Development of a Robust Wind Tunnel Balance for Wingsuit Aerodynamic Testing

by

Timothy Allen Sestak

Submitted to the

Aviation, Aeronautics, and Aerospace International Research (A^{3}iR) Conference

January 14-17, 2015

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Background

Flying wingsuits is the fastest growing facet of skydiving. A wingsuit is a usually a fabric construction, worn on the human body with cloth membranes between the arms and body and between the legs of the wearer with the intent to provide an aerodynamic surface that allows the human body to glide through the air.

Current advanced wingsuit designs provide approximately a 3 to 1 glide ratio (Robson & D'Andrea, 2010). A typical wingsuit is shown in Figure 1. The wingsuit flyer glides approximately 3 feet forward for every one foot downward when flying for maximum glide. For comparison a common general aviation aircraft like the Cessna 172 has a power-off glide ratio of approximately 9 to 1, a high performance sailplane may have a glide ratio in excess of 30 to 1. Wingsuit performance is surprisingly poor and while the sport is exhilarating and inspiring the

Figure 1. The author flying his wingsuit

author believes the materials and methods of constructions of contemporary wingsuits are aerodynamically unsound and seriously degrade performance. It is possible that changes in materials used for construction of wingsuits and changes in the basic aerodynamic structure of the suit could double current glide ratios while maintaining the basic character of a flexible aircraft that is worn on the body like a wingsuit. Embry-Riddle undergraduate research students formed a group to assist in the research required to improve wingsuit performance and named the group, *Team Eagle Wingsuit*.

The Need for Wind Tunnel Testing of Wingsuit Technology

In the case of this study of wingsuit aerodynamics, the initial hypothesis was that woven fabric on an airfoil surface, as used in current wingsuit construction, acts as a seriously contaminated airfoil. Contaminated airfoil surfaces have been repeatedly shown in the literature to greatly reduce lift coefficients (Gregory & O'reilly, 1973; Reuss, Hoffman, & Gregorek, 1995; Timmer & Schaffarczyk, 2004). One of the simplest experiments to verify this hypothesis would be to measure the performance of lift and drag of an airfoil before and after the application of a woven fabric surface. Another observation is that the ram-air inflated airfoils used for wingsuit arm wings often deform in flight especially at the leading edges where airflow dynamic pressure is the greatest. Wind tunnel testing allows for a controlled environment where the aerodynamic variables of airspeed and angle of attack can be controlled systematically. The effect on lift and drag of various surface textures and the effect of distortion of the leading edge on ram-air inflated airfoils can then be quantified.

Wind tunnels are used for basic aerodynamic research of many sorts, from aircraft to automobiles and from airfoils to Olympic bobsleds and bicycles. In most cases it is important to measure the aerodynamic forces imposed on the test objects. The aerodynamic forces can be measured a variety of ways with a variety of sensors, each of which has advantages and disadvantages.

The equipment used to measure the aerodynamic forces on test articles in a wind tunnel is usually referred to collectively as *the balance*. The origin of this term is from times past when the force measuring devices were literally weights balanced on the end of long moment arms as used by the Wright Brothers and shown in Figure 2.

> “...you can see the genius of the Wright brothers. They devise these little balances. They’re built out of old hacksaw blades and bicycle spoke wire and they pin these little metal airfoil models on them. The fan starts moving at twenty-five mile an hour wind through that tunnel and the little balances move in such a way that they drop out the precise figures you need to calculate the coefficients of lift and drag.—Tom Crouch, author” (Garrigus, 2003)

Figure 2 . The balances used in the Wright brother’s first wind tunnel

The experiment at the origin of the development of the balance described in this paper was a study of wingsuit aerodynamics. There are numerous balance designs commonly used. The closed circuit wind tunnel at Embry-Riddle Aeronautical University’s, Tracy Doryland Wind Tunnel laboratory has a very useful modular test section design, shown in Figure 3 and Figure 4, where various experiments can be prepared in separate test sections and then moved interchangeably into the wind tunnel for study.

Functional Requirements

For this experiment the functional requirements of the balance necessary for successful completion of the experiment included:

a. Structural support for the balance hardware must fit into the available installation space in the modular test sections used by the Embry-Riddle Tracy Doryland Wind Tunnel Laboratory closed circuit wind tunnel as shown in Figure 3 and Figure 4.

b. The balance, power supply, and data acquisition system must fit into the available space in the modular test section

c. The system must be easy to use in the modular test section with simple, durable, and reliable, connectivity of sensor and data acquisition interfaces

d. The system must ensure reliable and repeatable test article attachment, position, and stability

e. The sensors and data acquisition system must be able to measure and store accurate and valid normal (lift) and axial (drag) force data within the expected ranges

f. The system must have provisions for protecting the balance from the possible adverse effects of uncontrolled flapping of flexible airfoils

Wingsuits: aeroelasticity and flutter taken to new extremes

Requirement f. in the above list, is the requirement primarily responsible for the need for the highly robust design of this balance. Ram-air inflated airfoils made of fabrics and other flexible sheets of material may oscillate and flap violently in the wind tunnel in free flow airspeeds of 60 to 140 knots. This requires the equipment used to measure the forces of lift and drag to be unusually structurally strong and stable while still allowing for the accurate measurement of lift and drag forces.

The initial test article to be used will be a rigid NACA 4418 airfoil 24” in span and 12” in chord. The NACA 4418 airfoil has a large diameter leading edge, is a relatively thick airfoil section, it also has a slight positive camber on the lower surface with a relatively large mean camber. The NACA 4418 airfoil was chosen as a baseline airfoil because its basic shape is similar to airfoils currently used in wingsuit construction. This low aspect ratio wing will be used to develop a baseline of performance for this study. First the baseline airfoil will be tested with a smooth rigid surface. Then the airfoil will be covered with fabrics and other materials like polyfilm laminate plastics and mylar film that are currently used for wingsuit construction. Ram-air inflated, fabric airfoils, similar to those currently used in wingsuit construction will also be tested. There exists the potential for the relatively large, ram-air inflated, fabric airfoil to flap

Figure 3 . Members of Team Eagle Wingsuit working on the modular test section for the Embry-Riddle Aeronautical University wind tunnel at Prescott, AZ. In the background is the wind tunnel with another test section module installed for use.

and oscillate uncontrolled in the wind tunnel airflow. The oscillatory loads imposed by such action could easily damage the fragile precision balances normally used in the Embry-Riddle wind tunnels. The balance design used for wingsuit aerodynamic researchwas required to accurately measure the lift and drag forces generated by the various configurations tested while being highly resistant to damage caused by possible severe oscillations of the test articles.

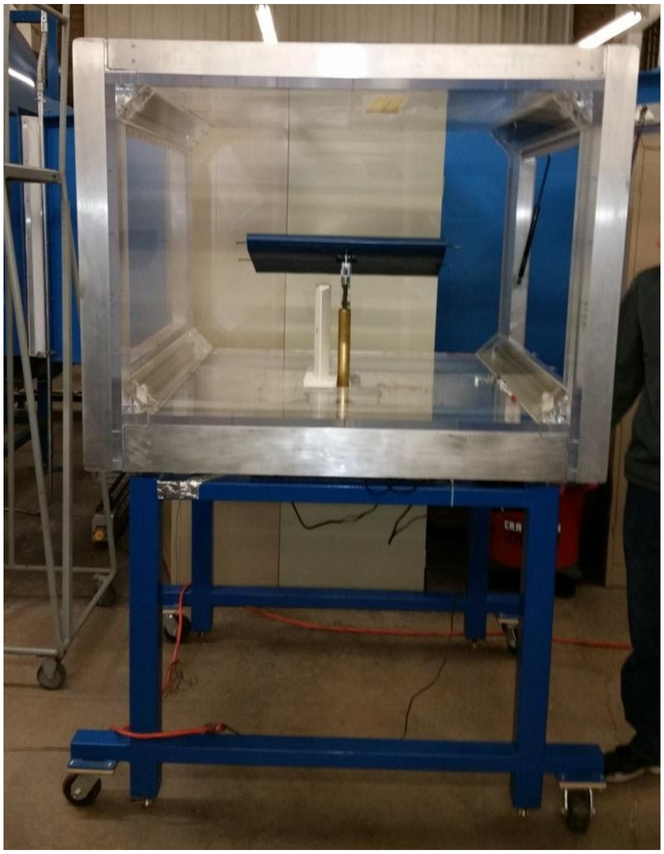

Figure 4. The modular test section used by Team Eagle Wingsuit removed from the wind tunnel in the Tracy Doryland Wind Tunnel laboratory at ERAU Prescott, Arizona with the balance and initial test article installed.

Design Decision Factors

The Embry-Riddle Aeronautical University, closed circuit wind tunnel in the Tracy Doryland Wind Tunnel laboratory is electrically powered and surrounded by other smaller electrically powered research wind tunnels and other electrical equipment. The electro-magnetic environment of the wind tunnel has been shown to be noisy and detrimental to unshielded strain gauge sensors so selection of sensors less susceptible to electric noise was desirable. This experiment requires the measurement of the lift and drag forces generated by the test articles and an accurate and reproducible angle of attack measurement.

Most research quality balances are made to determine three forces and three moments aerodynamically imposed on the model. Aerodynamic studies usually label these forces and moments: Normal, Side, and Axial, Forces; and Pitch, Yaw, and Roll, moments. A full 6-component balance measures all three forces and all three moments. Costs of commercially available, highly accurate balances can easily approach 100 thousand dollars. Two or three component balances can cost tens of thousands of dollars.

No commercially available balances were found that could meet both the need for strength and the modest budget allowed for this initial investigation of the effects of wingsuit materials on lift and drag. Research revealed several simple balance designs, which could be readily modified to support the needs of this study. The need for only two components, lift and drag, simplified the construction of the balance used for this study.

One important design decision is the use of either an external or an internal balance. External balances work outside the test article and can be constructed to be inside or outside the wind tunnel test section. The balance is externally connected to the test article and this introduces interference in the wind flow. Generally an external balance allows the changing of test articles easily which is a significant consideration in the wingsuit study since the test article will be changed several times. The complexity of the balance is primarily dependent on the components of force and moment to be measured.

Internal balances are generally embedded in the test article with the mechanical support for positioning in the test section and sensor feeds exiting the test article downstream in the wind flow. The complexity of the test article is increased by the need to integrate the balance structurally in each test article. The balance must be calibrated for variations in the center of gravity and the aerodynamic properties of each test article. Installation of new test articles is more complex with an internal balance. Most internal balances are commercially made, delivered pre-calibrated, and use custom data acquisition systems. The force and moment measurments vary and increased capability rapidly increases costs.

The decision was made to develop an external balance with the attachment armature projecting into the wind tunnel. The modular test sections of the ERAU wind tunnel are constructed of a one-inch thick clear lexan test section with an aluminum frame, mounted on a sturdy tubular steel base as shown in Figure 4. Between the floor of the test section and the tubular frame is an approximately 6 inch space where it was decided the balance apparatus would be mounted. The attachment of the test article to the balance would be accomplished by a rod projecting through a slot in the bottom of the test section. Shown in Figure 5, different features from two simple designs, one by McMahon, Jagoda, Komerath, and Seitzman, (2009) and one by Morris and Post (2010) were combined to form the final design used for the Team Eagle Wingsuit balance.

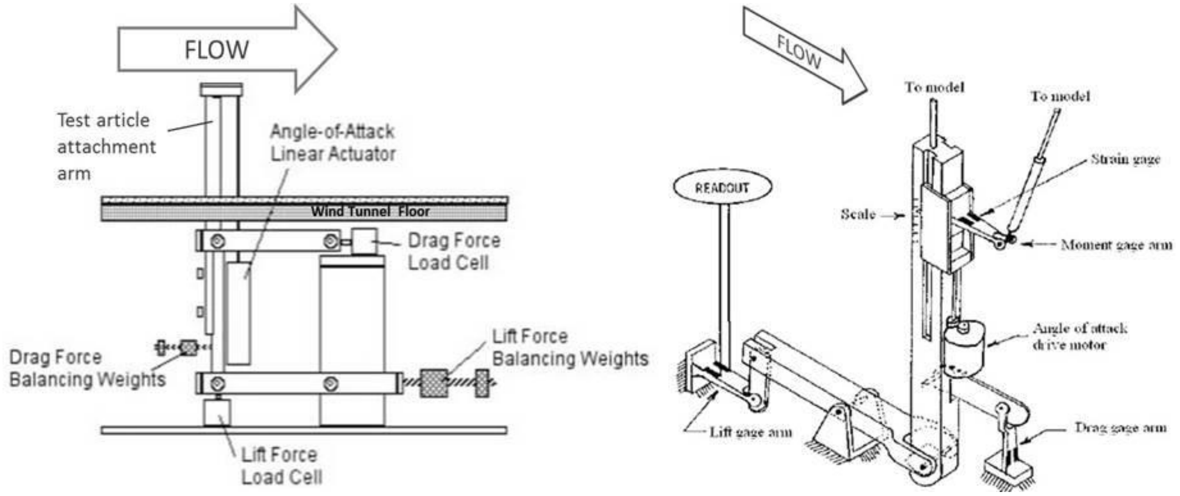

Figure 5. Morris and Post (2010) wind tunnel balance design on left and McMahon, Jagoda, Komerath, and Seitzman design on the right. Elements and concepts from both of these designs were used to create the Team Eagle Wingsuit balance.

Sensor Selection

Functions required by sensors used for this study in the Embry-Riddle wind tunnel and the application to wingsuit aerodynamics included:

- angle of attack measurement,
- lift measurement
- drag measurement
- precision
- reproducibility of measurements
    - predictable temperature response
    - minimal signal drift over time
    - minimal hysteresis
    - a lack of sensitivity to electromagnetic interference/noise
- sized to fit in the modular test section,

One of the more common sensors used in balance designs are strain gauge sensors that measure aerodynamic loads through voltage variations in small wires. Previous experience at the ERAU wind tunnel facility indicated an adverse electromagnetic environment that introduced unacceptable noise in unshielded strain gauges. Other sensor choices include piezo-electric sensors, capacitance load cells, hydraulic or pneumatic sensors, magnetoelestic torque sensors, or simple hanging weight balances.

Direct measurement of lift and drag loads with capacitance load cells was selected for this balance. Capacitance load cells come in a wide range of sensitivity and capacity, and are largely unaffected by electromagnetic interference. Capacitance load cells with a capacity of 100 lb maximum with 0.25 % of full range sensitivity were selected for the balance constructed for this experiment. The intent was to preload the cells to ensure the most sensitive and linear response region of the sensor was used for measurements. Rugged, capacitance, digital USB load cells from the LoadStar company offered direct measurement of load via the USB port of a PC. These capacitance load cells avoided the need for signal conditioners, or development of special software with a "plug and play" interface. One negative factor of the load cells used is they are large, approximately 1.2 inches tall and 3 inches in diameter and the attachment points increase the required space necessary to properly mount and operate the sensors. Each sensor cost $600 and the interface software cost $500.

Figure 6. Load sensor interface diagram (LoadStar, 2015)

A simple, electronic, inclinometer, at a cost of $160 was initially selected for angle-of-attack measurements. However, one of the sponsors of Team Eagle Wingsuit, *SBG Systems*, donated a 6-component miniature Attitude and Heading Reference System (AHRS) unit that was incorporated into the design. While the capabilities of this $1800 piece of equipment are far beyond its initial use as our wind tunnel inclinometer, it works well in this capacity and is planned for use in follow-on research. Its value is not included as a cost in this design.

The decision was made to mount the balance under the floor of the wind tunnel to use existing openings in the tunnel floor. The tunnel floor is supported by two large C-beams that offer 5.75 inches of clearance from the bottom of the C-beams to the bottom of the wind tunnel floor. It was determined that this was adequate space for the balance. The foundation of the balance was a plate of aircraft grade, hard, high strength, 7075 tempered aluminum attached to the bottom of the C-beams with 6 one-half inch diameter bolts. If this bottom plate had been purchased new it would have cost over $700 with shipping and we would have had to buy a full 48” x 24” piece of material to get the proper size needed. Ebay offered a piece of 7075 aluminum large enough to cut easily to the 20” x 31” required dimensions with little waste for only $130. All the bar aluminum used for the structure of the balance, was purchased from vendors on Ebay with savings over “new” material on the general order of 80% to 90%. By far the largest expense was having the various pieces precision machined for building and mounting the balance. 6061 aluminum ½ inch bar was used for the body and 3/8 inch bar was used for the moving parts of the balance. Precision machining expenses were approximately $1600 for all machined parts.

Design Features

Design of the balance was carefully preplanned and modeled in CAD before construction. CAD design allowed for planning of dimensions and analysis of potential interferences in the design. A side view of the balance design is shown in Figure 8.

Initially the pivot points for the force arms of the balance used small high-precision Stainless Steel ¼ inch Ball Bearings and precision shoulder screws for about $100. The small bearings proved to have inadequate bearing surface and allowed too much lateral motion in the balance arms. The attachment points were redesigned and replaced with ½ inch diameter TiCN-coated, low friction, 18-8 Stainless Steel Shoulder Screws and 1inch diameter bronze thrust bearings used as low friction washers, which provided the rigidity required with some increase in friction surface which was countered with synthetic lubricant. The TiCN-coated shoulder screws and bronze thrust bearings cost approximately $120.

The attachment post for the test article is a 14 inch long, 1.5 inch diameter brass rod, weighing just over 9 pounds. This and the other oversized balance components provide a measure of inertial damping in the potential case of uncontrolled oscillation of the test articles. This inertial damping is intended to reduce the force impulse to the sensors and allow time to reduce airflow or abort a test event, should the test article become unstable. The total weight of the suspended balance components, through which pass the measured forces, is approximately 20 lbs. Most of these components are shown in Figure 7. The suspended components include the balance bar, its attachments, the brass attachment bar and its threaded rod, the linear actuator and its attachment platform, and the other rods, clevises, and shoulder screws required for the final assembly without the test article. The linear actuator is an electrically powered automotive product with an 8” range of motion and the ability to produce 200 pounds of force. All components were selected to err towards the more durable and robust condition. This was in retrospect, a very good decision in that the estimates of the forces generated by the rigid test article were low and the current design reaches the limits of the sensors before a full range of angles of attack can be accomplished at the higher airspeeds. Pre-stall and stall oscillations of the rigid test article were violent and of a magnitude that required a redesign of the test article attachment point from one of aluminum, which failed at 140 knots, to an attachment device made of steel.

Figure 7. The balance bar with brass test article attachment rod, and linear actuator with mounting platform.

The initial design incorporated a system using a single point of contact between the balance and the lift sensor. This was done using a highly polished domed button on the lift sensor and a highly polished flat bolt head on the bottom of the brass rod which were both lubricated. This configuration was intended to provide a minimal contact with no lateral input to the lift sensor and is shown in Figure 8. The capacitance force sensors used are sensitive to lateral inputs that apply torque to the input interface. This arrangement was preloaded with weight transmitted through an attachment on the top of the bolt head, to pre-load the sensor. Lift generated by the test article would measure the reduction of weight on the sensor as lift.

While the concept appeared sound, initial measurements showed unexpected coupling of lift and drag and a high level of residual drag readings especially at high airspeeds requiring heavy preloading. It was suspected that the lift bolt/sensor dome interface would move imperceptibly down the side of the domed sensor input interface and provide both a torqueing moment on the lift sensor and a torque input into the drag sensor link which was held in place by the preload weight. This motion was partially the result of a high vibration environment at certain wind tunnel airspeeds and the oscillitory motions of the test article due to vortex shedding at high angles of attack. Flexing of the input bolt would misalign the surface of the bolt and allow it to slide down the sides of the sensor input dome. This visually imperceptible motion

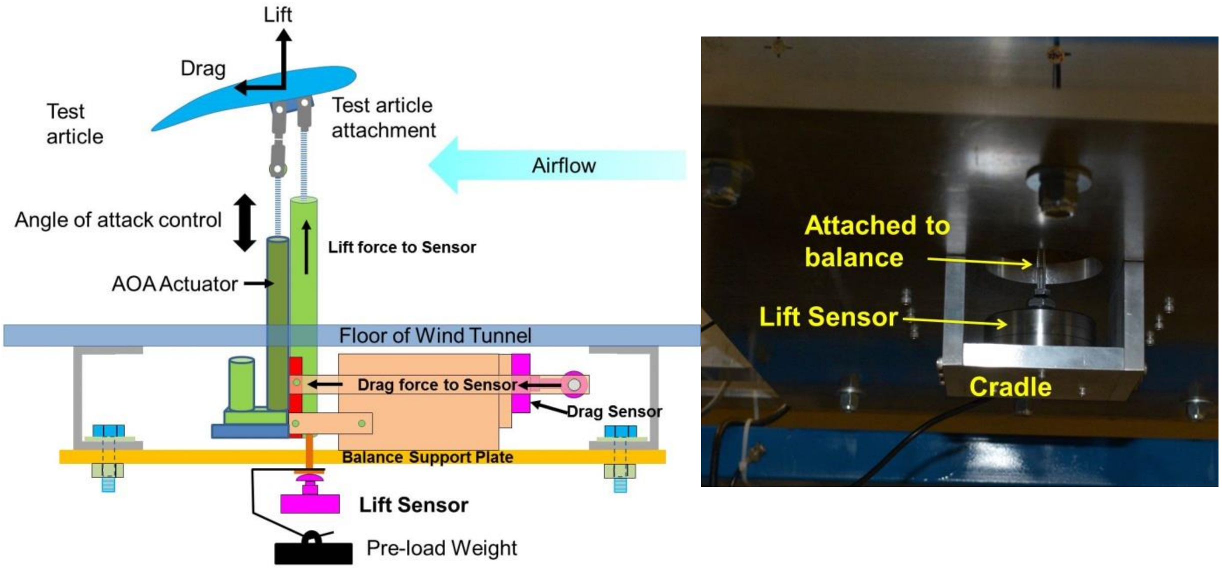

Figure 8. Diagram of initial balance design with domed lift sensor input interface and a photograph of the actual installation on the bottom of the balance support plate.

would result in ending a data run with both sensors showing unpredictable and variable residual loads from 0 to ±20 pounds of force in a no wind condition.

Consultation with the sensor manufacturer and a reconsideration of the environment to include the vibration resulted in a redesign that inverted the lift sensor, and captured it with a rotating eye bolt arrangement like the drag sensor which solved both the torqueing of the lift sensor and the need for a preload. This new design is shown in Figure 9.

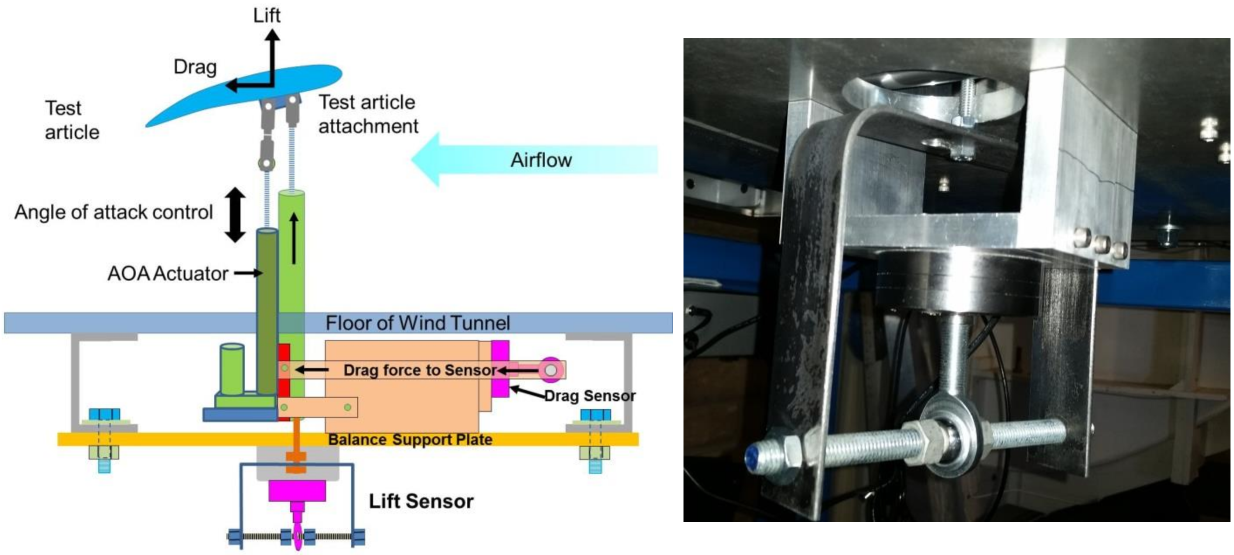

Figure 9. New design for balance lift sensor. Diagram of balance on left and photograph of the actual lift linkage to the sensor on right.

In an ideally constructed balance lift and drag forces would be isolated each from the other. Balance limitations and simplifications due to budget and other constrains often make complete isolation impractical. Coupling of balance lift and drag loads often results in conditions where changes in measured lift load results in changes in the measured drag load and vice versa. This coupling of the signals introduces inaccuracy and requires correction in the data reduction as a balance interaction correction. The amount of inaccuracy is measured while calibrating the load measurement system. Known inputs, usually from carefully measured weights are applied to the system, incrementally loading lift and drag and recording the output of the two data channels. The initial design calibration of this balance was not done in the vibration environment that existed when in experimental use and did not detect the flaw in the system. After the redesign the interaction corrections were very small and linear, even in the operating environment and will be included in the data reduction.

Conclusion

The project to design and fabricate a robust balance for wingsuit research has been a success. There have been numerous minor and a few major redesigns as problems with the initial concept were discovered but there were no insurmountable problems. The initial data of the baseline airfoil is encouraging. Figure 10 is a graph of preliminary data that matches the known performance of the selected airfoil well. The total cost of the project met our goal of costing less than $5000 including the changes to the design as the project evolved. The accuracy and repeatability of the data collected appear to be excellent and the project is continuing in to the research phase of pioneering wingsuit aerodynamic investigation.

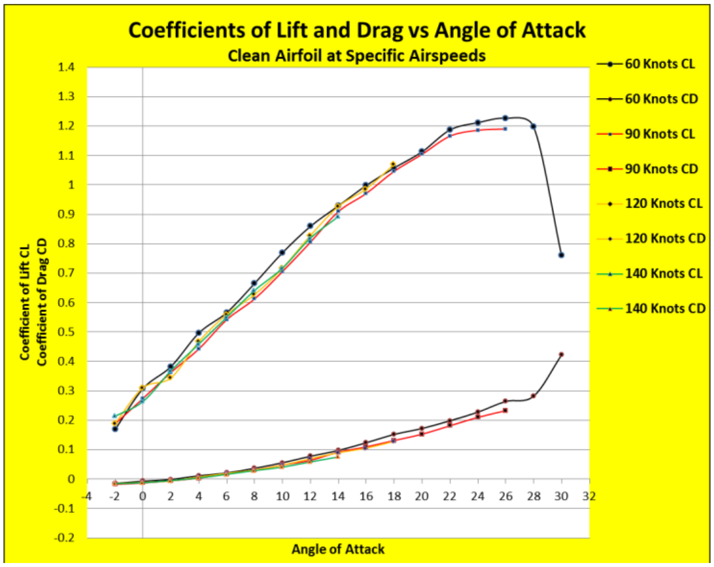

Figure 10. Iniital data collected on baseline airfoil using the robust balance developed for wingsuit aerodynamic research.

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