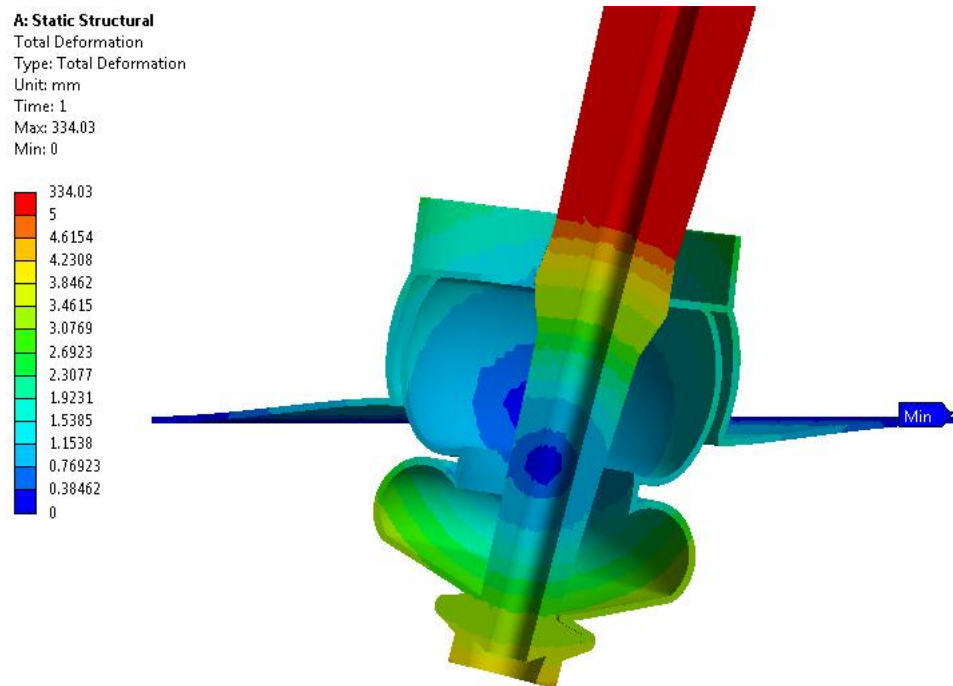


Figure 99: total deformation at the final load step.

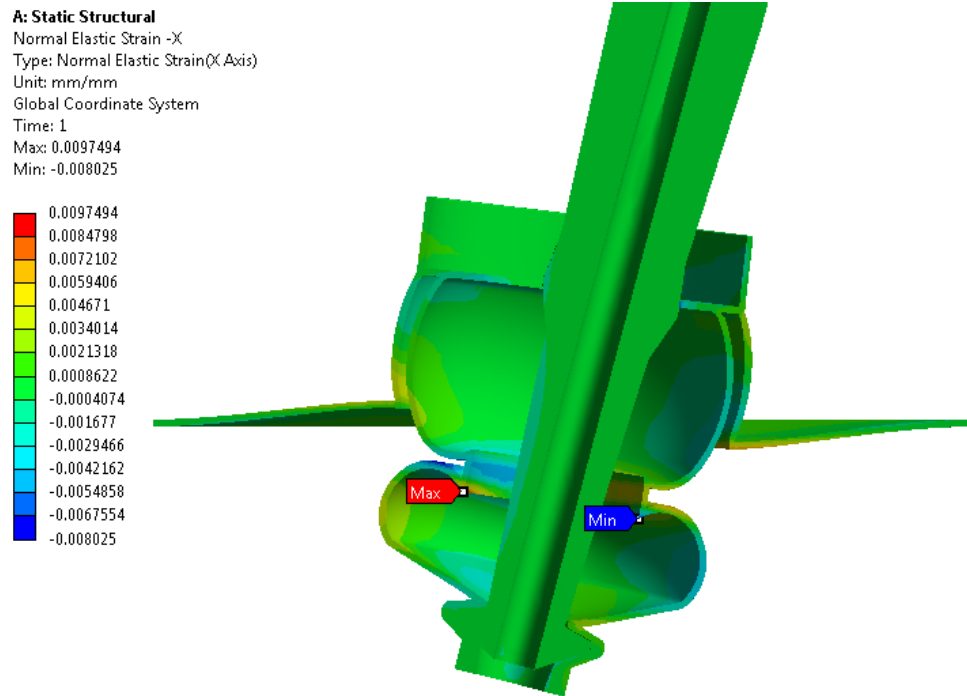


Figure 100: x-direction elastic strain at the final load step.

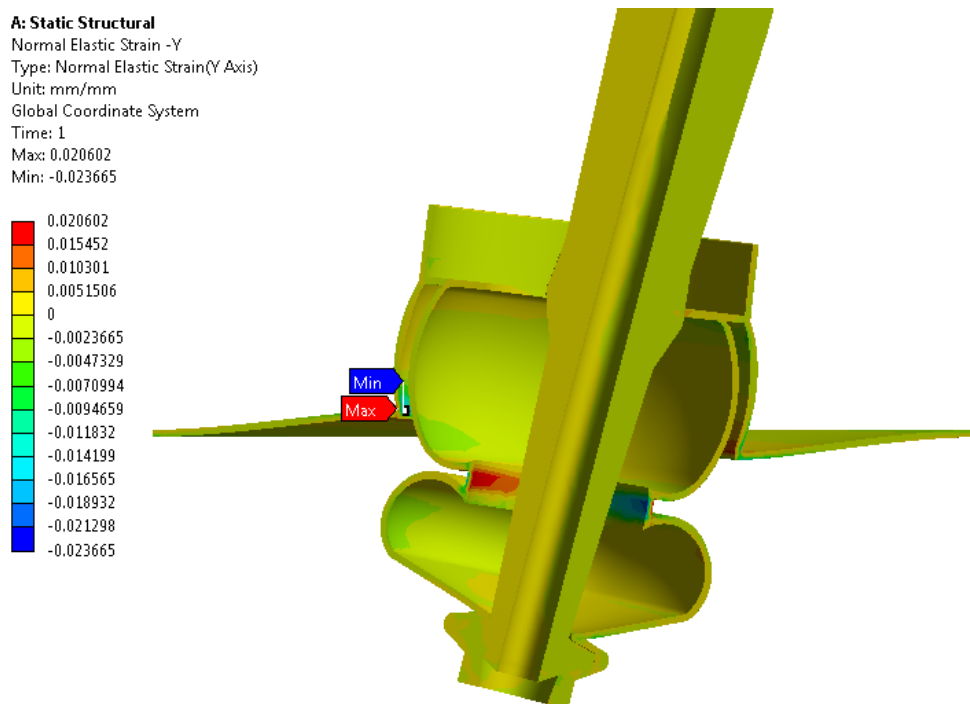


Figure 101: y-direction elastic strain at the final load step.

A: Static Structural
 Normal Elastic Strain -Z
 Type: Normal Elastic Strain(Z Axis)
 Unit: mm/mm
 Global Coordinate System
 Time: 1
 Max: 0.014948
 Min: -0.016741

0.014948
 0.012684
 0.010421
 0.0081572
 0.0058937
 0.0036302
 0.0013667
 -0.00089676
 -0.0031602
 -0.0054237
 -0.0076872
 -0.0099507
 -0.012214
 -0.014478
 -0.016741

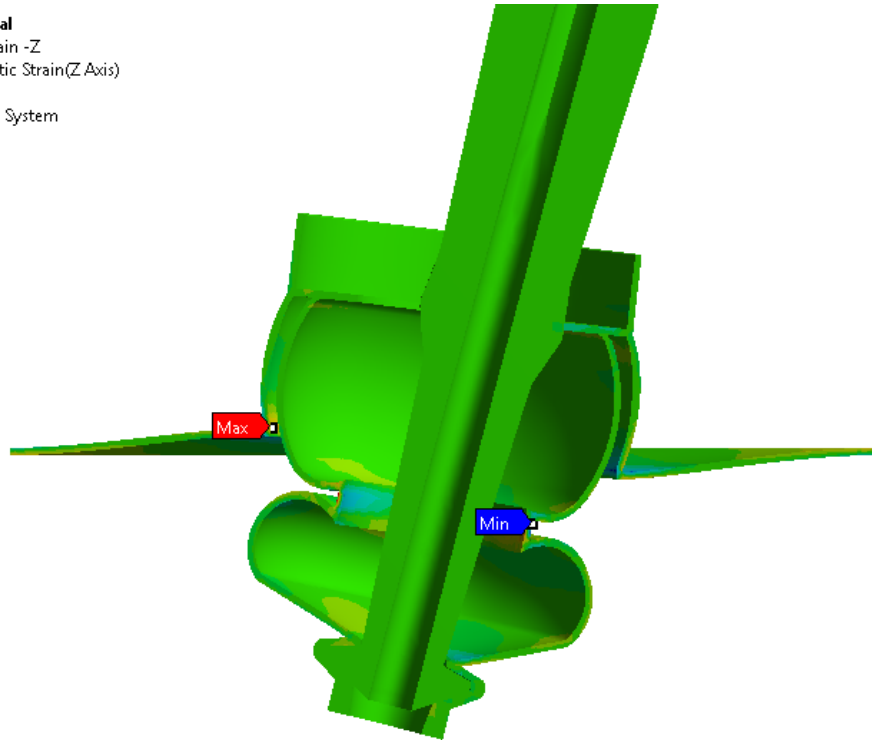


Figure 102: z-direction elastic strain at the final load step.

A: Static Structural
 Equivalent Elastic Strain
 Type: Equivalent Elastic Strain
 Unit: mm/mm
 Time: 1
 Max: 0.024397
 Min: 2.6434e-8

0.024397
 0.0091463
 0.003429
 0.0012855
 0.00048194
 0.00018068
 6.7738e-5
 2.5395e-5
 9.5206e-6
 3.5693e-6
 1.3381e-6
 5.0167e-7
 1.8808e-7
 7.051e-8
 2.6434e-8

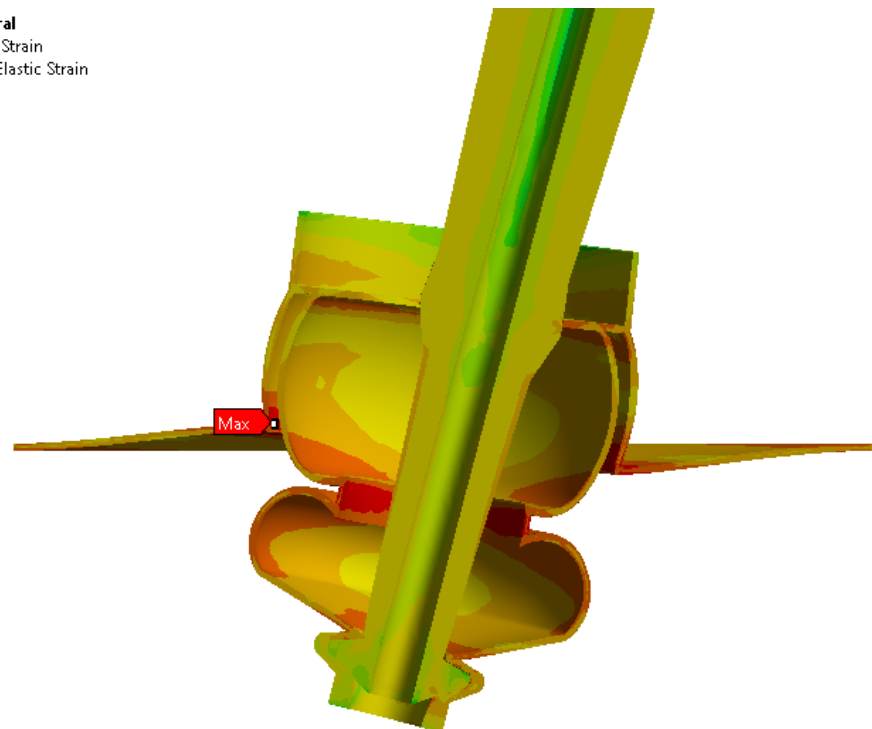


Figure 103: von-Mises or equivalent elastic strain at the final load step. Logarithmic scale.

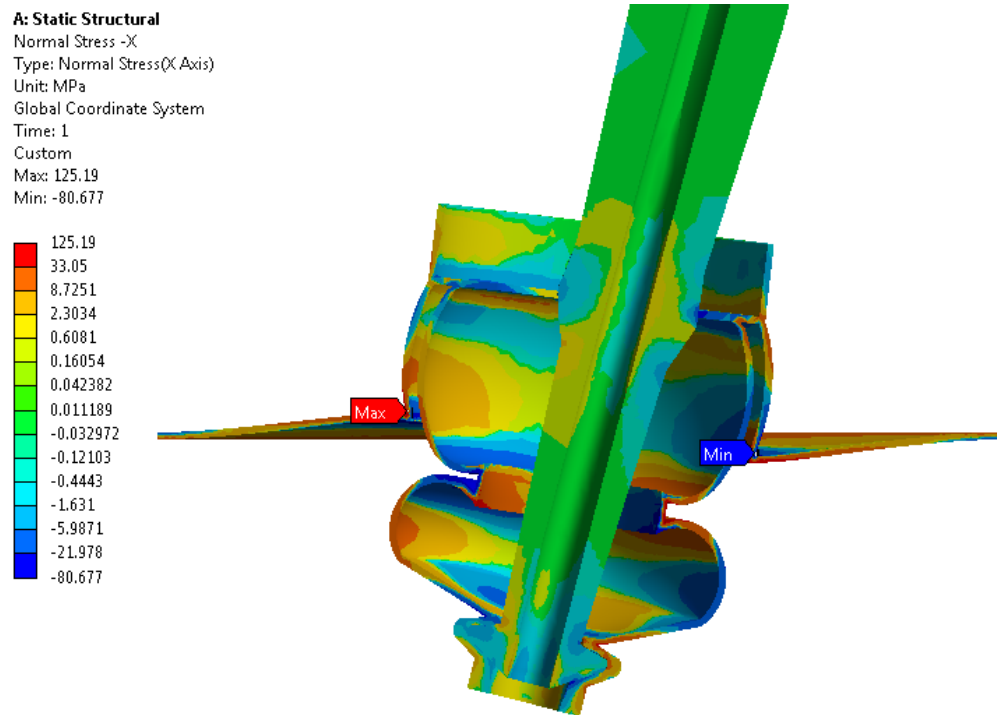


Figure 104: x-direction stress at the final load step. Logarithmic scale.

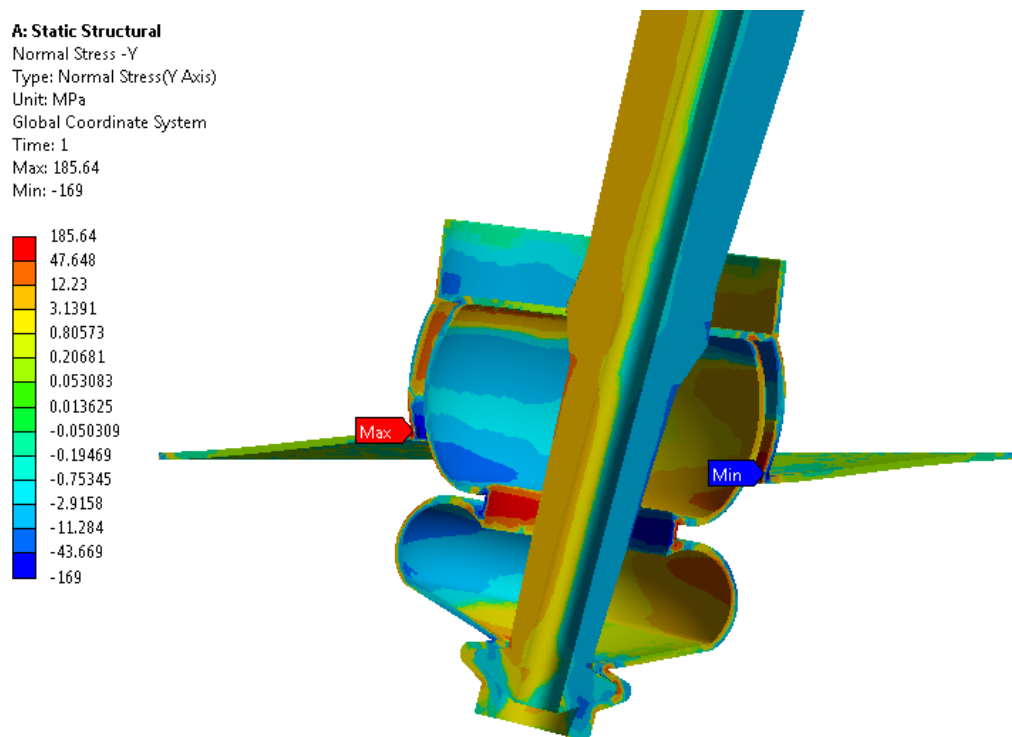


Figure 105: y-direction stress at the final load step. Logarithmic scale.

A: Static Structural
 Normal Stress -Z
 Type: Normal Stress(Z Axis)
 Unit: MPa
 Global Coordinate System
 Time: 1
 Max: 94.64
 Min: -88.3

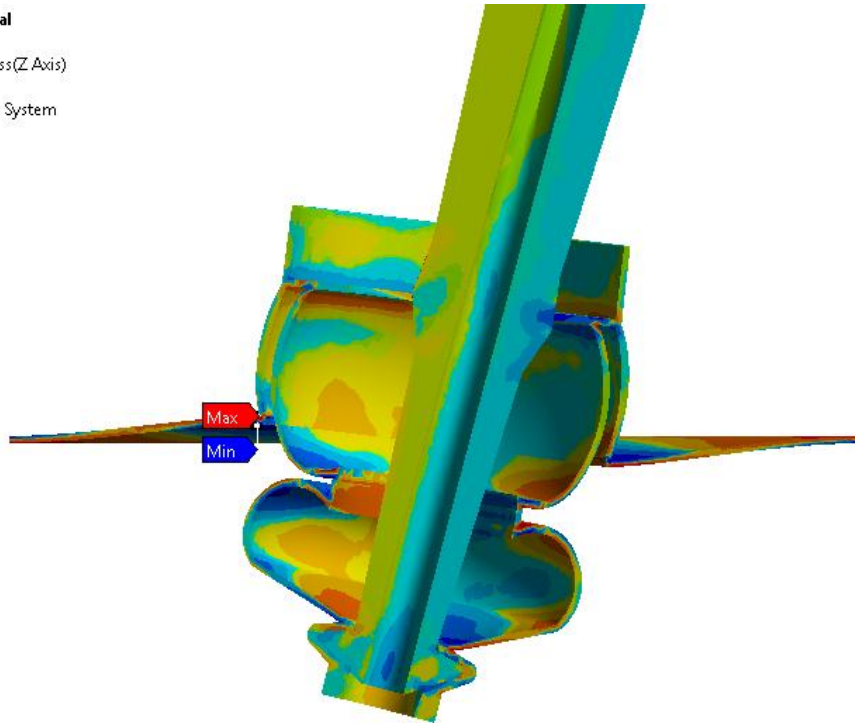
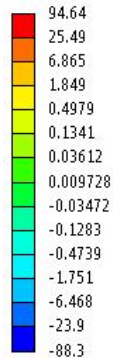


Figure 106: z-direction stress at the final load step. Logarithmic scale.

A: Static Structural
 Equivalent Stress
 Type: Equivalent (von-Mises) Stress
 Unit: MPa
 Time: 1
 Max: 121.98
 Min: 0.00023791

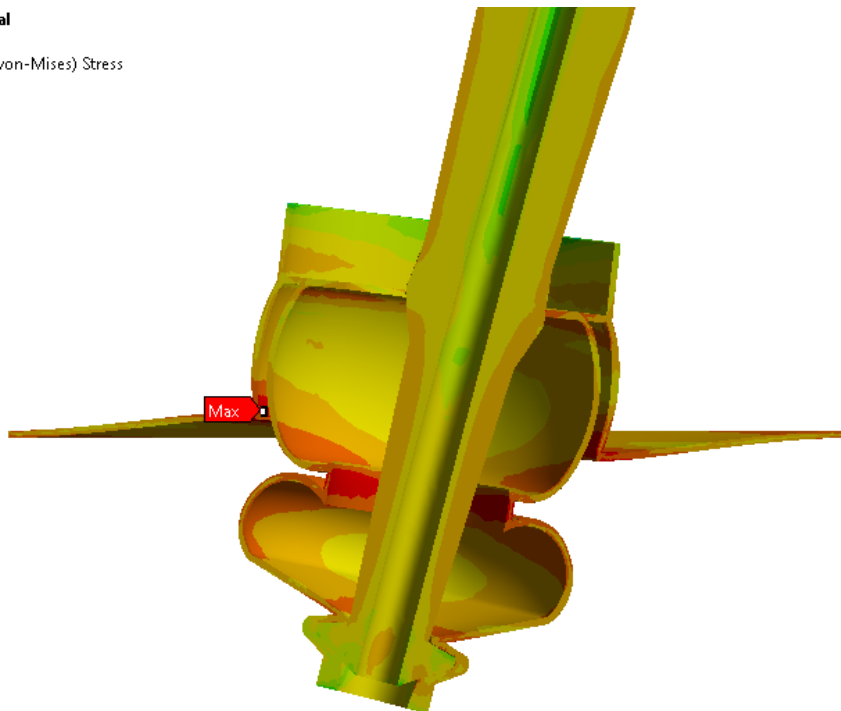
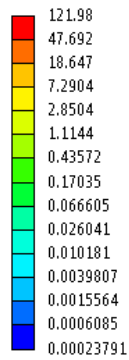


Figure 107: von-Mises or equivalent stress at the final load step. Logarithmic scale.

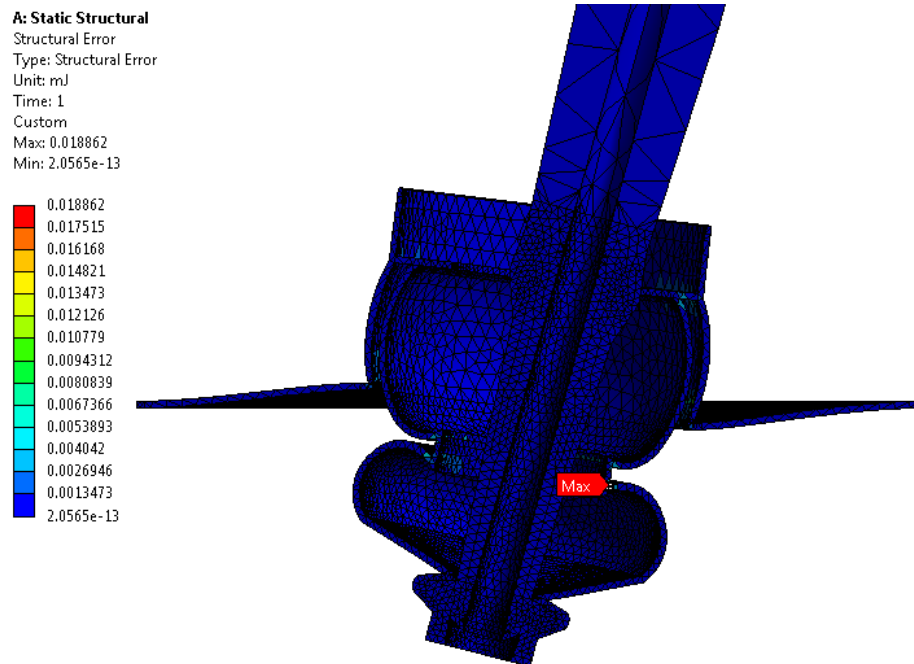


Figure 108: Structural Error. Recall from Chapter 3 that to check for mesh quality, a structural error plot was added, and small values of structural error, as is the case here, is a strong indication that the mesh quality is good.

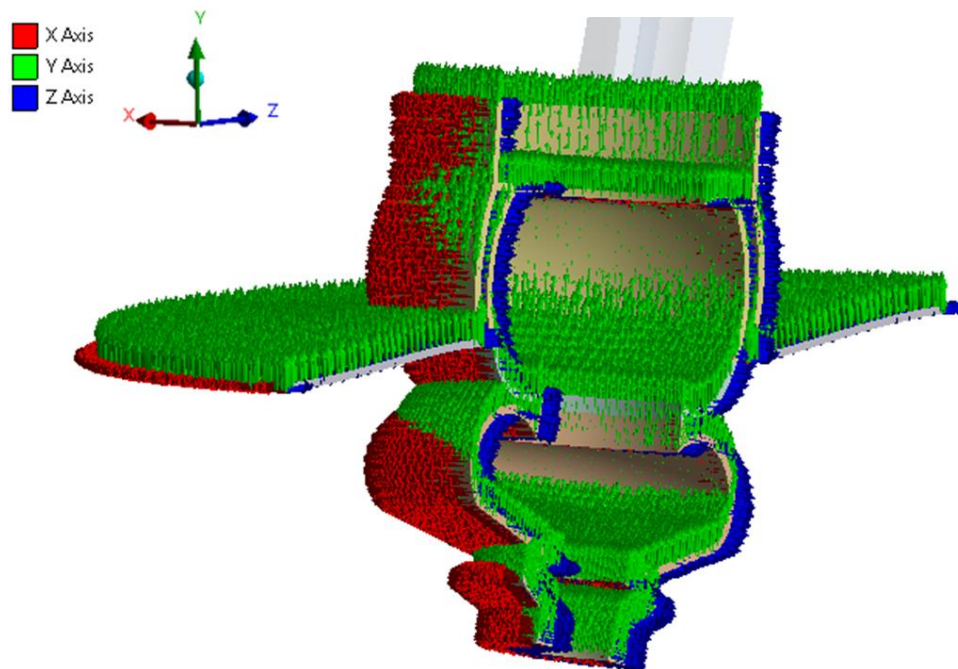


Figure 109: Elemental Triad. Each of the directions in which the socket's elements move are shown separately.

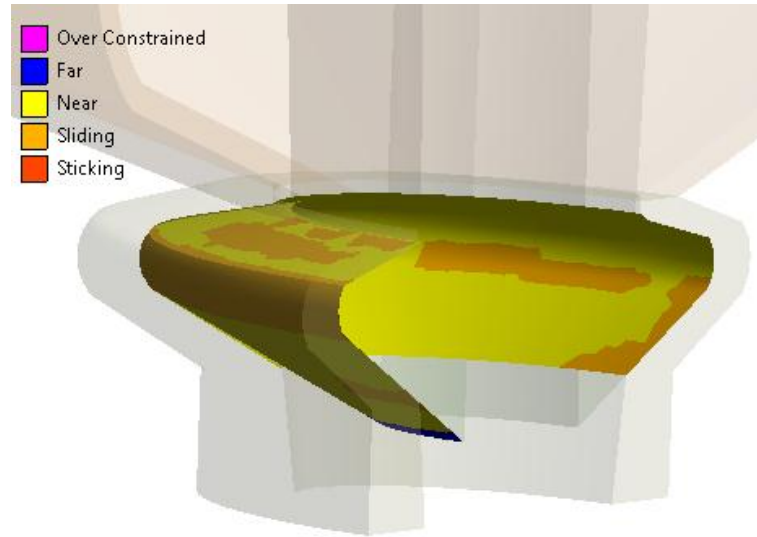


Figure 110: Contact Status, Hair and Socket Base

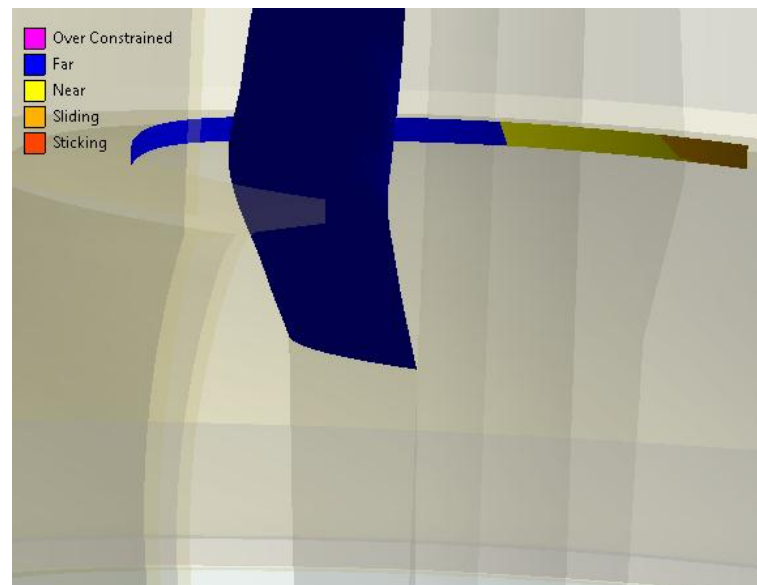


Figure 111: Contact Status, Hair Bulge and Socket Iris

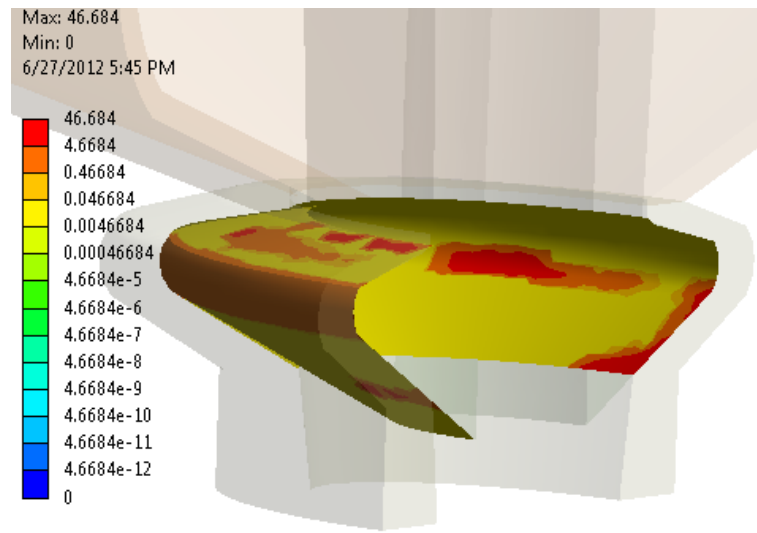


Figure 112: Contact Pressure (logarithmic scale), Hair and Socket Base

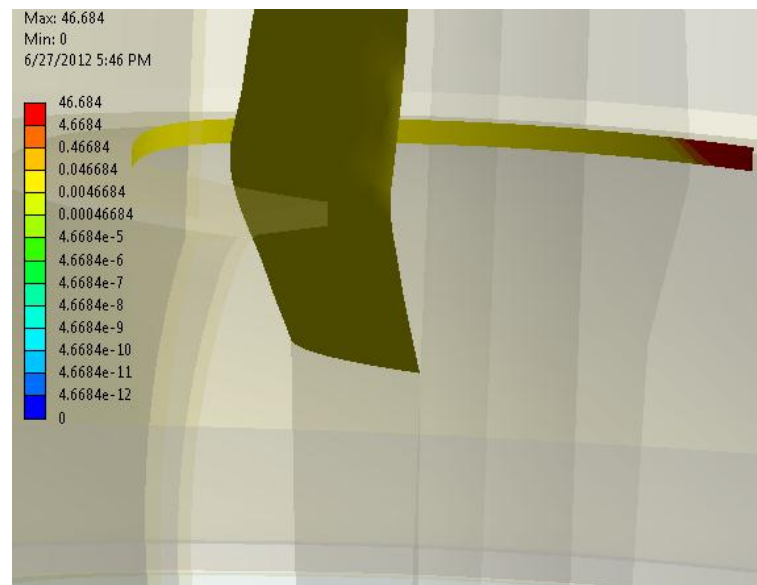


Figure 113: Contact Pressure (logarithmic scale), Hair Bulge and Socket Iris

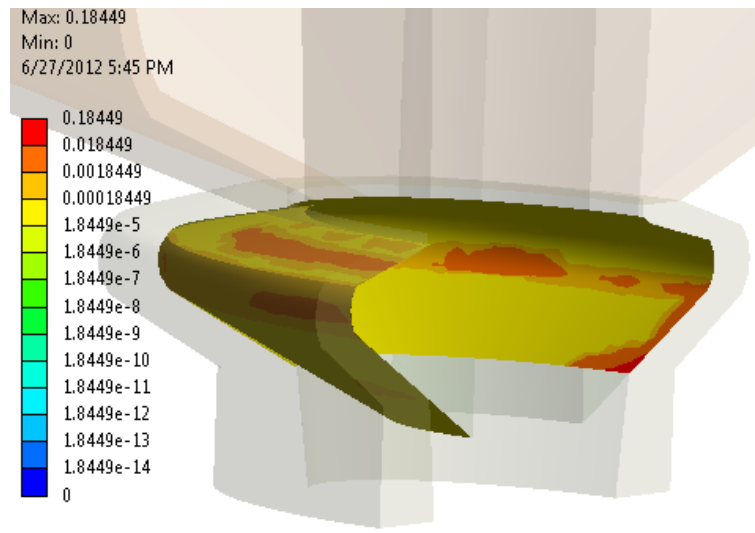


Figure 114: Sliding Distance (logarithmic scale), Hair and Socket Base

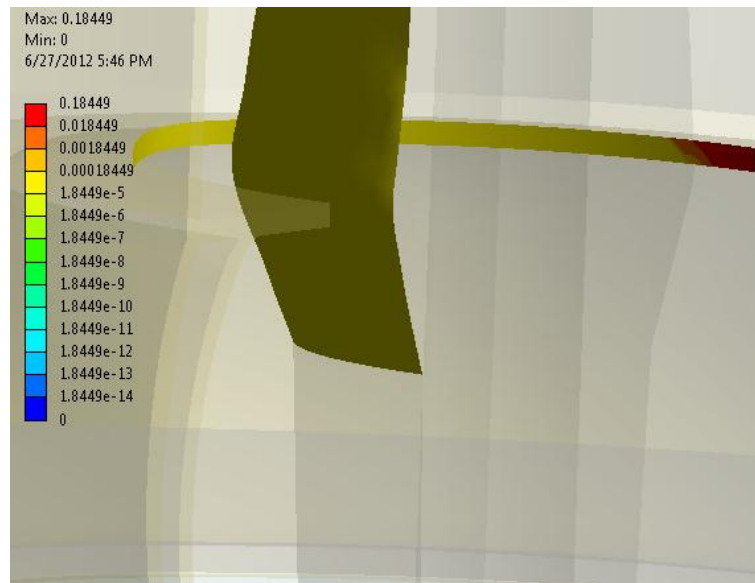


Figure 115: Sliding Distance (logarithmic scale), Hair Bulge and Socket Iris

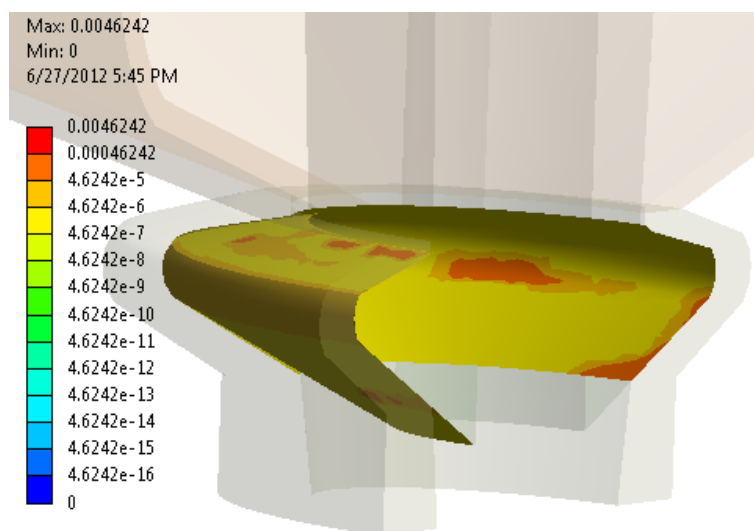


Figure 116: Penetration (logarithmic scale), Hair and Socket Base

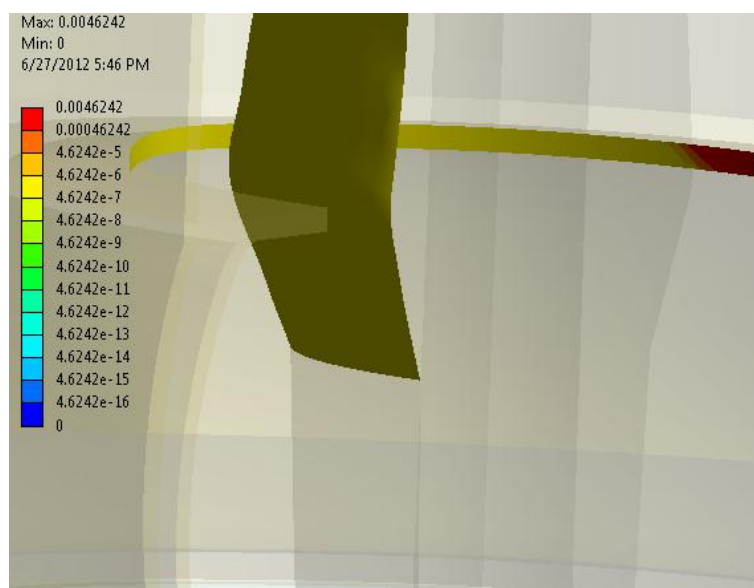


Figure 117: Penetration (logarithmic scale), Hair Bulge and Socket Iris

APPENDIX B

SIMILITUDE ANALYSIS

The drag coefficient and Reynolds number are both dimensionless quantities, and form the two pi groups.

$$\Pi_1 = \frac{F_D}{\rho V^2 D^2} \quad \text{Equation 15}$$

$$\Pi_2 = \frac{\rho V D}{\mu} \quad \text{Equation 16}$$

where F_D is the drag force, V is the wind velocity, D is the characteristic length of the geometry (which is the cylinder diameter in this case), ρ is the fluid density, and μ is the dynamic fluid viscosity.

1. All the dimensional variables first have to be listed. These variables have to be independent of each other. There are five independent variables in the two pi groups: F_D , D , V , ρ , and μ .
2. The variables have to be then expressed in terms of the three basic dimensions L (length), T (time), and M (mass).

$$[F_D] = \left[\frac{ML}{T^2} \right]$$

$$[D] = [L]$$

$$[V] = \left[\frac{L}{T} \right]$$

$$[\rho] = \left[\frac{M}{L^3} \right]$$

$$[\mu] = \left[\frac{M}{LT} \right]$$

Geometric variables have the L dimension only, and dynamic variables have the M dimensions only (25). Variables that either have T only or L and T are called kinematic variables. The number of primary dimensions in this problem is three.

3. Next, the number of repeating variables has to be selected. This number should be the same as the number of primary dimensions the problem contains, so three in this case. The repeating variables chosen are D , V , and ρ . F_D is not chosen as it is a dependent variable.
4. The number of pi groups (two) formed will be the total number of variables (five) minus the number of repeating variables (three).

$$[\Pi_1] = F_D D^a V^b \rho^c \quad \text{Equation 17}$$

The coefficients of any given dimension should sum to zero.

$$[M]^0 [L]^0 [T]^0 = \left[\frac{ML}{T^2} \right] [L]^a \left[\frac{L}{T} \right]^b \left[\frac{M}{L^3} \right]^c$$

Summing L:

$$0 = 1 + a + b - 3c \quad \text{Equation 18}$$

Summing M:

$$0 = 1 + c \quad \text{Equation 19}$$

Summing T:

$$0 = -2 - b \quad \text{Equation 20}$$

From the above equations, $a=-2$, $b=-2$, and $c=-1$, which when substituted in Equation 17 gives:

$$\Pi_1 = \frac{F_D}{\rho V^2 D^2}$$

The second pi group can be calculated in a similar manner.

$$[\Pi_2] = \mu D^a V^b \rho^c \quad \text{Equation 21}$$

The coefficients of any given dimension should sum to zero.

$$[M]^0 [L]^0 [T]^0 = \left[\frac{M}{LT} \right] [L]^a \left[\frac{L}{T} \right]^b \left[\frac{M}{L^3} \right]^c$$

Summing L:

$$0 = 1 + a + b - 3c \quad \text{Equation 22}$$

Summing M:

$$0 = 1 + c \quad \text{Equation 23}$$

Summing T:

$$0 = -1 - b \quad \text{Equation 24}$$

From the above equations, $a=-1$, $b=-1$, and $c=-1$, which when substituted in Equation 21 gives:

$$\Pi_2 = \frac{\mu}{\rho V D}$$

The second pi group can more conveniently be written as the Reynolds number

$$\Pi_2 = \frac{\rho V D}{\mu}$$

5. The two pi groups can now be related as

$$\Pi_1 = f(\Pi_2)$$

or

$$\frac{F_D}{\rho V^2 D^2} = f\left(\frac{\rho V D}{\mu}\right) \quad \text{Equation 25}$$

The Froude number is another dimensionless number that is a ratio of a body's inertial to gravitational forces and is defined as:

$$Fr = \frac{V}{\sqrt{gL}} \quad \text{Equation 26}$$

where V is velocity, g is acceleration due to gravity and L is the body's characteristic length. The Froude number can also be set as a pi group using the procedure outlined above.

$$Fr_{hair} = Fr_{model} \quad \text{Equation 27}$$

Therefore,

$$V_{model} = V_{hair} \sqrt{\frac{L_{model}}{L_{hair}}} \quad \text{Equation 28}$$

APPENDIX C:

CALCULATIONS

Drag Force per Unit Length

r = cylinder radius

η = viscosity of air at 20 degrees C

γ = Euler Constant, 0.577

ν = kinematic viscosity of air at 20 degrees C

U = air velocity perpendicular to cylinder

F = Drag Force

Re = Reynolds Number

$$r_a := \frac{5.75}{1000} \text{ mm}$$

$$Re_a(U) := \frac{2r_a \cdot U}{\nu_a}$$

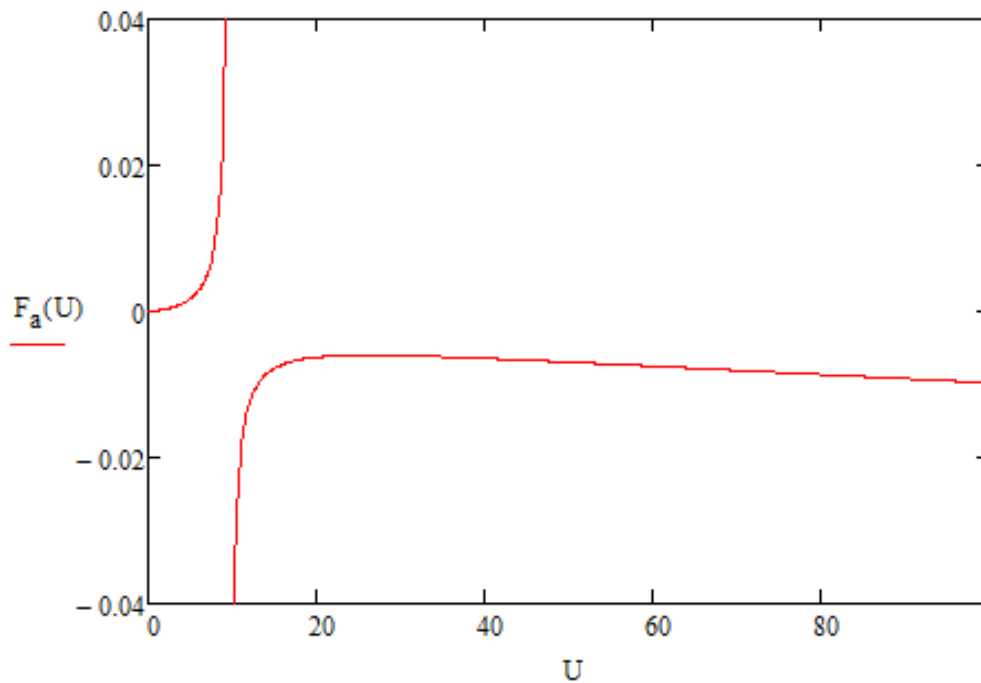
$$\eta_a := 1.82 \cdot 10^{-5} \frac{\text{N} \cdot \text{s}}{\text{m}^2}$$

$$S_a(U) := \left(\ln \left(\frac{8}{Re_a(U)} \right) - \gamma \right)$$

$$\gamma_a := 0.577$$

$$\nu_a := 1.5 \cdot 10^{-5} \frac{\text{m}^2}{\text{s}}$$

$$F_a(U) := \frac{8\pi \cdot \eta_a \cdot U}{2S_a(U) + 1}$$



The plot suggests that at higher velocities (and therefore Re number), Oseen's approximation cannot be used directly and a scale has to be used.

$$r := \frac{5.75}{1000} \text{ mm} \quad U := 85 \frac{\text{mm}}{\text{s}}$$

$$\eta := 1.82 \cdot 10^{-5} \frac{\text{N} \cdot \text{s}}{\text{m}^2}$$

$$\gamma := 0.577$$

$$\nu := 1.5 \cdot 10^{-5} \frac{\text{m}^2}{\text{s}}$$

$$\text{Re} := \frac{2r \cdot U}{\nu}$$

$$S := \left(\ln \left(\frac{8}{\text{Re}} \right) - \gamma \right)$$

$$F := \frac{8\pi \cdot \eta \cdot U}{2S + 1}$$

$$F = 4.107 \times 10^{-9} \frac{\text{N}}{\text{mm}}$$

Scaling Factor to match the drag force the model would be subjected to can be obtained from using the Buckingham Pi Theorem (as presented in Appendix B)

$$L_{\text{hair}} := 1.1 \text{ mm}$$

$$L_{\text{model}} := 1100 \text{ mm}$$

$$V_{\text{hair}} := 85 \frac{\text{mm}}{\text{s}}$$

$$V_{\text{model}} := V_{\text{hair}} \cdot \left(\frac{L_{\text{model}}}{L_{\text{hair}}} \right)^{0.5} = 2.688 \times 10^3 \frac{\text{mm}}{\text{s}} \quad \text{This formulation is also explained in Appendix B}$$

$$\text{ScalingFactor} := \frac{L_{\text{model}}}{L_{\text{hair}}} \cdot \left(\frac{V_{\text{model}}}{V_{\text{hair}}} \right)^2 = 1 \times 10^6$$

$$F_{\text{model}} := F \cdot \text{ScalingFactor} = 4.107 \times 10^{-3} \frac{\text{N}}{\text{mm}}$$

Torque and Spring Constant

f_1 = force per unit length of cylindrical hair shaft edges

L_1 = edge length of cylindrical hair shaft

f_2 = force per unit length of tapered hair shaft edges

L_2 = edge length of tapered hair shaft

n = variable used to find distances from points on the cylinder to the hair's center of rotation

d_1 = moment arm for cylindrical shaft

d_2 = moment arm for tapered shaft

F_1 = force on cylindrical edges

F_2 = force on tapered edges

τ_1 = torque on hair cylinder

τ_2 = torque on tapered hair section

τ_{sum} = total torque on the hair shaft

τ_{total} = scaled total torque that corresponds to the actual geometry of the hair

deflection = horizontal displacement of hair tip from the vertical

height = vertical unchanged height of the cylindrical hair shaft

θ = angular displacement of hair tip from the vertical axis

S_{constant} = spring constant

$$f_1 := \begin{pmatrix} 1.6 \\ 1.4 \\ 1.2 \\ 1.0 \\ 0.8 \\ 0.6 \\ 0.4 \\ 0.2 \end{pmatrix} \cdot 10^{-3} \frac{\text{N}}{\text{mm}} \quad n := \begin{pmatrix} 1 \\ 2 \\ 3 \\ 4 \\ 5 \\ 6 \\ 7 \\ 8 \end{pmatrix} \quad L_1 := 131\text{mm}$$

$$F_1 := f_1 \cdot L_1 = \begin{pmatrix} 0.21 \\ 0.183 \\ 0.157 \\ 0.131 \\ 0.105 \\ 0.079 \\ 0.052 \\ 0.026 \end{pmatrix} \text{N} \quad d_1 := 1071\text{mm} - \frac{131}{2}\text{mm} - 131(n-1)\text{mm} = \begin{pmatrix} 1.006 \times 10^3 \\ 874.5 \\ 743.5 \\ 612.5 \\ 481.5 \\ 350.5 \\ 219.5 \\ 88.5 \end{pmatrix} \text{mm}$$

$$\tau_1 := F_1 \cdot d_1 = 660.083 \text{ N}\cdot\text{mm}$$

$$f_2 := \begin{pmatrix} 0.05 \\ 0.025 \end{pmatrix} \cdot 10^{-3} \frac{\text{N}}{\text{mm}} \quad L_2 := 8.515 \text{ mm}$$

$$F_2 := f_2 \cdot L_2 = \begin{pmatrix} 4.258 \times 10^{-4} \\ 2.129 \times 10^{-4} \end{pmatrix} \text{ N} \quad d_2 := \begin{pmatrix} 18.7425 \\ 10.2275 \end{pmatrix} \text{ mm}$$

$$\tau_2 := F_2 \cdot d_2 = 0.01 \text{ N} \cdot \text{mm}$$

$$\tau_{\text{sum}} := \tau_1 + \tau_2 = 660.093 \text{ N} \cdot \text{mm}$$

$$\text{deflection} := \begin{pmatrix} 0.01 \\ 36.862 \\ 76.299 \\ 106.21 \\ 134.57 \\ 174.81 \\ 200.44 \\ 218.22 \\ 229.36 \\ 239.91 \\ 249.96 \\ 264.26 \\ 273.35 \\ 282.15 \\ 290.67 \\ 298.95 \\ 307.01 \\ 314.86 \\ 322.53 \\ 330.02 \end{pmatrix} \text{ mm} \quad \text{height} := 1048 \text{ mm} \quad \theta := \text{atan}\left(\frac{\text{deflection}}{\text{height}}\right) = \begin{pmatrix} 9.542 \times 10^{-6} \\ 0.0352 \\ 0.0727 \\ 0.101 \\ 0.1277 \\ 0.1653 \\ 0.189 \\ 0.2053 \\ 0.2155 \\ 0.225 \\ 0.2341 \\ 0.247 \\ 0.2551 \\ 0.263 \\ 0.2706 \\ 0.2779 \\ 0.285 \\ 0.2919 \\ 0.2986 \\ 0.3051 \end{pmatrix} \text{ rad}$$

The force was scaled up by 10^6 and the displacement by 10^3 in the model, so they are adjusted while calculating the corresponding torque that would act on an actual cricket hair. Also, the torque is broken down into the load-step fractions *ANSYS* used while ramping the applied load.

		0
$\tau_{\text{total}} :=$	0	3.3005×10^{-11}
	0.05	6.6009×10^{-11}
	.1	9.9014×10^{-11}
	.15	1.3202×10^{-10}
	.2	1.8153×10^{-10}
	.25	2.1453×10^{-10}
	.325	2.4753×10^{-10}
	.375	2.8054×10^{-10}
	.425	3.1354×10^{-10}
	.475	3.4655×10^{-10}
	.525	3.9606×10^{-10}
	.6	4.2906×10^{-10}
	.65	4.6207×10^{-10}
	.7	4.9507×10^{-10}
	.75	5.2807×10^{-10}
	.8	5.6108×10^{-10}
	.85	5.9408×10^{-10}
	.9	6.2709×10^{-10}
	.95	6.6009×10^{-10}
	1	6.6009×10^{-10}
$\cdot \tau_{\text{sum}} \cdot 10^{-9} =$		N·m

	0	
	9.3872×10^{-10}	
	9.0827×10^{-10}	
	9.8033×10^{-10}	
	1.0338×10^{-9}	
	1.0983×10^{-9}	
	1.1352×10^{-9}	
	1.2058×10^{-9}	
	1.3021×10^{-9}	
	1.3933×10^{-9}	
$S_{\text{constant}} := \frac{\tau_{\text{total}}}{\theta} =$	1.4801×10^{-9}	N·m
	1.6034×10^{-9}	
	1.6816×10^{-9}	
	1.757×10^{-9}	
	1.8298×10^{-9}	
	1.9004×10^{-9}	
	1.9689×10^{-9}	
	2.0355×10^{-9}	
	2.1004×10^{-9}	
	2.1637×10^{-9}	