Determination of the Loading on Bird Feather Shafts

Senior Project – Mechanical Engineering – 2008

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Introduction

In this project, structural optimization techniques were used to determine the loading on bird feather shafts. Specifically we looked at a single flight feather shaft from a Canada Goose. This feather shaft was CT scanned and imported as cross-sectional digital images into MATLAB, so that the geometry of the feather shaft could be characterized. A finite element model of the feather shaft was created, and then optimization techniques based on the strength and stiffness of the feather shaft were used to predict the loading.

Motivation/Background

The reason for undertaking this project was to better understand the mechanical properties of bird feather shafts. The information that we have learned from this project will later be applied to applications such as flight, and more specifically micro-aerial vehicles (MAVs). MAVs are used in a number of important applications including military, homeland security, and extraterrestrial flight. Originally we planned to look at hummingbird feather shafts, which MAVs mimic the flight patterns of very closely.

Bird wings are comprised of primary and secondary feathers that together form the lifting surfaces of the wings. The primary feathers emanate from the phalanges and carpometacarpus bones of the manus (hand), and the secondary feathers emanate from locations near the ulna and radius bones of the forearm. Now we can look at a primary feather of a hummingbird and it is important to note that the external appearance of a flight feather of the hummingbird is similar to that of larger birds only much smaller in size, **Figure 1**. This is important because we have examined the feathers of several different birds throughout this project. The feather shaft is made of keratin and divided into two sections, the calamus and the rachis. The calamus is located in the skin and has a consistent circular cross-section comprised of cortex. The rachis is located outside of the skin and supports the vanes. The rachis is comprised of cortex, medulla, and air space, but is of specific interest because of how the cross-section changes along the length of the rachis.

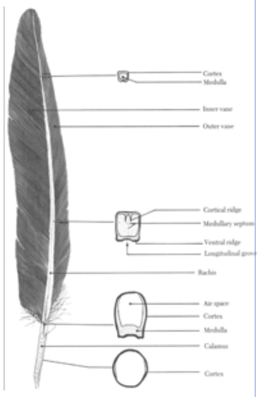

Figure 1 – A typical structure of a flight feather

(image courtesy of Prof. Andrew Rapoff, Ph.D.)

3D Beam Model/Optimization

The first step in the optimization was to develop a 3D beam code to model the feather shaft with the data provided from the geometric characterization. A standard beam code was developed with a typical element being comprised of two nodes, which are each able to have forces and moments in the x, y, and z directions. For our final model we simplified this to a force in the y direction, and a moment to correct for the force not being exactly on top of the shaft, **Figure 5**.

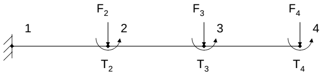

Figure 5 – A simplified 3-element model with node 1 fixed with respect to 6 DOF

With this model setup in MATLAB we then were able to run this model through an optimization code to determine the loading on the bird feather shafts as desired.

The goal of the optimization is to determine the loading on the feather shaft, by determining the maximum amount of stress that the feather shaft could handle before it would fail. We hypothesized that the feather shaft geometry has adapted over time so as to induce a state of uniform stress along the length of the shaft. With this assumption in mind the specific function that we looked to minimize can be seen below.

$$\sum_{i=1}^{N}(\sigma_u - \sigma_{1_i})^2$$

This function is based off of two variables: σ_u, which is the ultimate stress of the feather shaft, and σ_{1i}, which is the maximum nodal stress for each element in the finite element model.

Before we ran the optimization we also needed to parameterize our loads so that they could be determined at any point along the feather shaft. To do this we picked four pressure nodes along the feather shaft with two at the beginning and end, and the other two evenly spaced in between. By using shape functions we were able to determine the loads at any point along the feather shaft, **Figure 6**.

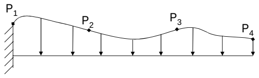

Figure 6 - A model of beam with the four pressure nodes used to determine the loading

A univariate search method was selected for the optimization. We are in the process of generating results.

Summary/Conclusions

The majority of our initial goals were realized by the end of this project. In MATLAB, we developed a 3D beam code within a univariate optimization code that could take any geometry as its input. As planned this code would determine the loading on the geometry based off of the constant stress hypothesis. Additionally, this code would provide an image of the geometry under this loading. We were also able to obtain cross sectional data for 12mm of a Canada Goose feather nearest to the wing. This data came out as expected with the highest moments of inertia occurring closest to the wing, and decreasing as we moved outward along the length of the feather shaft. Based off of these trends we were able to assume that the moments of inertia would continue to decrease as we continued to move outward along the length of the feather shaft, which was expected. This project has been very successful so far, and we are currently in the process of generating results from our optimization code. Additionally, once we gather more cross sectional data we will be able to apply the optimization code to this geometry and determine the loading on the Canada Goose feather shaft as desired.

Technical Approach

To characterize the geometry of the feather shaft we CT scanned the feather shaft in sections of 12mm using a Skyscan 1074. From these scans bitmap images of the cross-section of the feather shaft were taken every .028mm. These files were run through a MATLAB code written by Neel Bhatavadekar to determine the area and moments of inertia of the cross-section. This information will eventually be inputted into our finite element code, in order to determine the loading on the feather shaft by optimization.

Characterization of Feather Shaft Geometry

The CT Scanning was done with a Skyscan 1074, **Figure 2**, that Prof. Rapoff has in his laboratory. This machine works in a very similar way to that of a CAT scan machine used in most hospitals. The only difference is that in a hospital the machine rotates around the person, while in this application the specimen being scanned is rotated on a platform. Also due to the size of the machine it is only able to handle very small specimens. As a result multiple scans were needed to fully characterize the geometry of the feather shaft.

After running the scanner along with two associated programs we received an output of the cross sections in a bitmap image form, **Figure 3**. These output files were then inputted into the MATLAB files written by Neel Bhatavadekar to determine the cross-sectional properties. Specifically the program found the area of the cross section as well as the centroidal and principal moments of inertia. It is important to note that the scan outputted 400 cross sectional images. We were able to pick out the data every 1mm along the feather shaft, based off of the fact that each cross section was spaced .028mm from one another. Once we had this smaller set of data which was more manageable we saw how the principle moments of inertia changed as we moved outward along the feather shaft. These results are compiled in **Figure 4** seen below. From the already determined trend lines, **Figure 4**, it makes sense that the moments of inertia should continue to decrease as we move outward along the feather shaft.

Figure 2 – An image of the Skyscan 1074

(image courtesy of http://www.microphotonics.com/skyscan/1076/skyscan1074.gif)

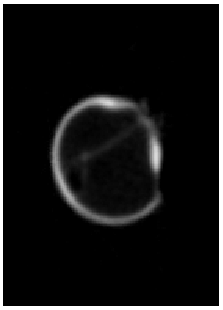

Figure 3 – An zoomed in image of an arbitrary cross-section of a Canada Goose feather shaft

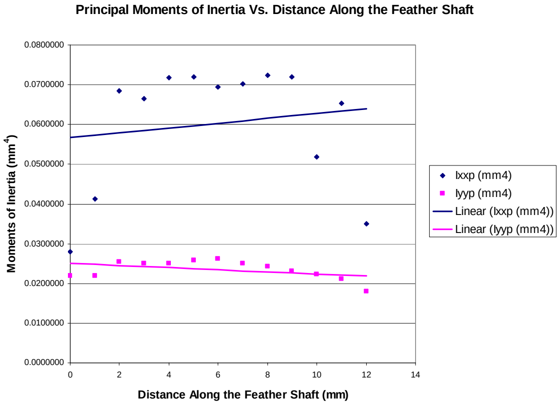

Figure 4 – A graph of the preliminary results from the cross sectional data of the first 12mm of the Canada Goose feather shaft

Future Work

We were able to complete a substantial amount of work during the last two terms of this project, but there is still a lot more that can be done with this project. The current method for obtaining the cross-sectional data of any scanned specimen takes a substantial amount of time, and this time could be substantially reduced if the outputs from the scanner software could be converted into a SolidWorks model. This is because SolidWorks could then easily output the cross-sectional data desired. It would also be interesting to compare the data for a variety of birds, and this should not take too much more time give the work we have accomplished on this project. This topic has not had a lot of research done on it, which leaves open a lot of possibilities.

Acknowledgements

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