Two-Directional Fiber Optic Load Cell

Heather R. Everhart[1], Sephia G. Hendrix[2], Shelbie R. Jackson[3], Javen S. Renner[4]
Mississippi State University, Starkville, MS, 39759, United States of America

The Bagley College of Engineering at Mississippi State University requires a cost-effective multi-axis force sensor that can be used in their wind tunnel and other equipment. To address this issue, a multi-axis load cell and testing rig using fiber optics was developed. The design features a cylindrical metal bar with optical fibers arranged in a parallel configuration on the exterior surface. The team went through several trial-and-error designs to arrive at the best overall concept for the project. The final design includes a connection point that will be inserted into a standard-sized cavity in a model subjected to forces during testing. The resulting testing data will provide multi-axial force measurements in strain units that will be converted into force units for practical applications. The device will be calibrated by applying specific loads in axial directions to ensure accurate results. Additionally, strain gauges will be used to validate the results obtained from fiber optic testing. The project's outcomes will indicate whether further advancements in force sensing using fiber optics would be worth pursuing.

Nomenclature

A	=	area of model body
C_L	=	lift coefficient
E	=	modulus of elasticity
I_{xx}	=	moment of inertia about X plane
I_{xz}	=	moment of inertia about X-Z plane
I_{yy}	=	moment of inertia about Y plane
I_{zz}	=	moment of inertia about Z plane
L	=	lift
M	=	pitch moment
N	=	yaw moment
P_A	=	axial force
P	=	roll rate
Q	=	pitch rate
R	=	yaw rate
S	=	planform area
V	=	velocity
ε	=	strain
ρ	=	air density
σ	=	stress

I. Introduction

THE fundamentals of wind tunnel testing data rely on the detection of forces in roll, pitch, and yaw directions. Experiments that lack forces in the X, Y, and Z directions are of little value. A fiber optic load cell was designed to attempt to improve the traditional foil gauge balances. The load cell was fabricated, tested, and improved to achieve optimal results. The goal of this project was to develop a two-directional system that utilized fiber optics to sense forces along X and Y axes by integrating fiber optics into an aluminum rod. The fiber optic was adhered onto the

[1] Student, Aerospace Engineering, Walker Hall, Mississippi State, MS, 39762, Student - 1369277.
[2] Student, Aerospace Engineering, Walker Hall, Mississippi State, MS, 39762, Student - 1422147.
[3] Student, Aerospace Engineering, Walker Hall, Mississippi State, MS, 39762, Student - 964337.
[4] Student, Aerospace Engineering, Walker Hall, Mississippi State, MS, 39762, Student - 1422753.

surface of the metal rod using epoxy. This model was configured and tested in the wind tunnel, and the LUNA machine measured the deformation strain. The collected data has been converted into readable units of force. Upon completion, this project may result in a patentable product-system capable of measuring forces and moments during model experimentation.

The application of fiber optics in research studies has been around for years. Literature reviews were initially conducted to gain a collective understanding of the use of optical fibers as well as to gain more complex knowledge of the underlying technology that makes them a valuable choice for this project. In reviewed articles, optical fibers were used in several ways to read deflection and strain readings on a body where force is applied. Small readings were taken in some applications by using fiber optics and mirrors to measure light refraction off objects moving in water. Meanwhile, other applications researched measured forces at hypersonic speeds in a wind tunnel at which the optical fibers were negatively affected due to the large thermal intensity. There are also studies where the fiber optics were used similarly to this project but with strain gauges attached to back up the data that was read. Additional research was conducted to make an informed decision on which metal and epoxy materials to use in this project to achieve the best results.

The specific application of fiber optics for this project is to be used as a force gauge. When the fiber optic strand is deformed, a strain reading will be produced. This strain reading will then be converted into force measurements to give the user beneficial data. While this is not the first approach to create a fiber optic force sensor for wind tunnel use, each one has a different approach due to all the potential that comes with using optical fibers.

II. Model Concept Design Development

The design for this project went through several variations. Different physical design concepts to localize the deflection were evaluated. Using a bundle of fiber optic wires embedded into resin versus using individual wires on a metallic structure was also considered. Each design was carefully evaluated based on its advantages, disadvantages, and ability to produce the desired results.

Initially, the project was based on the concept of using a bundle of optical wire embedded in a cylindrical solid resin much like a ball. However, further evaluation revealed that this approach with the use of fiber optics would not produce the results desired. There were concerns about crossover interference, misconstrued outputs within the data, and the rigidity, strength, reusability, and durability of the resin. All these concerns prompted changing the overall scope to use a metallic material as the main structure of the design with fiber optics adhered to the exterior.

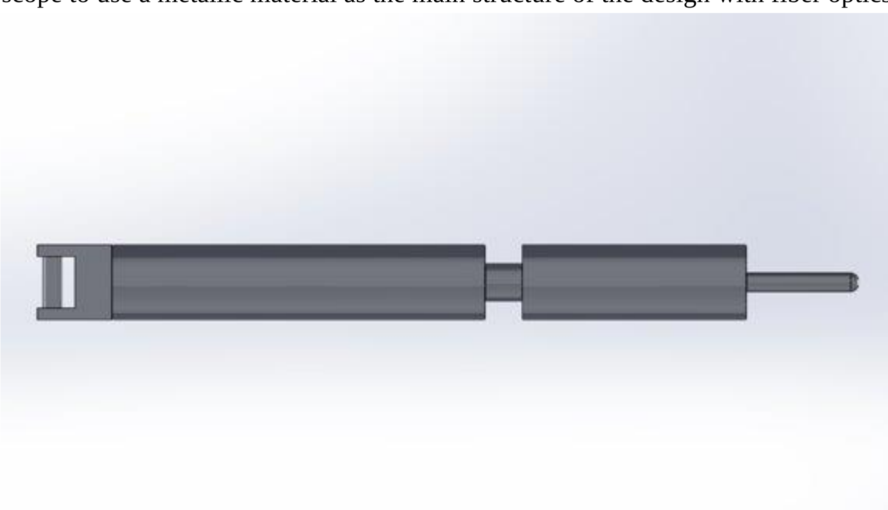

Figure 1. CAD rendering of previous concept design.

The idea of localizing the deflection of the bar was a design concept that went through multiple iterations. The first design considered is notching the bar at a specific point as shown in Figure 1 to allow for the deflection to be localized, thereby amplifying the fiber optic data readings. The optical fiber would be adhered to the surface of the bar but bridge across the notched section giving it the ability to respond based on perceived deflection of the fibers. Farther iterations of this notched concept included two notches on the bar to allow for higher accuracy. An alternative design included the idea to have empty space through a section of the bar to localize the deflection. This design progressed from two holes to four holes to account for both degrees of freedom.

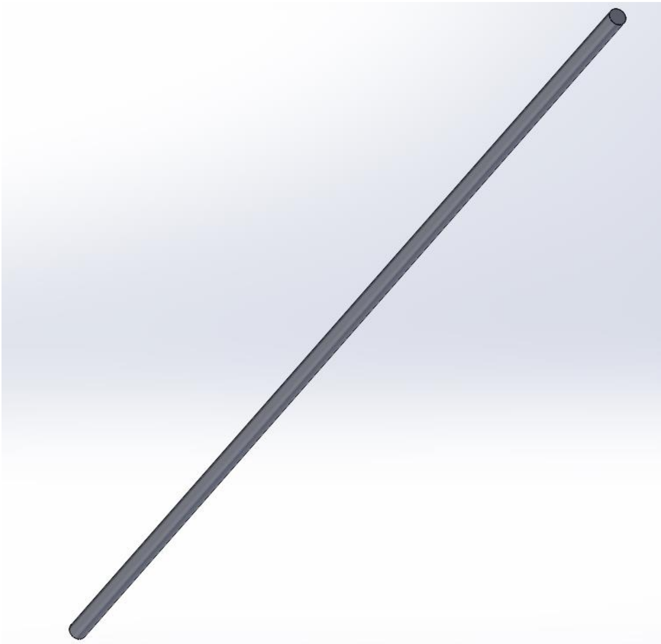

Figure 2. Final concept design.

The final design chosen for this experiment was a simple cylindrical bar with fiber optic strands running the length of the testing area in a parallel pattern. This design, as seen in Figure 2, was chosen after considering all of the factors needed to test this idea. The previous designs were deemed inadequate for the purposes of this project. The designs included removing a portion of the structure, which would affect the reusability and longevity of the force sensor. With the designs having notches or holes that had the fiber optic wire crossing open space, there was large potential for hysteria in the data at the beginning and end points of the fiber where it bridges the gap in the material. An additional disadvantage of the previous designs concerned the fiber optic wires breaking across the gap or being damaged by microscopic cracks.

For the final design with a solid bar, the optical fiber will be attached to the bar using an epoxy adhesive to ensure proper positioning. The scope of the project being limited to two degrees of freedom allows for the location and amount of optical wire to be optimized. The optical wire will be placed in four parallel lines down the bar. Each line will be offset by 90 degrees to have exact placement on each axis. Although there are only two axes being evaluated, having the four lines of optical fiber will allow for heightened accuracy of the output. The deflection is not localized in this design, but it allows us to take an average of the deflection along the length of the bar. One advantage to this design is that there are no gaps in the structure that can cause additional stress on the fiber optic wire. Additionally, with the solid bar, the concern of longevity or reusability is at a minimum compared to the other designs considered. The force sensor will be connected to the wind tunnel through a pre-existing installed contraption allowing for quick editing and length control. The connection point on the force sensor to a model will consist of a standard apparatus that is easy to duplicate and design to when other students are using the system.

III. Equipment (Luna ODiSI-B)

Figure 3. LUNA ODiSI-B system.

Luna Innovations' Optical Distributed Sensor Interrogator (ODiSI-B) uses swept-wavelength coherent interferometry to measure temperature and strain using optical fiber as the sensor. The ODiSI-B can test a structure at many specific points of interest over an extended area. Optical fibers undergo well-defined physical changes due to changes in temperature and strain. The ODiSI-B is therefore, at any given time, able to measure the strain or temperature throughout the length of the fiber, at intervals as low as 0.64mm. By comparing measurements made at two separate times, the ODiSI-B calculates and displays the change in strain or temperature. The ODiSI-B utilizes fiber optic sensors ranging from 1m to 20m in length to make distributed strain and temperature measurements of a test article. Due to the small diameter of the fiber

(<0.2mm), the fiber can be routed into locations not usually possible with foil gauges and thermocouples. The ODiSI-B can differentiate the sensing fiber from other fiber optic devices (patch cables, switches, etc.) and is therefore able to be reconfigured without a change in measurement data.

IV. Experiment Mathematical Analysis

The strain readings that will be outputted from the Luna ODiSI-B must be converted into values of force to determine the reliability of the fiber optic load cell design. The model will be assumed as a two-directional cantilever beam, achieving force values along the X and Y axes. The modulus of elasticity of the material of the bar will be used in Hooke's Law, as shown in Eq. 1 (Allen & Haisler, 1985), to convert the strain values output from the data readings to stress values.

$$\varepsilon = E\sigma$$

Eq. 1

Next, using the integral of the stress with respect to the area of the model (Eq. 2), the value of uniaxial force loading will be found shown in the equation below.

$$P_A = \int_A \sigma \, dA$$

Eq. 2

This structural analysis will be performed for the values measured along the X and Y axes separately. The lift equation (Eq. 3) below is given as a relationship amongst air density, velocity, planform area, and the lift coefficient.

$$L = \frac{1}{2}\rho V^2 S C_L$$

Eq. 3

Equations 4 and 5 are the pitch and yaw moment equations in terms of six degrees of freedom. These equations are shown as relationships between pitch, roll, and yaw rates and moments of inertia of the model body.

$$\dot{R}I_{zz} - \dot{P}I_{xz} + QRI_{xz} + \left(I_{yy} - I_{xx}\right)PQ = N$$

Eq. 4

$$\dot{Q}I_{yy} + PR(I_{xx} - I_{zz}) + (P^2 - R^2)I_{xz} = M$$

Eq. 5

To ensure the accuracy of the retrieved data, the lift, pitch, and yaw aerodynamic force and moment equations will be used to evaluate the needed forces in realistic terms and for comparison of equivalency to the measured force data.

V. Experimental Setup

Testing has not been performed to this date, however set up and requirements to implement both dry testing as well as wind tunnel testing are known and discussed in this section.

A. Dry Testing Setup

In dry testing, both aluminum and steel bars will be evaluated to determine the strength and elasticity up to a maximum weight. Limitations come with using the Luna ODiSI-B, such as noise and sensitivity related to detecting small load changes. For each material, the minimum weight needed to produce usable data will be determined through testing. This must be data readings that are stronger than the vibrational noise standardly produced. Additionally, the maximum magnitude of force that the bar is capable of handling without permanent deformation to the metallic structure or fiber optic wire needs to be determined.

The length of the testing area must be determined. While the bar itself will be longer than just the testing area, that is the most important section. This section's length needs to be long enough to acquire an adequate amount of data but not so long that it skews the results due to extreme deflection.

To determine the sensitivity of the software output, the change in weight must be evaluated. To define the minimum change that the system can detect, single pound weights will be added until the system detects a change in weight. This value is pertinent to advance on to wind tunnel testing. Knowing how small or large of an increment there can be between detected weight values will allow us to know what angle of attacks to use for wind tunnel testing. The material used will be finalized based on the results of this variation and the maximum and minimum weight that each material can withstand. The goal is to pick the material that is strong enough to handle the necessary force loads for testing but flexible enough to detect the slight changes in force.

Another goal of dry testing is to determine if the strain values received from using the Luna ODiSI-B result in the final force values applied. The strain values received will be converted into force values usable for the experimenter in a wind tunnel. When forces of a known magnitude are applied to the bar strain values will be recorded and then converted to force values, these force values should then be equal to the applied forces. This would validate that the conversions from strain to force are accurate.

B. Wind Tunnel Testing Setup

The second stage of testing will involve using a wind design in the wind tunnel at Mississippi State University. Once all specifics are known including material, length of the bar, accuracy of conversion values, maximum and minimum strength and all results from dry testing are obtained, wind tunnel testing will be able to begin.

A 2-D wing design that spans the entire width of the wind tunnel will be used to avoid wall and vortex interference. The selection of a NACA airfoil will be decided to create a model of the 2-D wing that will be inserted into the wind tunnel for testing. The advantage of using a NACA airfoil allows previous testing data to be available to compare results. The goal is for testing data received from this experiment to match up to that of previous testing data for the specific NACA airfoil at varying angles of attack.

Using the 2-D wing design allows for an evaluation of lift and yaw forces to be separated. The ring would be oriented horizontally to evaluate the lift force at a particular velocity and angle of attack applied within the wind tunnel testing environment. To evaluate the yaw force, the ring would be oriented in a vertical fashion at set velocities and angles of attack. Having the ability to evaluate these forces separately allows for validation that the obtained values are accurate.

VI. Goals for Results

Testing has not been completed; however, the goal of the project is to have the properly applied forces output in the data. With appropriate use of calibration, the lift and yaw forces received in the data from testing should align with that of results from standard testing using strain gauges. The testing should also line up to previous testing results available for the specific NACA airfoil being used.

If the testing data does not produce the expected results, there will be an evaluation to find where errors occur. Dry testing will be performed to ensure that the physical bar and fiber optic set up is working properly and has not been damaged in any way. Once that is complete, farther evaluation will be conducted to determine why dry testing produces applicable results, but wind tunnel testing does not.

If all testing in the localized directions produces the expected results, the option to move on to 3-D testing is available. The results between the two testing set ups will be compared to verify if the fiber optic testing is producing appropriate results. Additionally, the ability to see how airflow around the 3-D wing affects the results produced.

VII. Application

Within this project's scope, using fiber optics in place of strain gauges could have effects larger than just 2-D strain evaluation. The project, with more work and time, could transition into a 3-D model considering wing tip vortices as additional variables. This would be able to replace conventional strain gauges and force balances with easier integration and reliable results if the institution had a LUNA ODiSI-B or comparable technology.

This design could lay the groundwork for wide use of fiber optics in force sensing. The foundation of this project could be used for wearable technology, underwater hydrodynamic evaluation, travel infrastructure security and evaluation like bridges and roads, civil evaluation, and extensive wind tunnel evaluation when the fiber is embedded into the skin or core of the design.

VIII. Conclusion

There is much more to learn about the benefits of utilizing fiber optic wires in the aerospace industry. This includes further research to be worth developing when considering using fiber optic wires to obtain forces acting on a body in an aerodynamic setting. Students developed a solid basis of the concept to begin testing using the simple solid bar and parallel fiber optic pattern design. The testing methods and procedures are also set up for success in finding more information to see how the use of these fiber optics can be further investigated. The model will be fabricated, set up to the attachment points, and sensitivity tested. Then, the 2-D wing design may be tested to gather data from the fiber optic wires. This data may then be cross-referenced with already known data and data gathered from strain gauges to determine the accuracy and usefulness of the fiber optic force-sensor design. This project may also be developed further than the scope of this paper to encapsulate a larger field of view, perhaps using a different fiber optic force gauge design or to include 3-D models.

Acknowledgments

The authors appreciate the advice and support from the faculty in Mississippi State University's Aerospace Engineering Department.

References

[1]Drake, D., Sullivan, R., and Wilson, J., "Distributed strain sensing from different optical fiber configurations," Inventions, vol. 3, 2018, p. 67.

[2]García, Y. R., Corres, J. M., and Goicoechea, J., "Vibration detection using optical fiber sensors," Journal of Sensors Available: https://www.hindawi.com/journals/js/2010/936487/#abstract.

[3]Vasudevan, B., Padbidri, S., and Chandra Kishore, M., "Flow diagnostics using fibre optics," Sadhana, vol. 32, 2007, pp. 7–18. (https://www.ias.ac.in/article/fulltext/sadh/032/01-02/0007-0018)

[4]Rev. Sci. Instrum. 76, 043704(2005); https://doi.org/10.1063/1.1889233Submitted: 17March2004 • Accepted: 22January 2005 • Published Online: 01 April 2005

[5]"Luna Innovations | fiber optic sensing and measurement systems" Available: https://lunainc.com/sites/default/files/assets/files/resource-library/ODiSI-B-Users-Guide.pdf.

[6]Allen, D. H., and Haisler, W. E., Introduction to Aerospace Structural Analysis, John Wiley & Sons, February 1985.