Loss of Longitudinal Control of a Mini-Ultrastick UAV

Jyot Buch

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Abstract

The goal of this memo is to convince the reader that the manufacturing company is not responsible for the loss of control of a mini-Ultrastick UAV (an abbreviation for Unmanned Aerial Vehicle) and related consequences that happened recently. By means of an experimental data and logical arguments, it is shown that the mini-Ultrastick UAV have a stable flight behavior per design. This claim is based on the systematic tests that were conducted during the well-established design and verification procedure. Further, by looking at the photograph taken right before the flight (Exhibit A), it has been concluded in this report that the operator flying the airplane loaded the aircraft in a way that causes loss of vertical plane motion (commonly referred to as longitudinal) flight stability.

Contents

1 Introduction

Recently, an unfortunate incident involving loss of control of a mini-Ultrastick has been reported for the law suite. A mini-Ultrastick was used for aerial photography which lost longitudinal control and fell into the windshield of a car traveling 60 mph on the I-94. In addition to the damage to the car, the plaintiff, who happened to be the host of a popular TV tabloid show was seriously injured and required extensive facial reconstructive surgery. The picture of the mini-Ultrastic taken right before the flight is shown in Exhibit A, which is an important evidence for the claim made in this report.

An Unmanned Aerial Vehicle (UAV), commonly known as a drone, is an aircraft without a human pilot aboard. The flight of UAVs may operate with various degrees of autonomy: either under remote control by a human operator or autonomously by onboard computers. The use of UAV is rapidly expanding to commercial, scientific, recreational, agricultural, and other applications, such as policing, peacekeeping and surveillance, product deliveries, aerial photography, agriculture, smuggling, and drone racing [2].

As a company, we deeply care about the safety and reliability of the UAVs that are being designed and developed by our researchers and engineers. The UAVs manufactured by our company are thoroughly tested in the lab facilities before being certified and available for the civilian use, for ensuring safety and reliability. There are well-established and systematic test procedures for characterization of mini-Ultrastic UAV in the wind tunnel lab specifically for vertical plane motion which is referred to as longitudinal motion. Wind tunnels are large tubes with air moving inside and are used to copy the actions of an object in flight. Researchers use wind tunnels to learn more about how an aircraft will fly [3]. It is worth noticing that using wind-tunnel experimental data is a well-established and well-known practice to characterize an aircraft. Using the data collected from these experiments, one can understand how the incoming airflow will interact with aircraft's shape and relative arrangement (geometry). Incoming airflow results into aerodynamic (the study of motion of air) forces and moments.

In what follows, specific terms are defined to support the rest of the discussion in this report.

- **Force:** is any interaction that, when unopposed, will change the motion of an object.
- **Moment:** is a measure of force's tendency to cause a body to rotate *about a specific point*.
- **Equilibrium:** is a state of an object for which the total force and moment acting on it results in to zero net effect
- **Static Stability:** refers to a tendency of an object to return to the equilibrium condition after being perturbed from an equilibrium point. In this report, we use term "Stability" to refer to static stability, however stability is a very general term.

- **Center of Gravity:** is a point for an object where entire mass of the object can be assumed to be centered around. Often forces and moments are assumed to be acting at the center of gravity. Here, in this context, that object is mini-Ultrastick.
- **Elevator:** is a movable part of the horizontal tail of an aircraft which is often used to control the motion in a vertical plane. By deflecting elevator up or down an operator create a moment to either pitch up or pitch down *i.e.* nose up or nose down.
- **Lift:** (L) is an upward force generated by the wings of the aircraft which helps to *lift* it up from the ground.

It is a common practice to normalize lift and moment about center of gravity to have them non-dimentionalized. These normalization happens through the surface area of the wing (S), air density (ρ) and free stream velocity (U_∞). The resulting quantities are known as lift coefficient (C_L) and moment coefficient (C_M).

The goal of this report is to describe the methodology, experimentation, and results of the longitudinal flight characteristics for the mini-Ultrastick, and to discuss some critical design parameters of interest. As it will be more clear from section 3 that airplane was designed to be stable. Moreover, the loss of longitudinal control is not because of the design flaw, but because of the operator's carelessness in loading the mini-Ultrastick. The key assumptions made during the experiment are listed below.

- Available maximum elevator deflection on the mini-Ultrastick is $\pm 18^o$
- The maximum weight of the mini-Ultrastick (airplane + payload) is $W_{max} = W = 0.8$ kg $\times$ 9.81 m/s^2 = 7.848 N

For more details on experiment and notations, the reader is refereed to the wind tunnel lab manual [4].

2 Apparatus and Methods

2.1 Apparatus

The experiment was conducted in a closed return (CR) wind tunnel at the University of Minnesota - Twin Cities at hight (altitude) of 250 m above sea level. The CR tunnel was operated using a software program called `crtunnel`, interfaced to a desktop computer which gave operational inputs specified by the user and received data values on the velocity, density and pressure of the free stream flow as well as the forces on the test body measured by the sting (6 degrees-of-freedom strain guage). The test section of the CR tunnel has a cross section of 1×1.25 m, and the tunnel operates by a 100 hp variable speed motor with a propeller, that produces a maximum flow speed of 38 m/s. Setting the speed of the free stream required setting a frequency value on an interface outside of the tunnel. One free-stream velocity was used for this experiment, and thus only one frequency was used, $f = 22$ Hz, which produced a free stream speed of approximately $U_\infty = 8$ m/s. This velocity was used for all data samples collected. A mini-Ultrastick was placed on a strain guage balanced sting located within the test section as shown in Figure 1. The sting was capable of measuring forces as well as their corresponding moments. For more information on this lab facility reader is referred to the website [3] or the lab manual [4].

The sting itself was pre-positioned in the center of the wind tunnel by a lab technician and was not moved throughout the experiment. The only physical orientation that was manipulated after this was the angle of the test body relative to the free stream flow. This value known as angle of attack (α) was varied from -10^o to 22^o. Additionally, the mini-Ultrastick had the capability of adjusting its elevator deflection, δ_e, through three values by use of remote controlled controller. These values were $\delta_e = -18^o$, $\delta_e = 0^o$, and $\delta_e = 18^o$. Velocity and free stream measurements were obtained from a pitot tube located within the wind tunnel that provided values based upon ram air entering it. The values measured were then sent to the computer prompt and were available for users to see and log the data [4].

2.2 Methods

Experimentation began by ensuring that the mini-Ultrastick was secured within the CR wind tunnel, and that the door was latched properly. Angle of attack, α, was set to an initial value using `crtunnel` software. The sting was tared to ensure no force and moment contributions by the weight of the aircraft itself. Wind tunnel speed was set by increasing the frequency of the propeller to $f = 22$ Hz, which set the free stream velocity to approximately $U_\infty = 8$ m/s. At the set flow speed and α, elevator angle, δ_e, was varied over three values: $\delta_e = -18^o$, $\delta_e = 0^o$, and $\delta_e = 18^o$. The process of varying δ_e at different α was completed through a range of $-10^o < \alpha < 22^o$ at increments of 2^o. At each instance, the wind tunnel was turned off and the sting was tared after obtaining the new α. Free-stream velocity U_∞ was brought back to the same value of $U_\infty = 8$ m/s, where δ_e was again varied through $\delta_e = -18^o$, $\delta_e = 0^o$, and $\delta_e = 18^o$. In total, 3 sets of force data corresponding to each elevator deflection were obtained for each α.

Static Margin (SM) is an important quantity that is to be considered for static stability and it is defined as the negative of the slope of the C_M vs C_L curve. Alternative definition includes $SM = -(h_{CG} - h_{NP})$. Where, h_{CG} and h_{NP} are the locations of the center of gravity and neutral point as a fractions of mean chord length (or mean width of the wing $\bar{c}$), respectively. Neutral point is a point at which if the center of gravity travels then the aircraft becomes neutrally stable. Which means the tendency of returning to equilibrium point is lost. This phenomena is also discussed in section 3.

In determining the aft limits of the center of gravity (CG), it is important to understand what is the role of each component contributing to the moment. It is desired that for the aircraft be trimmable (can be brought back to equilibrium) at some elevator deflection. This means that the total moment coefficient be zero, or $C_M = 0$. Likewise, the slope of the C_M vs. α curve must be $C_{M_\alpha} \leq 0$, or else a positive change in angle of attack will cause a positive moment. A final constraint is the line intercept, C_{M_0}, must be $C_{M_0} \geq 0$, or else the aircraft will not be trimmable at positive α.

3 Results and Discussions

C_M vs. C_L plot obtained from the wind tunnel experimental data is shown in Figure 2. It can be seen that, at higher values of C_L, the mini-Ultrastick approaches stall limits i.e. the angle α beyond which the wings do not produce enough lift force. Further there are some nonlinearities and structural vibrations show up at higher α which makes the region more uncertain. As lower angle of attack results are more accurate, we use the MATLAB (a technical computing software which is used to process and analyze the experiment data) command `fit` to obtain the linear model approximation. Solid lines in the Figure 2 suggest a linear fit curve. The key results of interest are summarized in the following table for different values of elevator deflection angle δ_e.

Table 1: Summary of Experimental Results

Characteristics	$\delta_e = -18^o$	$\delta_e = 0^o$	$\delta_e = +18^o$
Static Margin (SM)	0.1255	0.1177	0.1409
Neutral Point (x_{NP}) (inches)	3.1472	3.0822	3.2762
Neutral Point (h_{NP}) (fraction of $\bar{c}$)	0.3755	0.3677	0.3909

In understanding the aft limit of the aircraft, consideration is placed on increasing or decreasing SM, which directly relates to changing the slope of the C_M vs. C_L curve, while also maintaining a stable and trimmable aircraft. To maintain the latter condition, the C_M vs. C_L curve for the mini-Ultrastick must maintain a negative slope, with a positive C_{M_0} for static longitudinal stability of the aircraft. Looking at the experimental data, our analysis shows that since static margin is positive the aircraft was designed to be stable. If the center of gravity is moved backward beyond the neutral point, then the slope of the curve C_M vs C_L curve will become positive and aircraft will not be statically stable as the static margin becomes negative. Thus aft limit distance being one of the important parameter will be same as neutral point, $h_{cg,AL} = 0.3755$ or $x_{cg,AL} = 0.0799$ m.

Looking at the photograph from Exhibit A, we see that the mini-Ultrastick which was being used for ariel photography had a camera mounted on board to take pictures. However, due to carelessness of the operator this camera was mounted towards the end of the aircraft which moved the center of gravity far beyond neutral point. In this situation due to wind gust or any other external disturbance, if the aircraft is perturbed then it will cause the positive moment about the center of gravity due to positive slope of the C_M vs C_L curve which will move the aircraft further away from the equilibrium point and eventually there will result in to increase in α as it will reach the nonlinear region of the C_M vs C_L curve. Due to high angle of attack, the aircraft can get stalled *i.e.* it does not produce enough lift. That means aircraft's tendency to return to equilibrium point is lost and aircraft is no longer statically stable. Thus, this can be a very hazardous situation to operate the aircraft.

The technical details are available in the users manual of the mini-Ultrastick aircraft and every user is recommended to read it before they load the aircraft by means of any external instrument such as camera. Further reader is encouraged to refer to [1] or [5] for more technical details on longitudinal flight characterization. We now provide the summary of this report.

4 Summary

In this report, wind tunnel test data for mini-Ultrastick UAV were analyzed. Often the center of gravity remains at the same place for UAVs like mini-Ultrastick unless loaded by some additional payload. Stability of a flight was assessed using static margin. In summary following three cases can be listed:

- If SM is positive then aircraft is statically stable, that means center of gravity is ahead of the neutral point and positive change in angle of attack will induce the negative moment which will bring it back to the equilibrium condition. This can be viewed as a torsional spring attached to the .
- If SM is 0 then aircraft is neutrally stable, as it does not produce the restoring moment against the positive change in the angle of attack but stays at the new equilibrium condition.
- If SM is negative as happened to be in this case when mini-Ultrastick was loaded by a camera near the tail, then aircraft can not be put back in to the equilibrium condition and accident like this are likely to happen. An operator needs to be careful in order to fly the aircraft in a safe manner.

The aft center of gravity limits was calculated to maintain the stable flight envelope. That means in a trimmed longitudinal flight, if an unloaded aircraft is perturbed then it will have a tendency to come back to the trim condition. The characterization of the mini-Ultrastick has allowed important characteristics and stability for the aircraft to be ensured. Thus we conclude that the it is not a design flaw but the carelessness of an operator that caused this unfortunate accident.

References

[1] Robert C Nelson et al. *Flight stability and automatic control*, volume 2. WCB/McGraw Hill New York, 1998.

[2] Unmanned aerial vehicle wikipedia, `https://en.wikipedia.org/wiki/Unmanned_aerial_vehicle`.

[3] Wind tunnel lab information, `https://www.aem.umn.edu/facilities/windtunnel/`.

[4] Wind tunnel lab manual, aem 4303, spring 2019.

[5] Jyot Buch. Longitudinal flight characteristics for mini-ultrastick uav, aem 4303, spring 2019.

Figures

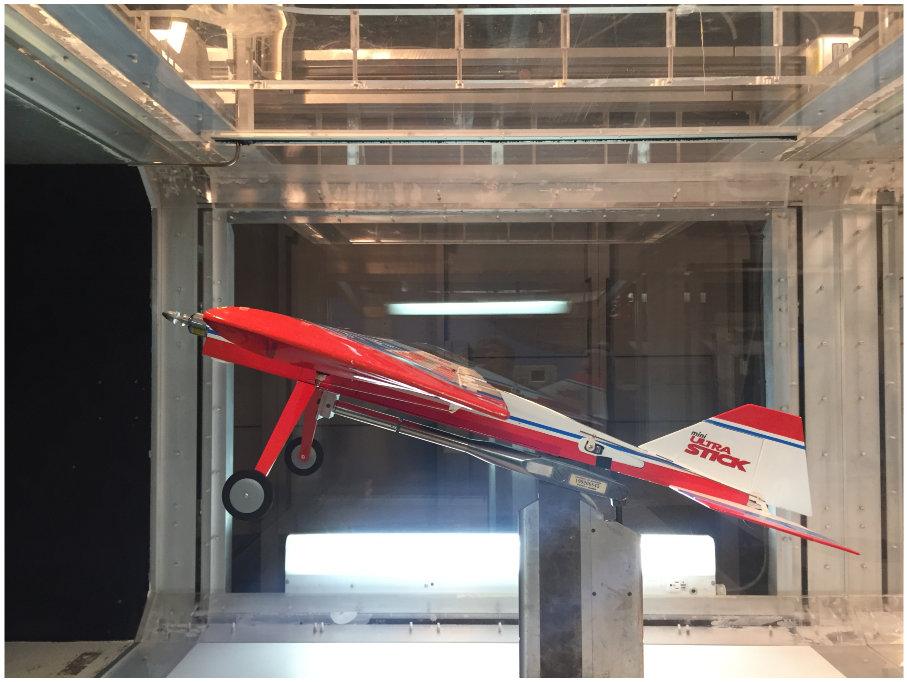

Figure 1: Experimental Setup

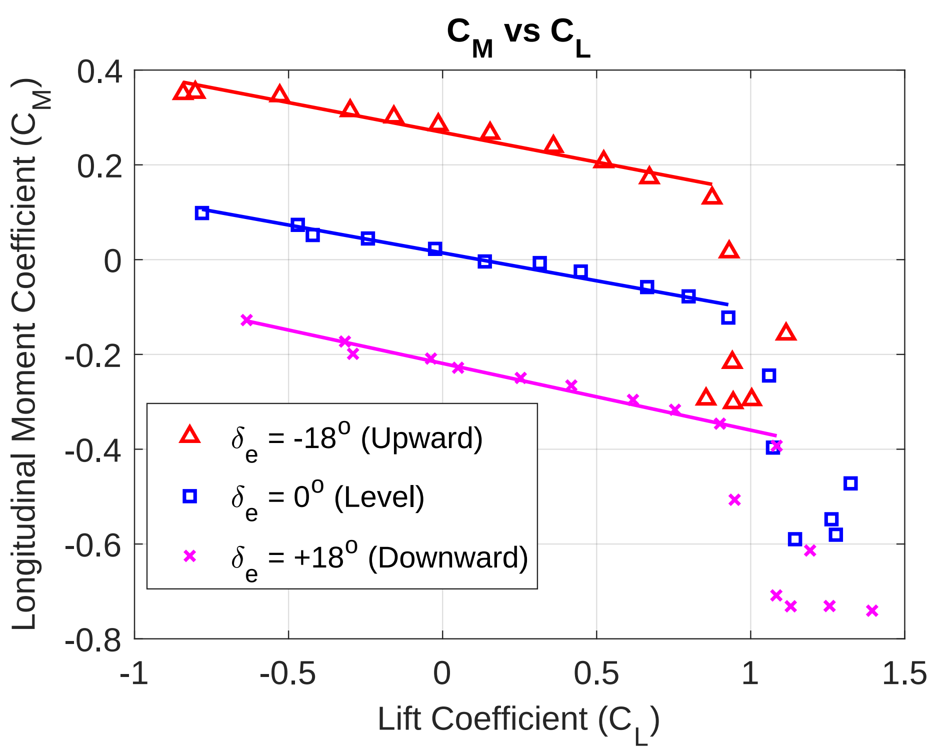

Figure 2: Longitudinal Moment Coefficient vs Lift Coefficient