Flight Testing Validation of Theoretical Stability Modeling for a 3D-Printed UAS

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This paper investigates the accuracy of theoretical testing methodology for a 3D-printed Unmanned Aerial System (UAS). The main characteristics investigated included aircraft longitudinal and lateral directional responses and its stability. Utilizing bifilar pendulum testing, the aircraft's moments of inertia were calculated, and a MATLAB script was then used to model the aircraft's wing and calculate the aerodynamic coefficients. These values were then entered into a second MATLAB script that calculated the aircraft's roll modes. The theoretical roll modes were then tested for their validity against the aircraft's responses in air during flight testing. The results from the different testing methods were then analyzed and compared, and their validity discussed.

I. Nomenclature

α	=	angle of attack
β	=	angle of sideslip
CD	=	total drag coefficient
CL	=	total lift coefficient
Cl	=	coefficient of lift
Cm	=	pitching moment coefficient
Cn	=	yawing moment coefficient
CY	=	side force coefficient
ISO	=	isometric view
I_x	=	moment of inertia about the x-axis (roll inertia)
I_y	=	moment of inertia about the y-axis (pitch inertia)
I_z	=	moment of inertia about the z-axis (yaw inertia)
P	=	roll rate
Q	=	pitch rate
R	=	yaw rate
T	=	time period

II. Introduction

With the revolution of 3D printing, its applications have become more widespread. With hundreds of different methods to print and hundreds more materials available to print with, 3D printing is showing up in every aspect of

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our lives. From medical uses like implants and pharmaceuticals to toys, eyewear, and firearms, it is practically unavoidable to use a product that doesn't use a form of 3D printing in its fabrication process. Industries have traditionally relied on big, slow, expensive machines to manufacture parts; however, many are making the shift to additive processes to reduce waste and increase efficiency. This shift has not only streamlined the production pipeline but has also enabled rapid iteration, allowing designers and engineers to move from concept to physical prototype in a fraction of the time once required. This has enabled many companies to test their designs using small-scale prototypes, explore more complex geometries, and revise ideas without the financial risk that is used to accompany early-stage development.

This phenomenon has spread into the aerospace industry and is being utilized to manufacture equipment in a fraction of the time for a fraction of the cost. Aerospace manufacturers have embraced additive techniques to create components that would be extremely difficult to fabricate using traditional subtractive methods. As new developments in 3D fabrication are discovered, the applications are endless. From mass-producing specific intricate parts to printing complete unmanned aircraft, it's hard to believe that what was once an impossible task is now becoming an automated process. The ability to experiment with new airframe shapes, internal structures, and aerodynamic concepts has opened the door to unprecedented design freedom. As the difficulty of building aircraft diminishes, the availability of testing flight dynamics and properties becomes exponentially easier. However, the rise in the quantity of aircraft doesn't reflect the rise in quality per se. There are plenty of designs for 3D printable aircraft or aircraft parts that can be sold without knowing if they perform as designed, and many fail to consider structural limitations, material behavior, or how the final printed geometry will hold up during real-world flight conditions.

The focus of this project is to evaluate the feasibility of 3D printed aircraft as industry-relevant platforms by comparing computational modeling predictions with experimentally observed flight behavior. MATLAB-based stability modeling is used alongside Vortex Lattice Method (VLM) analysis to establish baseline aerodynamic and stability characteristics, which are then validated through flight testing of a fully 3D printed fixed-wing aircraft. Stability derivatives are computed to assess longitudinal and directional stability and are compared directly with experimental results. This approach allows assessment of MATLAB's capability to accurately capture the flight dynamics of additively manufactured airframes while simultaneously evaluating whether 3D printed aircraft can serve as reliable, low-cost alternatives to traditional Unmanned Aerial System (UAS) platforms.

III. Methodology

A. UAS Design

The research was conducted using the UAS Stallion design by Flightory, a 3D printed remote controlled (RC) plane company. The Stallion design is a hand-launched fixed-wing, V-Tail UAS with vertical takeoff and landing capabilities, with additional modifications to the original design. The standard fixed-wing design was chosen as it more accurately resembles a traditional aircraft required for the vortex lattice MATLAB implementation for linear aerodynamic wing applications. The UAS has a fully printed body comprised of Lightweight Polylactic Acid (LW-PLA), Polyethylene Terephthalate Glycol (PETG), and Polylactic Acid (PLA). The structure is held together by carbon fiber rods, threaded inserts, small M3 screws, and Cyanoacrylate (CA) glue. The upper surface of the fuselage is removable to access the batteries, required controllers, and electronics. The 3D printed design is also highly modular and easy to modify for a variety of tests and research purposes [2].

The Stallion design was selected out of other UAS platforms because of its adaptability and modular design. The team traded the time necessary to print the body for the ease of assembly that comes with other UAS's typically used for research. The UAS is also more sustainable and reusable for future research projects, due to the rigidity that accompanies the 3D printed design.

The Stallion is described as a "high-performance 3D printed twin-motor RC Plane with a modular design. Crafted for optimal performance and customization for various applications" [2]. Wingspan for the Stallion is 1340 mm (4.40 ft), and the length is 990 mm (3.25 ft). The estimated weight of the aircraft is around 1500 – 3000 grams (3.31 – 6.61 lbs.) [1]. The actual weight is dependent on the materials and the flight components, such as batteries and motors, used. All the components for the UAS were available online, further making the Stallion and choice for research.

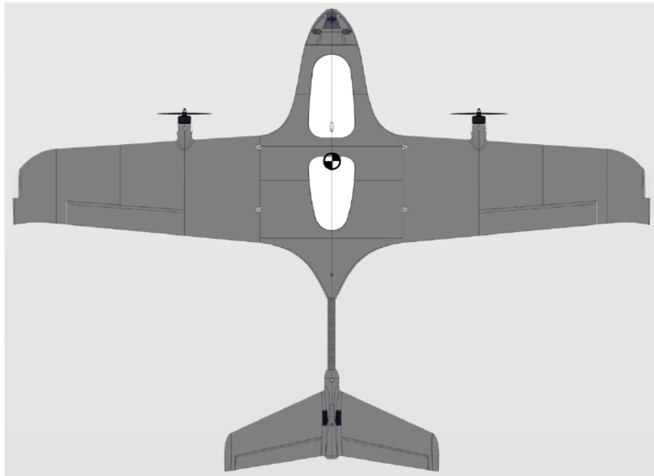
Figure 1. Stallion Design Top View [1].

B. UAS Assembly

The team used two recently developed, affordable Fused Deposition Modeling (FDM) printers to manufacture the parts of the aircraft. After performing several tests to find the optimal setting for the LW-PLA at various speeds and nozzles, the team began printing. Over the course of a month, with each piece needing between one and eight hours individually, the UAS slowly took shape. After completing the prints that required LW-PLA, the team began testing and printing with the PETG.

Over the next month, the process of constructing the UAS began. After sanding each of the parts to remove external discrepancies and using a tile saw to cut the carbon fiber rods to the desired length, each of the pieces was glued, and the carbon rods were inserted to complete the airframe. After the airframe was completed and the parts were shipped, the avionics were inserted, and the propellers and motors were attached.

C. Pendulum Testing

The aircraft was tested for its mass moments of inertia using the bifilar pendulum method in accordance with the equation.

$$I = \frac{mgLT^2}{4\pi^2 d^2}$$

Where:

m = mass of the aircraft and all the flight hardware
g = gravitational acceleration
L = length of the pendulum string
T = Period of oscillations
d = distance along the axis of interest between the pendulum strings

The aircraft was weighed to get its mass, and utilizing two parallel strings of equal length, the aircraft was set up as follows to get its period:

1. Roll Inertia, I_x: Strings were attached to the aircraft above its wings such that the motion of the oscillation occurred about the body x-axis.
2. Pitch Inertia, I_y: Strings were attached along the aircraft's fuselage centerline such that the motion of the oscillation occurred about the body y-axis.
3. Yaw inertia, I_z: Strings were attached to the aircraft, rotated 90º from the roll inertia position above its wings, such that the motion of oscillation occurred about the body z axis.

A small angle displaced the aircraft and then allowed to swing freely for 10 oscillations. The time for these 10 oscillations was recorded, and the period, T, was found via

$$T = \frac{N}{10}$$

Where N is the time taken in seconds for 10 oscillations to occur.

This was necessary for the dynamic stability analysis of the aircraft using the fundamental aircraft flight dynamics equations. These moments of inertia allow for the analysis of the different roll modes and ultimately the interpretation of the dynamic stability of the aircraft.

D. UAS Modeling & Simulation

Utilizing the MATLAB code 'Tornado' [3], the aircraft was modeled to acquire its aerodynamic coefficients. 'Tornado' uses standard vortex lattice theory. The law of Biot-Savart was used to get the flow field around the aircraft, and the forces acting on each segment of the vortex were calculated using the Kutta-Jukovski theorem [3]. The aircraft was modeled in 'Tornado' as follows:

1. Geometry: The aircraft's lifting surfaces were physically measured for their airfoil type, root chord, tip chord, planform shape, etc., and these were used for the model's geometry.
2. State Model Features: These included the angle of attack, sideslip angle, roll angular rate, pitch angular rate, yaw angular rate, and the air speed for the aircraft in flight.
3. Post Processing: From the post processor, the files and plots necessary to gather the aerodynamic coefficients were gathered.

The aerodynamic coefficients were then used to form the linearized state space model of the aircraft using a second MATLAB script. This same script was also used to finally simulate its dynamic response to elevator, aileron, and rudder inputs and output plots for the phugoid, long period, Dutch roll, spiral, and the roll mode time histories.

IV. Simulation Modeling and Results

The VLM software 'Tornado'[3] was used to generate aerodynamic coefficients and stability derivatives of the Stallion UAS in low-speed flight. The purpose of this was to use these simulations as a pre-flight prediction test to assess the accuracy of VLM modeling relative to flight testing and determine its feasibility as a prediction tool. The model captured the wing-lifting effects of the wings and the v-tail, enabling coefficient trends and derivatives for comparison with flight data.

Tornado utilizes a Cartesian body-fixed coordinate system. The X axis is aligned with the longitudinal body axis increasing aft, the Y axis is positive out of the starboard wing when no dihedral is present, and the Z axis is right-hand perpendicular to both axes and is positive upward. This coordinate system was used consistently across all drone modeling to compute aerodynamic and stability coefficients.

In Tornado, the aircraft reference point designates the moments about which the aerodynamic coefficients are computed. Therefore, for simple modeling, the reference point and aircraft center of gravity were set at the same location to ensure that the pitch, yaw, and rolling moments were calculated about the mass center.

The center of gravity location was taken from the Stallion manual and rechecked using physical measurements, and the aerodynamic coefficients were nondimensionalized using Tornado's internally computed reference quantities as listed in the table below.

A. Geometry

Due to 'Tornado' being a VLM software, only the aircraft's major lifting surfaces were modeled, namely the wings and the tail. The main wing was represented as a symmetric lifting surface mirrored across the XZ axis. The wing planform was defined using measured root chord lengths, taper ratios, dihedrals, line sweeps, etc. A single partition was used due to the wing planform being one consistent geometry. The ailerons were modeled as partial span flaps consistent with the Stallion design geometric position, and the control surfaces were defined to deflect antisymmetrically to imitate aileron control deflection. The winglets were ignored for this model due to it not having a significant impact on the lifting coefficients. The main wing ailerons were defined over the outboard portion of each wing with a flap chord fraction of 0.27.

Similarly, the V-tail was modeled as one symmetric lifting surface with a dihedral angle consistent with the physical V-tail measurements. Each surface used the same tip ratios and taper ratios derived from direct measurements. The ruddervators were modeled as a single control surface on each tail, since it spans almost the entire Stallion tail geometry. Their functionality was represented through symmetric deflections for elevator inputs and antisymmetric deflections for rudder inputs.

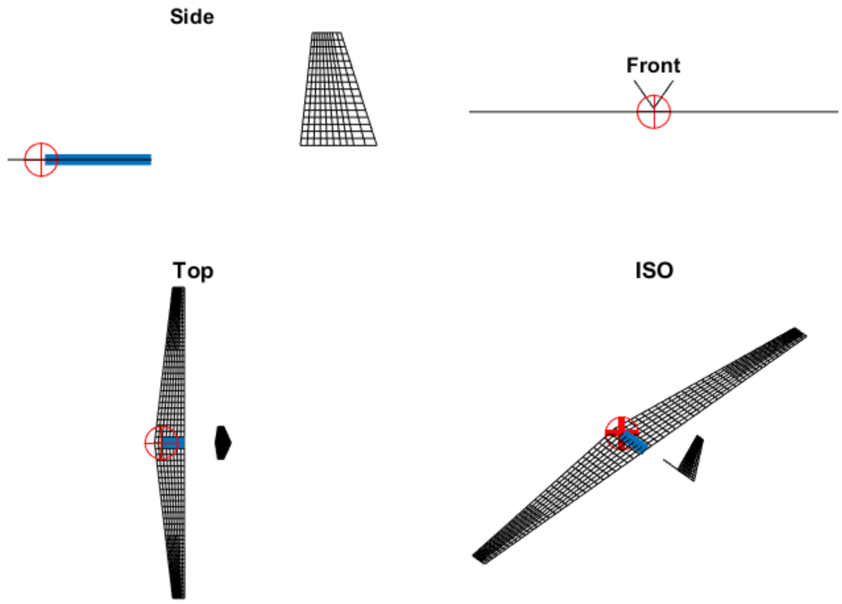

Figure 2. Three View Diagram of Stallion Modeled in Tornado [3].

The airfoil selection of the wings was selected using a best estimate in the National Advisory Committee for Aeronautics (NACA) series. This was because ‘Tornado’ does not house any Eppler airfoils, so the NACA 2410 was selected to simulate the estimated camber characteristics for the main wing, while the NACA 0009 profiles were selected for the V-tail surfaces.

All lifting surfaces were discretized using linear mesh spacing with 8 chordwise panels and 16 spanwise panels per semi-span. This resolution was selected to minimize noise and was verified to produce stable aerodynamic coefficients.

B. Simulated Flight Conditions

All simulations were conducted at a freestream velocity of 18 m/s and sea level density. These conditions were chosen based on the manufacturer’s indication of its best flight conditions. Compressibility conditions were ignored due to the aircraft still being below Mach 0.3. Static aerodynamic solutions were computed using Tornado’s free-stream wake model. The initial analysis was performed at zero angle of attack along with zero pitch, yaw, and roll to verify symmetry and baseline coefficient behavior.

An angle of attack and an angle of sideslip sweep were then conducted from -5° to 10° in 1° increments, generating lift, drag, and pitching moment polars. From this sweep, the aerodynamic coefficients and stability derivatives were extracted. These results were all based on the model geometry's reference quantities. The resulting data, as seen below, will be used for comparison with flight-test measurements in the future.

TORNADO CALCULATION RESULTS, Derivatives

JID:	stallionv5static				
Reference area:	0.47811	α [deg]:	0	P [rad/s]:	0
Reference chord:	0.18928	β [deg]:	0	Q[rad/s]:	0
Reference span:	2.682	Airspeed:	18	R[rad/s]:	0

CL derivatives :		CD derivatives :		CY derivatives :	
CL_α	5.5364	CD_α	0.0451	CY_α	0
CL_β	0	CD_β	0	CY_β	-0.1572
CL_P	0	CD_P	0	CY_P	-0.0069
CL_Q	9.5025	CD_Q	0.0734	CY_Q	0
CL_R	0	CD_R	0	CY_R	-0.063

Roll derivatives :		Pitch derivatives :		Yaw derivatives :	
Cl_α	0	Cm_α	-1.7197	Cn_α	0
Cl_β	0.0097	Cm_β	0	Cn_β	-0.0287
Cl_P	-0.6052	Cm_P	0	Cn_P	0.0071
Cl_Q	0	Cm_Q	-5.3895	Cn_Q	0
Cl_R	0.0264	Cm_R	0	Cn_R	-0.0119

Figure 3. Tornado Results [3].

C. Results and Expected Comparisons

From the results seen above, the primary lift, drag, and pitching moments were extracted. The computed lift curve slope, $C_{L\alpha}$ was 5.5364 per rad. This is consistent with expectations for small fixed-wing UASs. At zero angle of attack, the aircraft maintains a positive lift coefficient due to the camber of the airfoil. The pitching moment derivative with respect to the angle of attack, $C_{m\alpha}$ was -1.7197 per rad, which indicates a positive static longitudinal stability. The lift coefficient exhibits a linear dependence on angle of attack over the evaluated range.

It should be noted that since Tornado employs a body-fixed coordinate system with the x-axis positive aft and z-axis positive upwards, the sign of the lateral directional derivatives differs from conventional flight dynamics formulations. For the purpose of this paper, the computed negative $C_{n\beta}$ of -0.0287 actually corresponds to positive directional stability. Similarly, this would affect the calculated $C_{l\beta}$ value of 0.0097, which then must be interpreted as a stable dihedral effect.

This was verified by conducting a Beta sweep from -5° to 10° as shown in Figure 4. The directional stability $C_{n\beta}$ has a negative slope, which in Tornado would indicate that the aircraft is stable. In a similar fashion, the roll stability $C_{l\beta}$ has a positive slope aligning with the positive z-up axes in Tornado.

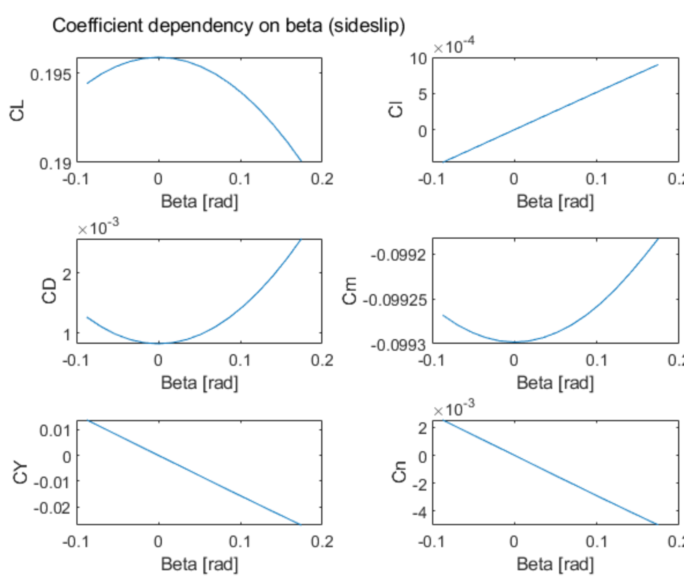

Figure 4. Beta Sweep of Stallion Aircraft [3].

The angle of attack sweep was conducted over the same range from -5° to 10° as indicated in Figure 5. The linear lift slope indicates that the flow remains attached throughout the entire evaluated range, which suggests that the wing is producing lift effectively. The positive lift coefficient at zero angle of attack is indicative of the cambered airfoil ensuring cruise efficiency. The negative pitching moment slope displays the longitudinal stability of the aircraft.

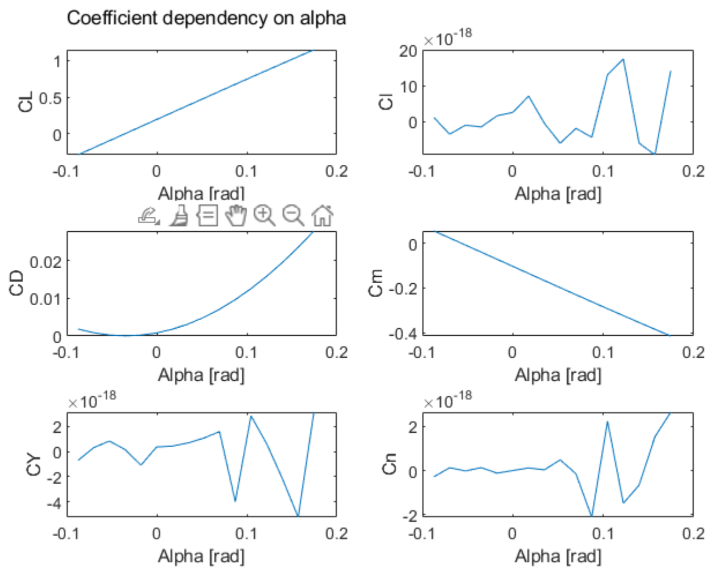

Figure 5. Alpha Sweep of Stallion Aircraft [3].

Based on the program results as well as the stability derivatives obtained, it can be stated that the Stallion aircraft should perform in an expectedly highly stable and controlled manner during flight testing. This is due to its high-placed wing and V-tail geometry. The aircraft exhibits stability in both the longitudinal and lateral-directional axes, meaning that it should respond well to disturbances in those directions, quickly returning to its equilibrium point. This indicates that the Stallion should possess predictable responses to elevator, rudder, and aileron inputs, providing the operator with high control authority and requiring minimal pilot correction to maintain a steady flight path.

D. Future Work

Bifilar Pendulum testing will be completed to further analyze the stability of the aircraft numerically. This is required as the flight dynamics equations require the mass moment of inertia about all three axes. After the dynamic stability of the aircraft is assured, flight testing to validate the analytical results will commence.

V. Conclusion

This paper presented a methodology for evaluating the flight stability of a 3D-printed UAS by combining the VLM base theoretical modeling with physical flight testing. The Stallion UAS was selected for its modular, adaptable airframe design. The aircraft was fabricated primarily from LW-PLA and PETG materials using FDM printers. The VLM software was programmed to compute a full set of aerodynamic coefficients and stability derivatives for the wing and V-tail geometry. The VLM analysis demonstrated that the Stallion UAS exhibits positive longitudinal stability, with a pitching moment derivative of -1.7197 per rad. Similarly, lateral stability was confirmed through the beta sweep analysis, which revealed a stable dihedral effect and a positive directional stability, mainly due to high wing placement and V-tail geometry. The simulated responses to elevator, aileron, and rudder inputs further supported the prediction that the UAS will exhibit controllable and steady flight. Future flight testing and bifilar pendulum testing will validate the theoretical results, which will determine the degree to which this modeling approach can be relied upon.

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