

Dynamic Stability Characterization of the Dragonfly Entry Vehicle Configurations During the EDL Preparation-For-Powered Flight Phase

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NASA's Dragonfly mission will deliver a rotorcraft to Saturn's largest moon, Titan, to enable exploration and search for building blocks of life. The Entry, Descent, and Landing (EDL) phase of the mission will use an aeroshell to deliver the rotorcraft Lander to an above surface release altitude. This paper discusses the dynamic stability characterization of the Entry Vehicle during the final phase of EDL called Preparation for Power Flight (PPF). This phase of flight under the main parachute is particularly challenging with its very low free-stream velocities and multiple configuration changes along with the rotors spooling up. The Dragonfly program uses statistical metrics computed from Monte Carlo (MC) simulation results to determine if flight performance requirements are satisfied. A comprehensive dynamic aerodynamic model suitable for direct use in these MC studies was developed and then integrated with the other vehicle systems in the simulation environment. The data for this aerodynamic model were obtained by conducting static and forced oscillation tests in the NASA LaRC 20FT Vertical Spin Tunnel on 7.78% and 15.56%-scale models of various PPF configurations. The tests showed that the reduced frequency was by far the most important parameter for accurately modeling oscillatory dynamics of the PPF configurations.

Nomenclature

C_{DS}	= parachute drag area
C_m	= pitching moment coefficient
C_{m_q}	= damping-in-pitch derivative, $\frac{\partial C_m}{\partial (q \cdot L_{ref}/2V_\infty)} + \frac{\partial C_m}{\partial (\dot{\alpha} \cdot L_{ref}/2V_\infty)}$, per radian
C_{m_α}	= pitching moment coefficient derivative w.r.t. to angle of attack, static pitch stability
C_n	= yawing moment coefficient
C_{n_r}	= damping-in-yaw derivative, $\frac{\partial C_n}{\partial (r \cdot L_{ref}/2V_\infty)} - \frac{\partial C_n}{\partial (\dot{\beta} \cdot L_{ref}/2V_\infty)} \cos(\alpha)$, per radian
C_{n_β}	= yawing moment coefficient derivative w.r.t. to angle of sideslip, static directional stability
D	= aeroshell maximum diameter
f	= frequency, Hz
I_{yy}	= mass moment of inertia about the pitch body-axis
I_{zz}	= mass moment of inertia about the yaw body-axis
k	= reduced frequency parameter, $\omega \cdot L_{ref}/(2V_\infty)$
L_{ref}	= reference length
M	= freestream Mach number
q	= body-axis pitch rate
$\bar{q}_\infty$	= freestream dynamic pressure
$\hat{q}$	= non-dimensional pitch rate, $(q + \dot{\alpha})/2 \cdot L_{ref}/(2V_\infty)$
$\hat{r}$	= non-dimensional yaw rate, $(r - \dot{\beta})/2 \cdot L_{ref}/(2V_\infty)$
r	= body-axis yaw rate
Re_D	= Reynolds number based on reference length, $V_\infty L_{ref}/\nu$
S_{ref}	= reference area, $\pi L_{ref}^2/4$
V_∞	= freestream velocity
X_r	= distance from CG to triple bridle confluence point
α	= angle of attack

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$\dot{\alpha}$	=	time rate of change of angle of attack
β	=	angle of sideslip
$\dot{\beta}$	=	time rate of change of angle of sideslip
ν	=	kinematic viscosity
ω	=	oscillatory frequency of the Entry Vehicle, $(2\pi f)$, rad/s

Acronyms and Abbreviations

ADB	=	Aero Database
CG	=	Center of Gravity
CONOPS	=	Concept of Operations
Csys	=	Coordinate System
DAS	=	Data Acquisition System
DOF	=	Degrees of Freedom
EDL	=	Entry, Descent, and Landing
EV	=	Entry Vehicle
FO	=	Forced Oscillation
LaRC	=	Langley Research Center
MC	=	Monte Carlo
MOI	=	Moment of Inertia
MRC	=	Moment Reference Center for the aeroshell aerodynamics
NFAC	=	National Full-Scale Aerodynamics Complex
OML	=	Outer Mold Line
POST2	=	Program to Optimize Simulated Trajectories II
PPF	=	Preparation for Powered Flight
RBS	=	Rotary Balance System
RS	=	Reduced Stroke (Posed) configuration
TBCP	=	Triple Bridle Confluence Point
VST	=	NASA LaRC 20FT Vertical Spin Tunnel

I. Introduction

NASA's Dragonfly mission, led by Johns Hopkins Applied Physics Laboratory, will deliver a relocatable Lander to explore prebiotic chemistry and habitability of Saturn's moon Titan. This vehicle is a quadcopter with dual counter-rotating three-bladed rotors, simply referred to as a rotorcraft Lander or just Lander. The Entry Vehicle (EV) for the Entry, Descent, and Landing (EDL) phase will use a blunt axisymmetric aeroshell to deliver the Lander to an above surface release altitude similar to the Concept of Operations (CONOPS) shown in Fig. 1 and details are given Ref.

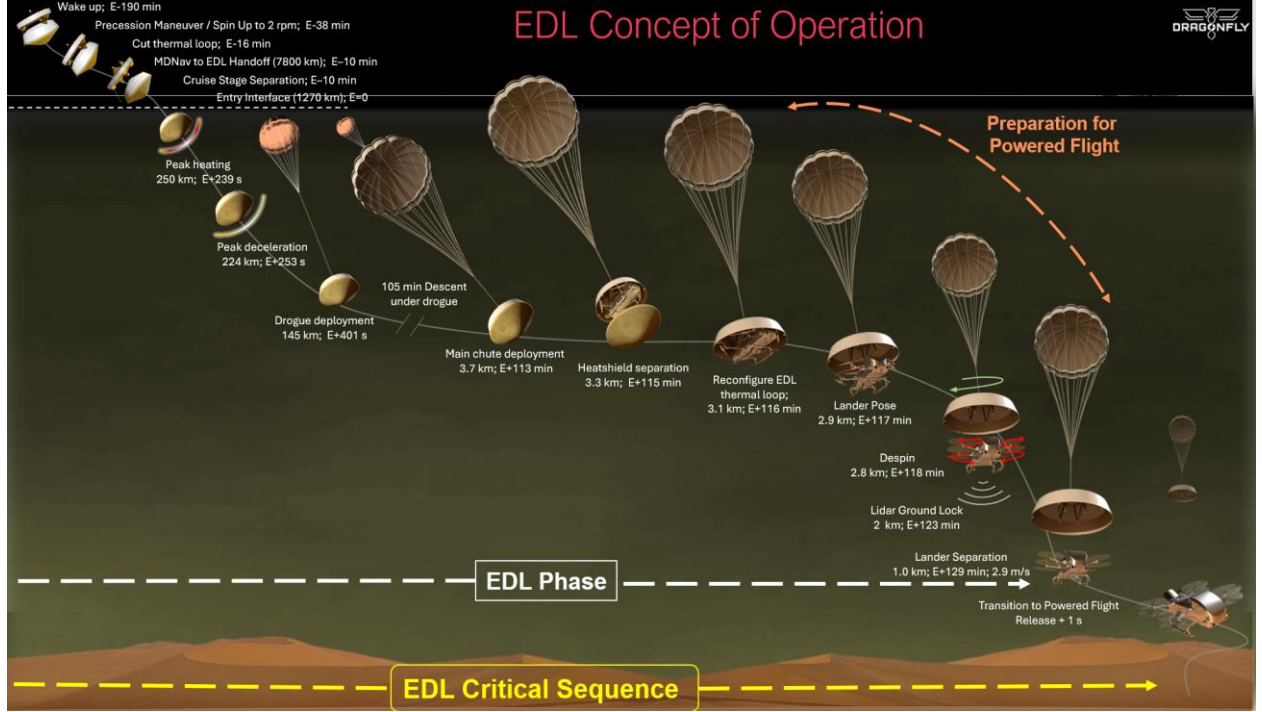


Fig. 1 Dragonfly EDL Concept of Operations on Titan from Entry Interface to Lander Release.

[1]. The EDL phase begins at Entry Interface (EI) where the aeroshell descends passively from at an altitude of ~ 1300 km until it reaches the drogue deploy altitude of 145 km and $M \sim 1.5$. For approximately 105 minutes the aeroshell descends under the drogue to the main parachute (or, just “main”) deploy altitude of 3.7 km and $V_\infty = 7$ m/s. Once the main has inflated, the heatshield is jettison starting the EDL Preparation for Powered Flight (PPF) sub-phase. During the 10–13-minute PPF phase the EV is descending under the main. The Dragonfly program uses the 6-DOF Program to Optimize Simulated Trajectories II (POST2) simulation tool to model the EV's flight dynamics during EDL. POST2 models the EV with a parachute (drogue or main) as a two-body problem. This paper focuses on the wind-tunnel testing and the development of the dynamic aero model of the EV PPF configurations only. Similarly, the dynamic aero model for the aeroshell in the $M = 1.05$ down to heatshield jettison flight regime is given in the companion reference [2]. The Dragonfly program uses statistical metrics computed from the POST2 Monte Carlo (MC) simulation results to determine if flight performance requirements are satisfied. The dynamic aerodynamic models are implemented in the 6-DOF aerodynamic database (ADB) for the POST2 MC studies.

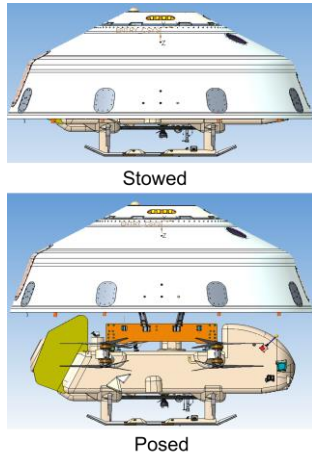


Fig. 2 Sketch of the EV in the Stowed and Posed configurations.

During PPF the EV will be in one of two configurations. Initially, the Lander is stowed in the backshell (stowed position) then, to clear the rotors for startup, lowered about 1 m to a position just outside the backshell (posed position), as shown in Fig. 2. The name of the EV PPF configurations will be called Stowed and Posed. The posed position is necessary to activate the rotors in preparation for Lander separation and transition to powered flight. Once the rotors become active, they remain at idling speed if not being used for the de-spin maneuver. The de-spin maneuver is used to remove the 2 RPM spin rate intentionally induced during cruise stage separation.

Modeling the dynamic aero of the EV during PPF is especially challenging given the unorthodox configurations flying under a main parachute at very low speeds (~ 3 m/s), with spinning rotors, and enough flight time (10-19 minutes) to allow the dynamic aero to significantly impact the flight dynamics. There is an EDL performance requirement that the EV shall not have a lateral angular rate greater than 12 deg/s and off-nadir angle greater than 34° at Lander separation. The system dynamics predicted in POST2 MC simulations have been shown to be very sensitive to the dynamic aerodynamics model. It is very important to characterize these aerodynamic properties to accurately predict performance metrics.

Given the highly unorthodox configurations coupled with the PPF flight environments on Titan, there was no historical data to construct a dynamic aero model for the POST2 MC studies conducted prior to the one presented in this paper. Until this dynamic aero model was available, the dynamic stability derivatives, C_{mq} and C_{nr} , were assumed equal with a value of zero. Furthermore, the stability derivatives were assumed to be the same for the Stowed and Posed configurations. Then, to understand the potential impact of dynamic aero on the dynamics of the PPF configurations, a sensitivity study was conducted in POST2. The study was conducted by dispersing C_{mq} and C_{nr} about the nominal value of zero with a positive and negative constant increment. It was found that for very small positive values (~ 0.05 per rad) of C_{mq} and C_{nr} the vehicle would fail to complete the PPF phase for nearly all Monte Carlo cases. This high sensitivity to dynamic aero was severe enough that the program carried it as an independent risk at the EDL level.

To obtain the data to model the dynamic aero, a low-speed wind tunnel test of the Stowed and Posed configurations, using the captive forced oscillation technique, was planned and executed in the NASA LaRC 20 FT Vertical Spin Tunnel (VST). To help mitigate this risk of adverse dynamic stability characteristics, the project conducted drone drop tests of dynamically scaled models of the Stowed and Posed configurations flying with the main deployed (Fig. 3). These drop tests are to be used to assess the dynamics during PPF but were not available until after the forced oscillation tests. The captive and drop tests used the same Outer Mold Line (OML) and nearly the same geometric scaling. Simulation results of the drop test are given in Ref. [3]. The results of the forced oscillation tests will be presented in this paper.

The additional aerodynamic models for the PPF configurations are obtained from computational fluid dynamic (CFD) solutions. The highly complex aerodynamics associated with modeling the rotor aerodynamics and flow-field interactions with the backshell is a major effort of the Dragonfly program. The aerodynamics will be modeled using CFD due in part to the difficulty to scale experimental test results of a subscale rotorcraft. Even so, experimental testing has been conducted to provide data to assist the CFD solutions. The experimental data of the Lander in the Posed configuration is from a test conducted in the National Full-Scale Aerodynamics Complex (NFAC) wind tunnel [4] (Fig. 4) with and without the backshell.



Fig. 3 Drone Drop Tests of the Posed configuration with the main parachute deployed.

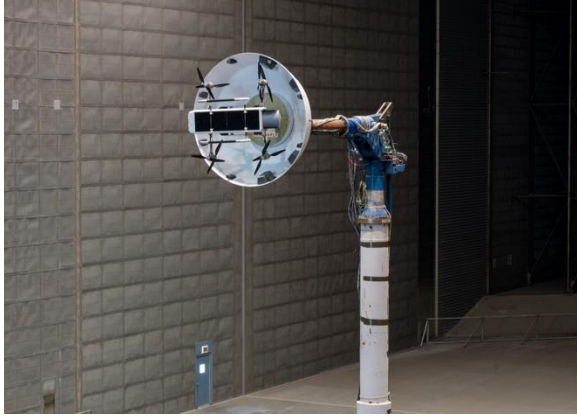


Fig. 4 NFAC wind tunnel test of the Posed Configuration

obtain the requisite aerodynamics for flight similitude on Titan are given. The test results are shown with discussion as it pertains to the dynamic aero model for the PPF configurations. The paper ends with a summary of the test and conclusions from the data analysis.

II. Test General Information

A. Test Facility and Hardware Description

The captive static and dynamic test techniques in NASA LaRC 20FT Vertical Spin Tunnel (VST) (Fig. 5) were used to efficiently measure static and dynamic aero data over a large parameter space. The VST is a continuous flow atmospheric wind tunnel, with an annular return passage, capable of dynamic pressures up to 335 Pa. The captive tests are performed by sting mounting the model on the Rotary Balance System (RBS). The RBS is designed to provide steady-state rotary motion about the model's wind axis for simulating spinning motion of flight vehicles. It also has the capability of testing the model statically or with 1-DOF oscillatory motion (forced oscillation). The forced motion, produced by an electric motor mounted at the base of the sting, oscillates the model about the centerline of the sting. For all methods, the RBS can set angle of attack, α , and angle of sideslip, β , independently over a 90 deg range.

As a matter of historical note, after 84 years of continuous operation, the Dragonfly PPF has the distinct honor of being the last test in VST. In support of aerodynamic modeling of the coning motion observed during the PPF drop tests, an exploratory test, using the rotary test technique, was being conducted on the RBS in March 2025 when VST ceased operations. The VST, continuously operated since 1941, became inoperative in March of 2025 when the RBS was transferred to the new Flight Dynamics Research Facility (FDRF). The FDRF combines the test techniques used in the NASA LaRC 12FT Low Speed Tunnel and the VST into a single facility. Details of using these test techniques in FDRF can be found in Ref. [5].

The primary objective of the VST forced oscillation tests was to obtain the dynamic aero coefficients, C_{mq} and C_{nr} , of the PPF configurations for direct use in the POST2 MC simulation studies. Secondary objectives of the test for the Posed configuration included impact studies of idling rotors and the reduced Lander to Backshell separation distance. The length of the structure that attaches the Lander to the backshell was being traded at the time of the tests. The original test objectives included determining roll damping. Unfortunately, wind-tunnel time constraints and since the EV conducts a de-spin maneuver to actively suppress rolling motions, the roll damping objective was eliminated.

A description of the EV PPF full-scale flight geometry and mass properties that were used to design the wind tunnel model and plan the test are presented below. Then, the wind tunnel facility and test techniques are briefly described. Next, the wind tunnel model configurations and test parameters to

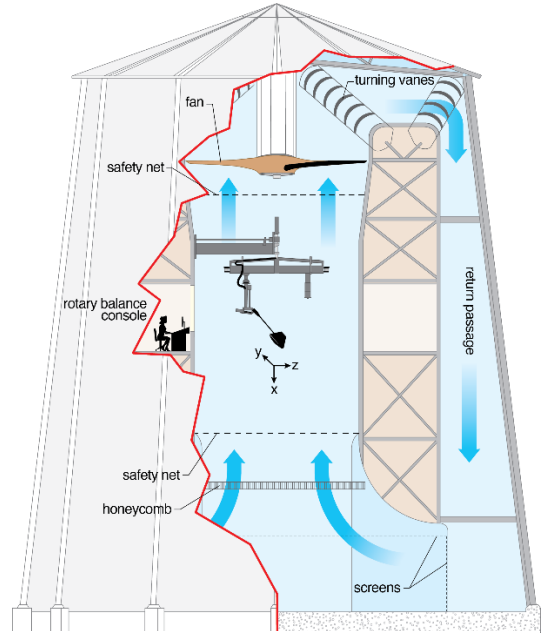


Fig. 5 NASA LaRC 20FT Vertical Spin Tunnel configured for captive static and dynamic testing of sting mounted models on the RBS.

The FDRF combines the test techniques used in the NASA LaRC 12FT Low Speed Tunnel and the VST into a single facility. Details of using these

B. Coordinate System, Reference Information, Full-Scale Geometry, and Mass Properties

The aerodynamic data presented in this paper are defined in a body-axis coordinate system with the origin at the center-of-gravity, CG, as shown in Fig. 6. This coordinate system, in this paper called “Aero Csys”, is used by the Dragonfly 6-DOF ADB. The maximum diameter of the aeroshell is used as the reference length, $L_{ref} = 4.50$ m, and the area of a circle with diameter L_{ref} defines the reference area, $S_{ref} = 15.90$ m². A sideview sketch of the Stowed and Posed configurations is given in Fig. 7. The sketch shows the location of the CG for each configuration. All the full-scale geometry and mass properties were the values being used by the project at the time of the test and given in the aero coordinate system. The aerodynamic moment reference center is at the CG for that configuration. The Stowed configuration has a mass of 2042 kg and moment of inertia (MOI) about the pitch and yaw body-axis of $I_{yy} = 2207$ kg-m² and $I_{zz} = 1707$ kg-m², respectively. The Posed configuration has the same mass as the Stowed, but the MOI have increased significantly to $I_{yy} = 3645$ kg-m² and $I_{zz} = 3040$ kg-m² due to the increase in the Lander and backshell separation distance. Additionally, assuming rigid Triple Bridle legs, the distance, X_R , from the CG to the Triple Bridle Confluence Point (TBCP) is required to determine the reduced frequency parameter. The design changes to the PPF configurations since this test, for example the rotorcraft now has 3-bladed rotors rather than 2-bladed, are not expected to have an impact on the dynamic aero model presented.

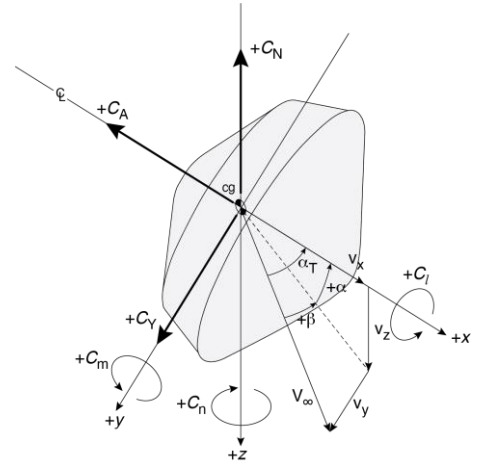


Fig. 6 Aerodynamic coordinate system (Aero Csys).

C. Wind Tunnel Model Description

Wind tunnel models for the FO test technique in the VST were designed for the Stowed and Posed configurations. All models could be mounted to the sting on either its pitch or yaw axis to obtain C_{mq} and C_{nr} , respectively. Models of the Stowed and Posed configuration, at scales of 7.78% and 15.56% were designed and fabricated to allow for

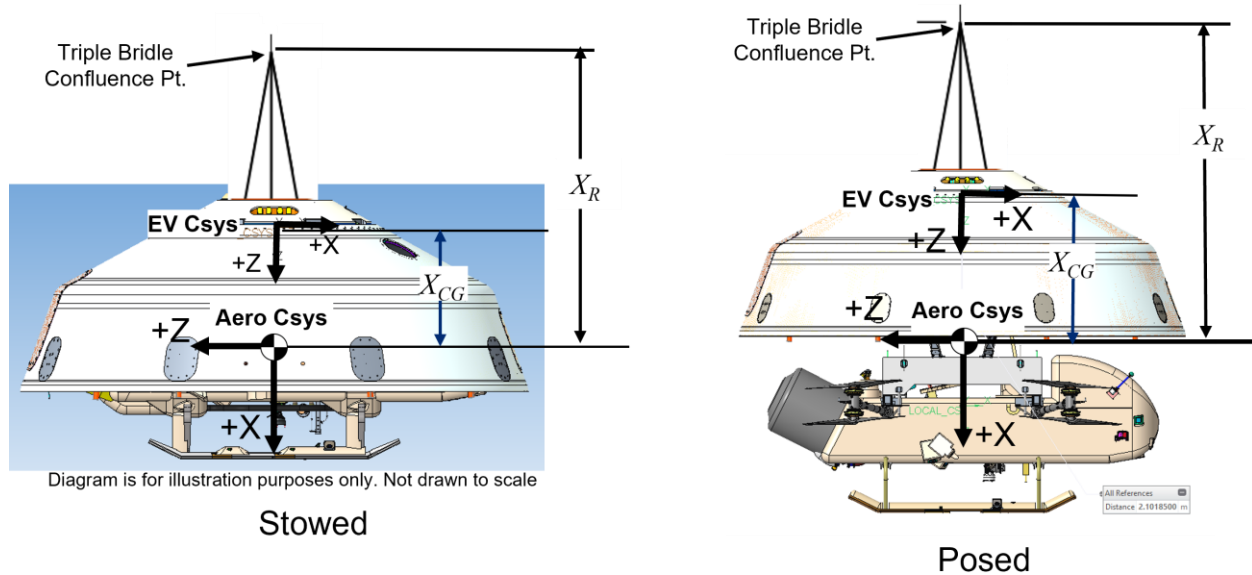


Fig. 7 Diagram of the Stowed and Posed configurations showing pertinent geometric details. Not drawn to scale. Location of CG is approximate.

testing with and without the backshell. Pictures of the 15.56%-scale model of the Stowed configuration mounted on the VST RBS forced oscillation apparatus for pitch and yaw oscillations are shown in Fig. 8 and the same for the 15.56%-scale model of the Posed configuration shown in Fig. 9. The Posed configuration model could be tested at two values of X_r to obtain data at the nominal posed position and at the reduced stroke (RS) posed position. For the RS posed position the distance from the Lander to the backshell is reduced by 0.372 m but the distance that impacts

dynamic aero is X_r . This value is reduced by 0.271 m. Rotor simulators were designed for the Posed configuration model to study the effect idling rotors.

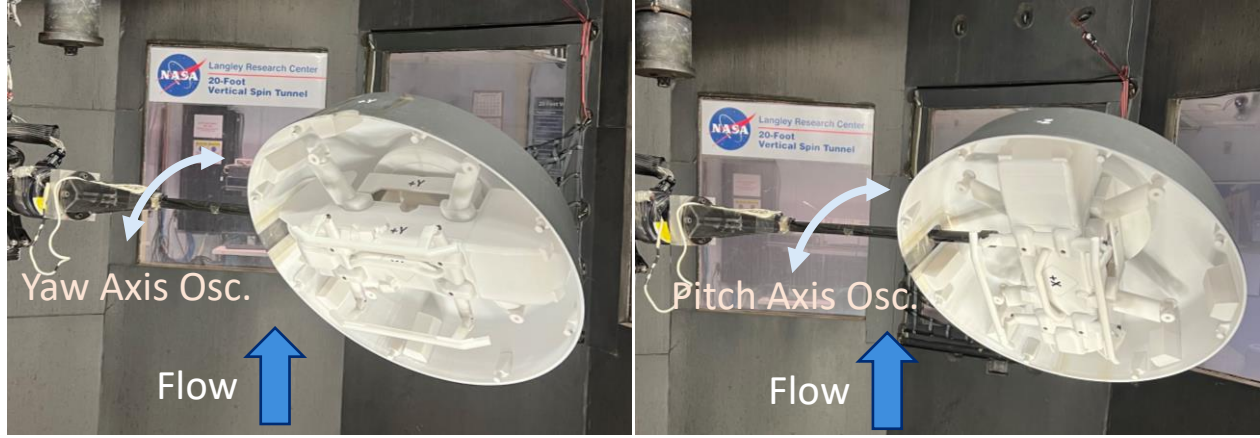


Fig. 8 15.56%-scale model of the Stowed configuration mounted for pitch and yaw axis forced oscillation testing.



Fig. 9 15.56%-scale model of the Posed configuration mounted for pitch and yaw axis forced oscillation testing.

D. Test Conditions and Test Matrix

To have relevance on Titan, the aerodynamics measured in the wind tunnel test must match similitude scaling parameters [6]. For dynamic tests of rigid-body motion, dynamic-scaling parameters must be matched in addition to the ones for static testing. The 1-DOF forced oscillation (FO) dynamic test technique was used to measure the aerodynamic data for calculating the dynamic stability derivatives, C_{m_q} and C_{n_r} . These coefficients are used to model the dynamic aerodynamics associated with oscillatory motion of the EV about its CG. The associated similitude requisites are the reduced frequency, $k = \omega L_{ref}/(2V_\infty)$, and non-dimensional angular rate parameters $\hat{q} = (q + \dot{\alpha})/2 \cdot L_{ref}/(2V_\infty)$ and $\hat{r} = (r - \dot{\beta})/2 \cdot L_{ref}/(2V_\infty)$. The following are the Titan full-scale physical properties used for dynamic scaling: Altitude = 2.4 km, $\rho = 5 \text{ kg/m}^3$, $g = 1.352 \text{ m/s}^2$, $V_\infty = 3 \text{ m/s}$, $L_{ref} = 4.5 \text{ m}$, and $Re_D = 10$ million.

The VST flow conditions for the nominal aerodynamic data were: $\bar{q}_\infty = 9.58 \text{ N/m}^2$ and $V_\infty = 4 \text{ m/s}$ with corresponding $Re_D = 100,000$ for the 7.78%-scale model and $Re_D = 200,000$ for the 15.56%-scale model. C_{m_q} was obtained for $-90^\circ \leq \alpha \leq 90^\circ$ and $-50^\circ \leq \beta \leq 0^\circ$ and C_{n_r} for $-90^\circ \leq \beta \leq 90^\circ$ and $-50^\circ \leq \alpha \leq 0^\circ$.

Rigid body oscillatory motion produces unsteady periodic flow field mechanisms (e.g. wake vortex shedding from flow separation at the exposed edge of the open backshell). These periodic mechanisms can produce surface pressure

fields that result in rigid body motion. Matching the reduced frequency parameter is required to capture these unsteady effects.

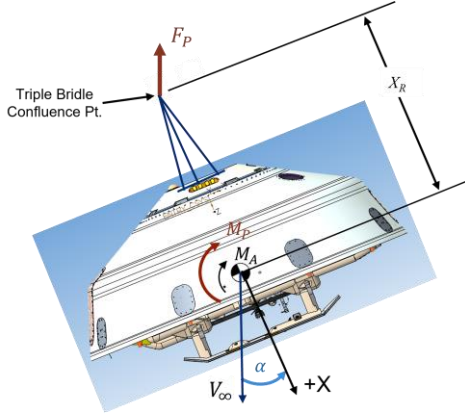


Fig. 10 Freebody diagram of a PPF configuration with main parachute deployed in planar motion. $M_P \equiv$ moment produced by the parachute drag force, F_P . $M_A \equiv$ EV aerodynamic restoring moment.

To determine scaled test conditions, a nominal reduced frequency was calculated assuming the PPF configurations with the main deployed can be modeled as a second order mass-spring system with 1-DOF planar motion [7, 8, 9]. The main is modeled as a point drag force applied at the distance, X_r , from the CG to the Triple Bridle Confluence assuming rigid bridle legs. For planar pitch motion, the free-body diagram of the system for the Stowed configuration is shown in Fig. 10. The diagram for the Posed configuration is the same except the distance, X_r , is longer. To determine the reduced frequency parameter for C_{mq} , the undamped natural frequency, ω , about the pitch axis is computed in Eq. 1. This equation is derived from the 1-DOF pitching moment equation of motion as shown in Ref [10], where (C_{DS}) is the drag area of the main parachute calculated using the reference dimensions of the EV. Note that Eq. 1 assumes the main experiences the same freestream dynamic pressure as the EV. From Knacke [11], this is a reasonable assumption given the canopy is approximately 8 body diameters downstream of the aeroshell. Knowing ω , the reduced frequency is determined from $k = \omega L_{ref}/(2V_\infty)$. The reduced frequency for C_{nr} is determined from 1-DOF motion about the yaw axis. It will differ from the k for C_{mq}

because $C_{n\beta} \neq C_{m\alpha}$ and $I_{zz} \neq I_{yy}$. The reduced frequency parameter, k , is slightly different for the Stowed and Posed configurations due to differences in the distance, X_R , and MOI. $X_R = 2.531$ m for the Stowed and $X_R = 3.170$ m for the Posed configuration. The values range from $k = 1.1$ to 1.45. In the VST, the maximum achievable value of k was 1.1.

$$\omega = \sqrt{\frac{-C_{m\alpha} \bar{q} S_{ref} L_{ref} + (C_{DS})_{chute} \bar{q} X_r}{I_{yy}}} \quad (1)$$

Sensitivity studies of the dynamic aero, C_{mq} and C_{nr} , to the similitude parameters were conducted. The sensitivity to reduced frequency, k , was studied by performing a large range, high resolution frequency sweep around trim. The sensitivity to non-dimensional angular rate was studied by holding the frequency constant while varying the amplitude with values from 5° to 25° . At a smaller subset of the test matrix the Posed configuration was tested with simulated idling rotors using porous disks.

When planning the test there was not any historical dynamic aero for a configuration even remotely close in geometric shape, especially at the scaled Titan test conditions. To help with understanding the validity of the C_{mq} and C_{nr} , the Stowed and Posed configurations were tested with the Lander only by removing the backshell but leaving the oscillation-axis location unchanged. An additional Posed configuration was tested to evaluate a smaller separation distance between the Lander and the backshell was being considered after the end of the original tests. This configuration is called Reduced Stroke (RS) Posed. Adequate repeatability and reproducibility runs were conducted to construct an uncertainty model suitable for the POST2 MC simulation studies.

E. Instrumentation and Data Acquisition System

Aerodynamic forces and moments were measured with the NASA LaRC SPT2C 6-component strain gauge balance mounted in the model along the pitch or yaw body-axis at the CG location of the configuration being tested. The digital angular position encoder signal, used by the forced oscillation motor to provide the desired sinusoidal motion, was numerically differentiated to obtain the pitch or yaw rate needed for computing the damping derivatives, C_{mq} and C_{nr} .

The analog data were acquired from the instruments using a NEFF™ 620 system. The analog signals were conditioned using a 6-pole Butterworth low-pass analog filter with a 50 Hz cut-off frequency. All data channels were acquired using NEFF™ sample-and-hold cards and identically filtered to eliminate any phase lag between channels.

The sample rate for the forced oscillation and static data was 250 samples per second. The sample time varied based on the number of cycles required for a given oscillation frequency.

III. Experimental Methods

The FO test technique was used to calculate the dynamic aero coefficients. This technique consists of sinusoidally oscillating the model at a given frequency and amplitude about each angle of attack where the damping derivative is to be determined. Details of the data processing used in the FO technique are given in Ref. [12] but some will be discussed here for clarity.

Data are acquired for a number of cycles (typically, 40) that was determined using a running standard deviation of the per-cycle damping derivative. The individual cycles are ensemble averaged. This average is called a mean cycle. The hysteresis of the forces and moments during the cycle represents the dynamic aerodynamics. The dynamic aero coefficients shown in this paper and implemented in the POST2 ADB were determined from the mean cycle using the specific point method. Recall that with the 1-DOF FO test technique, $q = \dot{\alpha}$ and $r = -\dot{\beta}$. Therefore, what the dynamic stability derivatives from the FO test technique are $\overline{C_{m_q}} = C_{m_\alpha} + C_{m_q}$ and $\overline{C_{n_r}} = C_{n_r} - C_{n_\beta} \cos(\alpha)$. To simplify notation, $\overline{C_{m_q}}$ and $\overline{C_{n_r}}$ will be replaced by C_{m_q} and C_{n_r} , respectively.

IV. Results and Discussion

The main objective of this section is to present and discuss the test results that are to be used to populate the dynamic aerodynamics nominal and uncertainty models for the Dragonfly PPF configurations for POST2 MC studies. The section will begin by showing C_{m_q} as it varies with α at $\beta = 0^\circ$ and C_{n_r} as it varies with β at $\alpha = 0^\circ$ for the Posed configuration. With no historical data to compare to, these data are used to provide an initial understanding of the dynamic stability. With a baseline understanding established, the dynamic aero for other PPF configurations as function of α , β , and reduced frequency will be shown. To determine if C_{m_q} and C_{n_r} need to be modeled as functions of α and β , the data will be shown for C_{m_q} versus β for $\alpha = 0^\circ$ and C_{n_r} versus α for $\beta = 0^\circ$ are shown. Next, the functional dependence of C_{m_q} and C_{n_r} on $\hat{q}$ and $\hat{r}$, respectively, is investigated. The final section will show, for each PPF configuration, the C_{m_q} and C_{n_r} nominal with uncertainty bounds that are used in the POST2 MC simulations.

In general, the dynamic aero will be shown with parameterized plots of C_{m_q} versus α and C_{n_r} versus β . When observing these plots, it is important to remember that they are plots of an aerodynamic derivative. The vehicle dynamics are impacted by time integration of $C_{m_q} \cdot \hat{q}$ and $C_{n_r} \cdot \hat{r}$ over multiple oscillation cycles where the amplitude can be growing or decaying. Damping effects are the result of the angular rate weighted integration of the area under the C_{m_q} and C_{n_r} curves associated with sinusoidal motion about trim ($\alpha = 0^\circ$, $\beta = 0^\circ$). Therefore, the values of C_{m_q} and C_{n_r} near trim will have the most impact and “spikes” in the data will be averaged out during the EOM integration process. Also, unless noted otherwise, the data is presented for forced sinusoidal motion with an amplitude of 10 deg and the rotor simulators off.

The dynamic stability derivatives for the Posed configuration, are shown in Fig. 11 as a plot of C_{m_q} vs. α , for $\beta = 0^\circ$ and C_{n_r} vs. β , for $\alpha = 0^\circ$ and $k = 0.25$. The plot shows that C_{m_q} has stable values between -0.1 and 0.0 for $\alpha < \pm 25$ deg with small unstable values for $\alpha \geq \pm 25$ deg. In comparison, C_{n_r} has nearly the same values and trends for $\beta \geq \pm 10^\circ$ as C_{m_q} does over the same α range. In contrast, C_{n_r} has highly nonlinear unstable values for $\beta < \pm 10^\circ$. The difference is due to different flow fields over the area of the backshell, as shown in Fig. 12, that is at the maximum distance from the rotation axis. This axis is coincident with the CG.

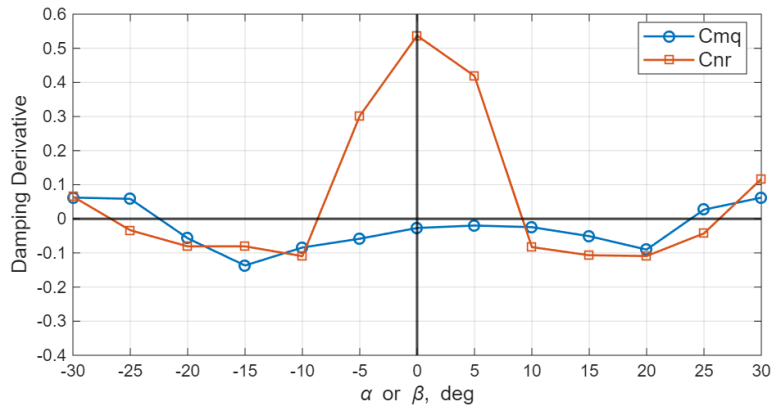


Fig. 11 Pitch and yaw dynamic stability derivatives for the Posed configuration. C_{m_q} vs. α for $\beta = 0^\circ$ and C_{n_r} vs. β for $\alpha = 0^\circ$, $k = 0.25$. Damping derivative units are per rad.

The surface pressures on this part of the backshell produce the maximum aerodynamic moments – pitching moment when oscillating about the pitch axis and yawing moment when oscillating about the yaw axis.

As shown in Fig. 12 with the model mounted on the pitch axis to measure C_{mq} , the flow over the area of the backshell at the maximum z-distance from the CG is diverted by the Lander. But, as shown in Fig. 12 with the model mounted on the yaw axis to measure C_{nr} , the flow over the area of the backshell at the maximum y-distance from the CG is basically unobstructed. When the EV is in the Posed configuration and oscillating about the yaw axis, the dynamic stability is like that of a windward facing concave body, which are highly unstable. To qualitatively assess the backshell flow field, yarn tufts were attached to the backshell, and their motion observed during the forced oscillation runs. The observations confirmed a difference in the attach flow patterns when oscillating in pitch than in yaw. The data from the runs with the rotor simulators installed will be used to provide additional evidence. The hypothesis is that if the windward facing concave backshell is causing the instabilities, then the presence of the rotors upstream of this concavity should affect the flow field in and around the backshell much like the Lander does to the backshell for pitch oscillations.

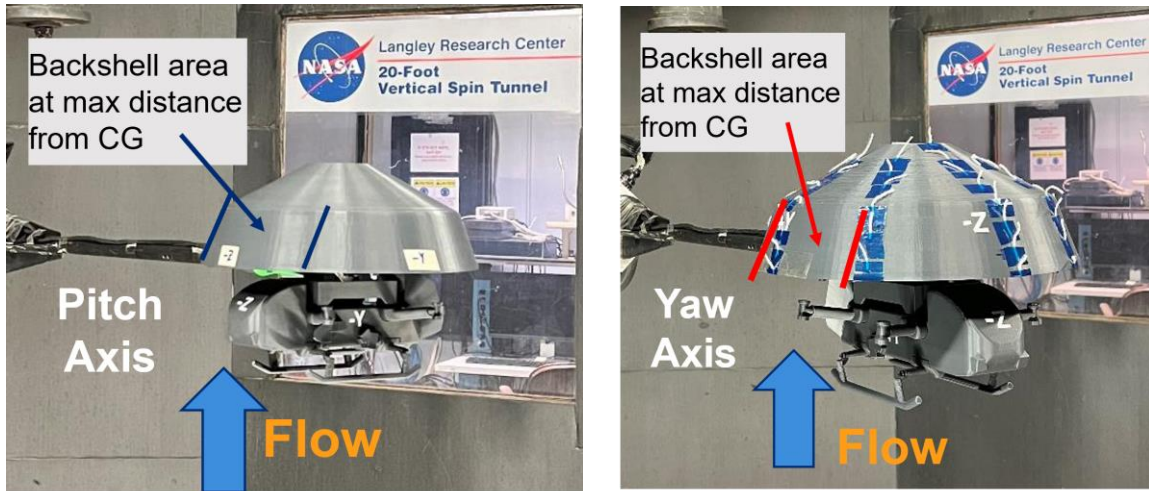


Fig. 12 The 7.78% -scale Posed configuration model in the VST illustrating the area of the backshell relative to the orientation of the Lander that explains the impact on dynamic stability.

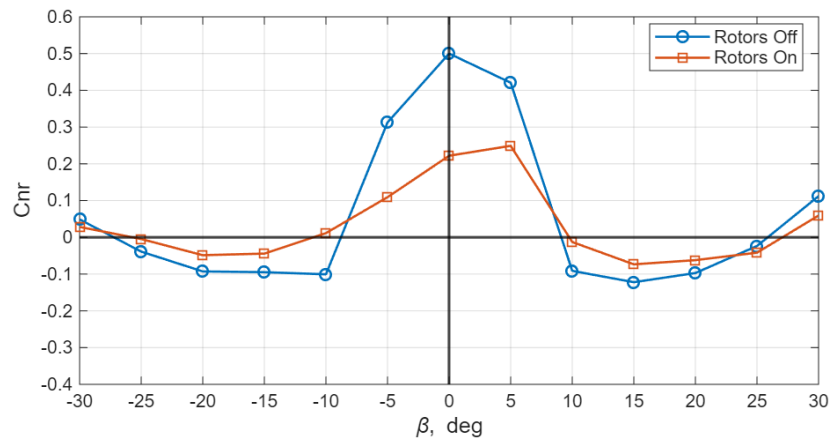


Fig. 13 Effect of idling rotors on the yaw dynamic stability derivative for the Posed configuration. $\alpha = 0^\circ$, $k = 0.25$.

Recall that the spinning rotors are simulated as idling rotors only. The rotor simulators are a circular disk with a geometrically-scaled diameter of the rotors and with a porosity to match the drag of the idling rotors. It is known that the flow field produced by the rotors is much more complex but accurate enough to provide trends. The C_{n_r} data from

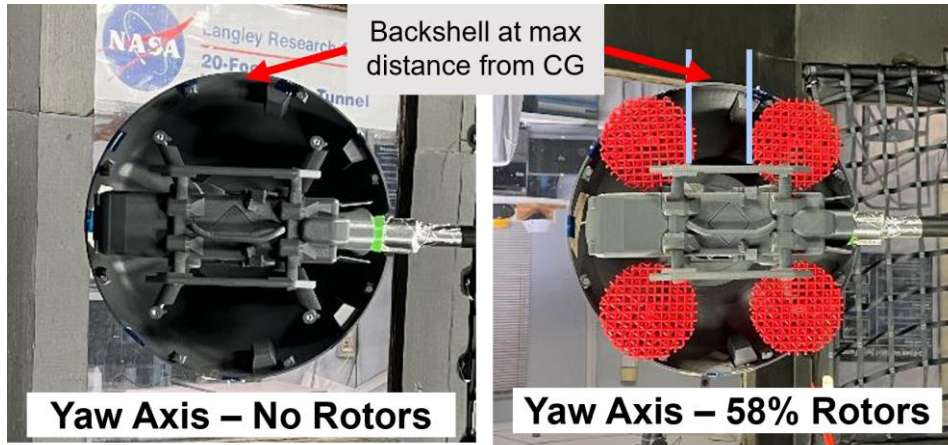


Fig. 14 The 7.78%-scale model of the Posed configuration mounted for yaw oscillations viewed looking downstream with and without the rotor simulators on.

Fig. 11 without the rotors is compared to the data with the rotors installed in Fig. 13. The data show modeling the presence of the idling rotors upstream of the backshell did affect the yaw dynamic stability and with a significant stabilizing effect. As shown, the rotors affect the backshell flow field, reducing the positive C_{n_r} values. However, the effect is not at the levels that the Lander affected C_{m_q} . While the rotor

simulators clearly affect the flow approaching the backshell, there are still clear geometric differences in the pitch and yaw planes. The rotors do not completely cover the area upstream of the BS at the max distance from the CG as the Lander does for pitch oscillations. In Fig. 14, the view shown is looking downstream at the Posed configuration mounted on the sting for yaw damping with and without the rotor simulators. These pictures show how the large presence of the rotors upstream of the backshell can significantly alter the flow field in and around the windward facing concaved backshell.

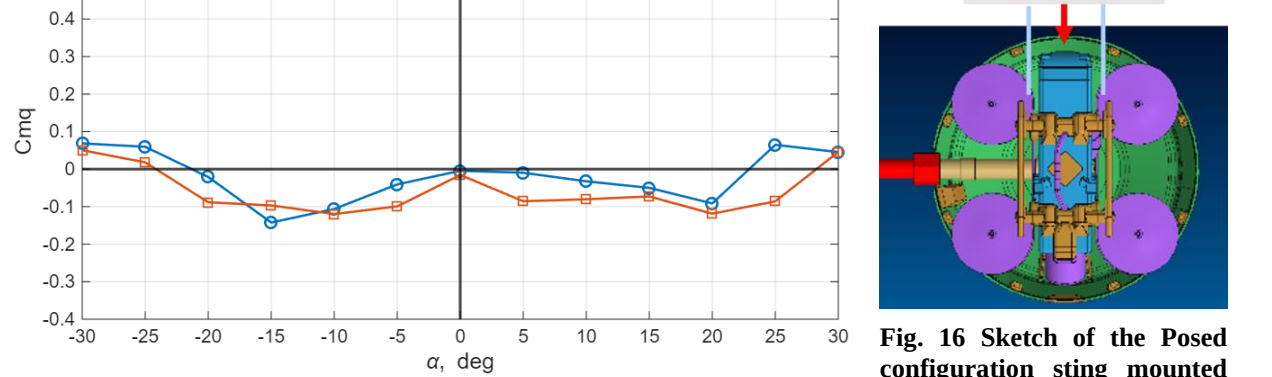


Fig. 15 Effect of idling rotors on the dynamic pitch stability of the Posed configuration. $\beta = 0^\circ$, $k = 0.25$.

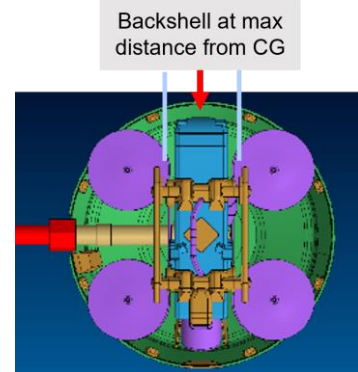


Fig. 16 Sketch of the Posed configuration sting mounted for pitch oscillations with rotor simulators on as viewed looking downstream.

A. Effect of Reduced Frequency at Trim Conditions

This section will show the effect of the reduced frequency parameter for the PPF configurations. As discussed in Test Conditions and Test Matrix section, the ability to conduct the wind tunnel test the reduced frequency parameter value for Titan similitude was challenging. For the PPF configurations, the reduced frequency range is $k = 1.1$ to 1.45 , with 1.1 being the largest value possible in the VST test. Also recall these values are estimates of the reduced frequency parameter. The dynamic aero tests of the aeroshell [2] showed a high sensitivity to k especially in the $M < 0.1$ flight



Fig. 18 Sideview of the 15.56%-scale models of the Stowed, RS Posed, and Posed configurations mounted for pitch oscillations in the VST to show the relative position of the Lander to the backshell.

regime. For these reasons, C_{m_q} and C_{n_r} are calculated for a large range of reduced frequencies. The effect of reduced frequency is investigated with high resolution frequency sweeps at the trim condition ($\alpha = 0^\circ, \beta = 0^\circ$) and with α or β sweeps at a subset of these k values.

To better understand how to model the Stowed and Posed configurations, the C_{m_q} and C_{n_r} data for the RS Posed configuration are compared. The RS Posed is the only configuration for which the effect of idling rotors was investigated at $k = 1.1$. This is the minimum value for flight similitude and the highest value that could be tested in the VST. These data are used to determine if the effect of the idling rotors is needed for the dynamic aero model in the ADB for POST2. Using a high-resolution frequency sweep over the range, $\sim 0.05 < k < \sim 1.1$, the effect of reduced frequency on the dynamic aero coefficients, C_{m_q} and C_{n_r} , for the Stowed, RS Posed, RS Posed with Rotors, and Posed configurations (pictured in Fig.

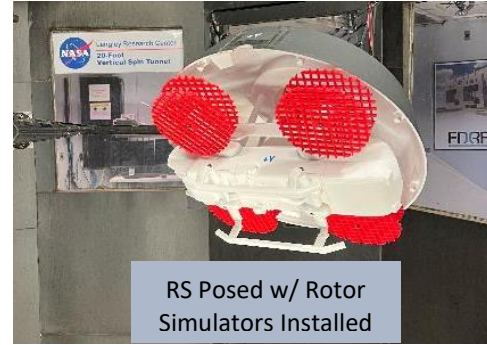


Fig. 17 15.56%-scale model of the RS Posed configuration with Rotor Simulators installed in the VST mounted for yaw oscillations.

17 and Fig. 18) are shown in Fig. 19 and Fig. 20, respectively. While only the highest k value matches flight conditions, the frequency sensitivity sweep provides valuable information, showing that PPF configurations will be flying at conditions where damping is nearly invariant with reduced frequency. The figures show that the dynamic aero coefficients have high unstable values at $k \sim 0.05$. In general, for all configurations, as frequency increases, C_{m_q} and C_{n_r} exponentially decays to a nearly asymptotic stable value at $k \sim 0.8$. All configurations have nearly the same C_{m_q} magnitude (Fig. 19).

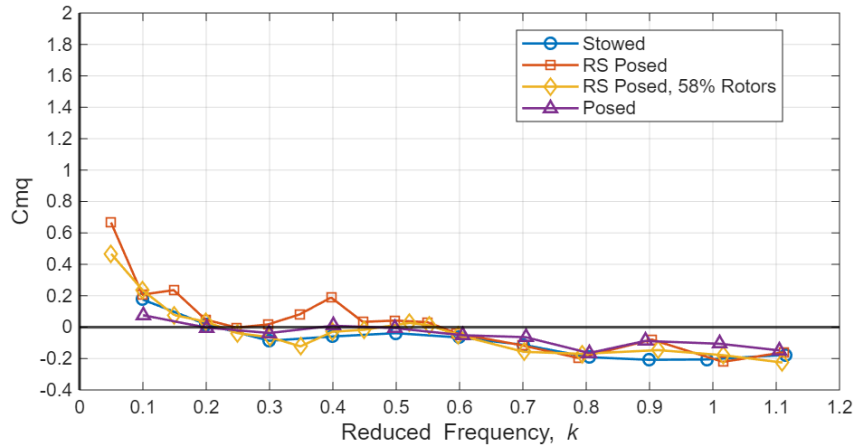


Fig. 19 Effect of reduced frequency parameter at trim conditions ($\alpha = 0^\circ, \beta = 0^\circ$) on C_{m_q} for the PPF configurations.

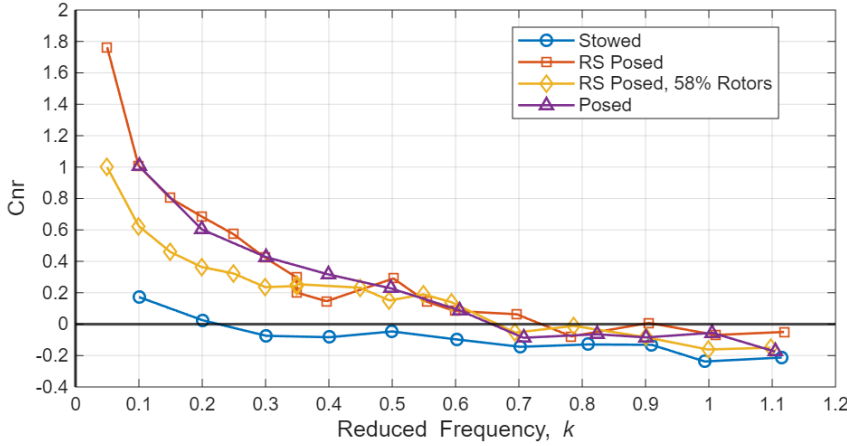


Fig. 20 Effect of reduced frequency parameter at trim conditions $\alpha = 0^\circ, \beta = 0^\circ$ on C_{n_r} for the PPF configurations.

on C_{m_q} and C_{n_r} . The C_{n_r} data for the Stowed configuration are significantly more stable compared to the Posed configurations and C_{n_r} has nearly the same values as C_{m_q} . This indicates that when the Lander is in the stowed position it causes a pressure field on the backshell that promotes stability regardless of the rotation axis. The C_{m_q} and C_{n_r} data in these figures show that the presence of the idling rotors upstream of the backshell have a significant stabilizing effect for $k < 0.5$. Therefore, this data shows that the final dynamic aero model will not require including the effect of rotors.

From the frequency sweeps, it is concluded that as k increases C_{m_q} and C_{n_r} have more stable values that eventually reaches an asymptotic value. The data strongly indicates that the C_{m_q} and C_{n_r} values for $k = 1.1$ can be accurately used for $k > 0.8$. This conclusion only applies to near trim conditions ($\alpha = 0^\circ, \beta = 0^\circ$). The next section shows the α and β parameter space of applicability.

In Fig. 20, C_{n_r} for the Posed configurations have large unstable values for $k < 0.6$ and high sensitivity to k compared to C_{m_q} for the reasons explained at the beginning of the Results & Discussion section. That is, in the Posed configuration the effect of the Lander's wake on C_{m_q} and C_{n_r} are different because of the asymmetry of the Lander orientation relative to the backshell.

Furthermore, comparing the data for the RS Posed to the Posed configurations shows that positioning the Lander 0.271 m closer to the backshell did not have a significant impact

B. Effect of Reduced Frequency for $|\alpha| \leq 90^\circ$ and $|\beta| \leq 90^\circ$

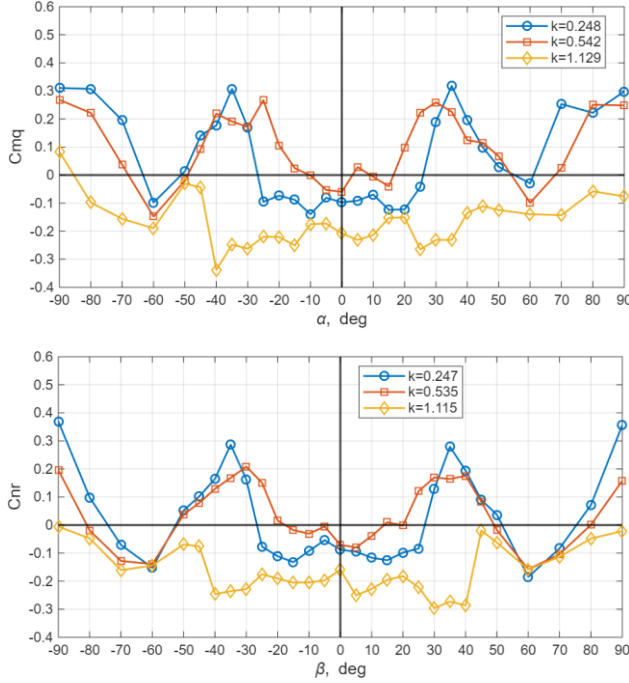


Fig. 21 Effect of k on the dynamic stability derivatives for the Stowed configuration: C_{m_q} vs. α , for $\beta = 0^\circ$ and C_{n_r} vs. β , for $\alpha = 0^\circ$.

configuration to go from being highly unstable in yaw damping to being stable. This trend is also observed for $30^\circ < |\beta| < 50^\circ$. Overall, with minor exception at α and β near $\pm 90^\circ$ the Posed configuration is dynamically stable in pitch and yaw for the flight similitude value of $k = 1.1$.

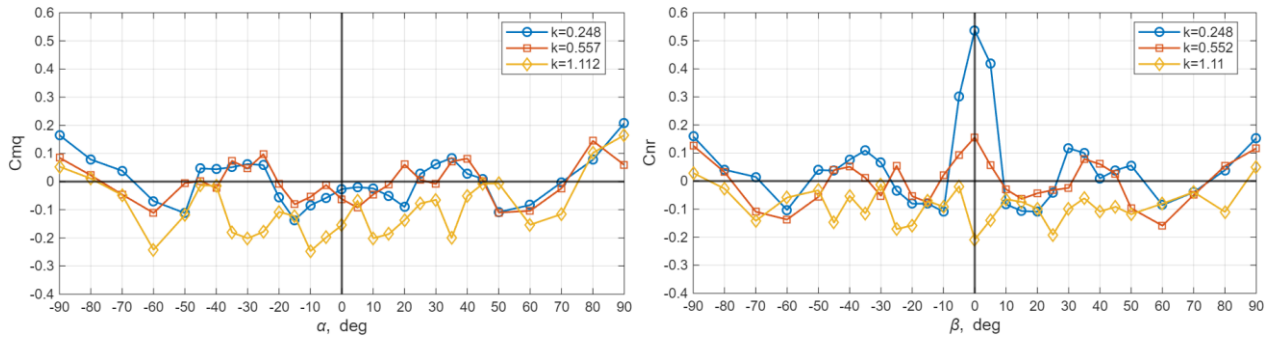


Fig. 22 Effect of k on the dynamic stability derivatives for the Posed configuration: C_{m_q} vs. α , $\beta = 0^\circ$ and C_{n_r} vs. β , $\alpha = 0^\circ$.

To summarize the observations made so far, with the Lander in the posed position, the dynamic stability is dependent upon the Lander orientation relative to backshell with the effect of adding a simulated rotor disk in the yaw plane upstream the backshell providing further evidence. Additionally, the effect of frequency results shows a significant difference in the dynamic stability derivatives the Stowed and Posed configurations. With these results it can be qualitatively concluded that the backshell surface pressures produce the aerodynamic moments responsible for the dynamic stability of the EV, but it is the shape and rigid-body oscillation frequency of the “forebody” induced flow field onto the backshell that drives these surface pressures.

The effect of reduced frequency, using values of $k = 0.25, 0.55$, and 1.1 , on the dynamic stability derivatives for the Stowed configuration is shown in Fig. 21 and for the Posed configuration in Fig. 22. In both figures, the data are shown as C_{m_q} vs. α , for $\beta = 0^\circ$ and C_{n_r} vs. β , for $\alpha = 0^\circ$.

For the Stowed configuration, Fig. 21 shows the effect of k on C_{m_q} varies with α with similar effect on C_{n_r} with β . Therefore, the following statements apply to both C_{m_q} and C_{n_r} . Within $\pm 30^\circ$ of trim, as k increases from 0.25 to 0.55 dynamic stability is reduced. For α or $\beta < -30^\circ$ and α or $\beta > 30^\circ$ the dynamic stability is approximately the same. With an increase in k from 0.55 to 1.1 this trend is reversed. For all α (except $\alpha = -90^\circ$) and β , C_{m_q} and C_{n_r} have stable values for $k = 1.1$. For $-40^\circ < \alpha$ or $\beta < 40^\circ$ the values range from -0.2 and to -0.3 . For α or β outside this range they are on average -0.1 .

For the Posed configuration, Fig. 22 shows that for C_{m_q} vs. α there is not a trend with k . The figure does show that C_{m_q} values for $k = 1.1$ are on average more stable than for $k = 0.25$ and 0.55 . Except for $|\alpha| > 70^\circ$, the Posed configuration is dynamically stable in pitch for $k = 1.1$. The data for C_{n_r} vs. β in Fig. 22 shows the significant effect of k within 10° of trim. In this 10° range, increasing k from 0.25 to 1.1 causes the Posed

C. Effect of Out-of-Plane Motion

Up to this point in this paper, all the data shown have been for C_{mq} calculated from pitch axis oscillations aligned with the pitch plane. Likewise, C_{nr} was calculated from yaw axis oscillations aligned with the yaw plane. In other words, C_{mq} as a function of α at $\beta = 0^\circ$ and C_{nr} as a function of β at $\alpha = 0^\circ$. Out-of-plane data runs were made to assess the effect of pitch and yaw axis oscillations not aligned with the axis of rotation on the dynamic stability derivatives. The out-of-plane runs were conducted for C_{mq} by varying β from 0° to -50° at $\alpha = 0^\circ$ and for C_{nr} by varying α from 0° to -50° at $\beta = 0^\circ$. The geometric asymmetries about the pitch and yaw planes are minor for the purposes of this investigation. The results of the investigation are shown in Fig. 23. All data are for $k = 1.1$.

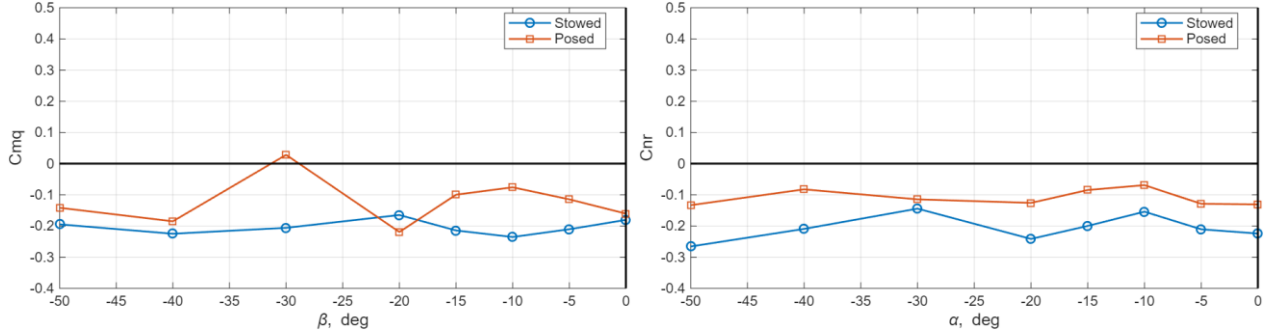


Fig. 23 Effect of out-of-plane motion on the dynamic stability derivatives for the Stowed and Posed configurations: C_{mq} vs. β , for $\alpha = 0^\circ$ and C_{nr} vs. α , for $\beta = 0^\circ$.

The data show that with the minor exception of C_{mq} at $\beta = -30^\circ$ that C_{mq} is essentially constant with β for both configurations. The data for C_{nr} vs α show that it is essentially constant with α for both configurations. Therefore, for the PPF configurations, C_{mq} can be modeled as a function of α for all β and C_{nr} as a function of β for all α .

D. Effect of Non-dimensional Angular Rate, $\hat{q}$ and $\hat{r}$

When conducting dynamic test techniques, matching the non-dimensional angular rate similitude parameter is used to assure that the induced flow field caused by the rate is accurately modeled. This section shows the results of

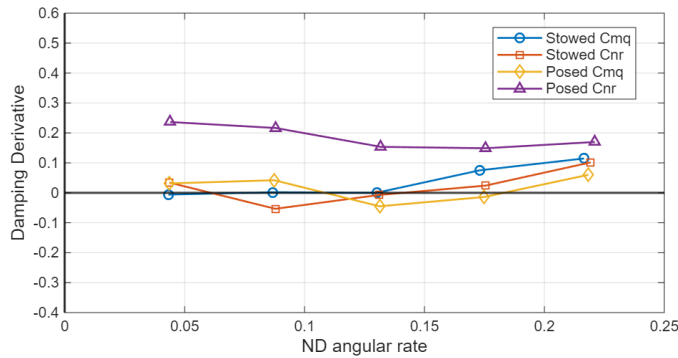


Fig. 24 Effect of non-dimensional angular rate on the dynamic stability derivatives for the Stowed and Posed configurations: C_{mq} vs. $\hat{q}$ and C_{nr} vs. $\hat{r}$, for $\alpha = 0^\circ$, $\beta = 0^\circ$.

a sensitivity study conducted to determine if C_{mq} and C_{nr} have a functional dependency on non-dimensional angular rate. The rate effect study was conducted using $\hat{q}$ and $\hat{r}$ sweeps for C_{mq} and C_{nr} , respectively, at $\alpha = 0^\circ$ and $\beta = 0^\circ$. Due to torque limitations of the forced oscillation motor the maximum reduced frequency possible was 0.55 instead of the desired 1.1. Since the data from the prior sections show that C_{mq} and C_{nr} are more stable at $k = 1.1$ than 0.55 then results shown should be conservative. The data from the $\hat{q}$ and $\hat{r}$ sweeps are combined into a single plot as shown in Fig. 24. The x-axis is $\hat{q}$ for the C_{mq} data and $\hat{r}$ for the C_{nr} data. The data in Fig. 24 show that for both configurations that C_{mq} and C_{nr} do not have a significant dependency on non-dimensional angular rate.

E. Nominal and Uncertainty Models

The dynamic aero models for the PPF configurations, Stowed and Posed, implemented in the ADB for POST2 are constructed based on the results and conclusions from the prior sections. For each configuration, the dynamic aero model consists of a nominal and a uniformly dispersed uncertainty increment of the dynamic stability derivatives C_{mq}

and C_{n_r} . The nominal values and uncertainties are only a function of α for C_{m_q} and β for C_{n_r} . The C_{n_r} data were symmetrized since the PPF geometry is nearly symmetric about the Aero Csys x-z plane. The C_{n_r} data were symmetrized by reflecting the $\beta < 0^\circ$ data about $\beta = 0^\circ$ and averaging with the $\beta > 0^\circ$ data. The C_{m_q} and C_{n_r} values were computed from data with a reduced frequency parameter value of 1.1. In the POST2 MC simulations and in the flight on Titan, the EV will experience a range of reduced frequencies. Results were shown that indicate that C_{m_q} and C_{n_r} determined from $k = 1.1$ test data are valid for $k > 0.8$.

The uncertainty model was constructed from the repeatability and reproducibility data from the test. The uncertainty is modeled as an increment to the nominal. The increment is at least 0.05. The uncertainties are applied with a uniform dispersion. The nominal curves, with the minimum and maximum uncertainty bounds, are shown for the Stowed configuration in Fig. 25 and for the Posed configuration in Fig. 26. The symbols in the plots are the experimental data from the repeat and reproducibility runs. The uncertainty increment is determined from these data. The data in the plots shows that the nominal has stable (negative) values with a few exceptions near α and $\beta = \pm 90^\circ$. The value of C_{m_q} and C_{n_r} at the upper bound of the uniformly dispersed uncertainties are close to zero with some α and β ranges that are slightly positive. While some of these values are large enough to cause significant dynamics the integrated effect of these derivatives during oscillatory flight would likely average to a stable value.

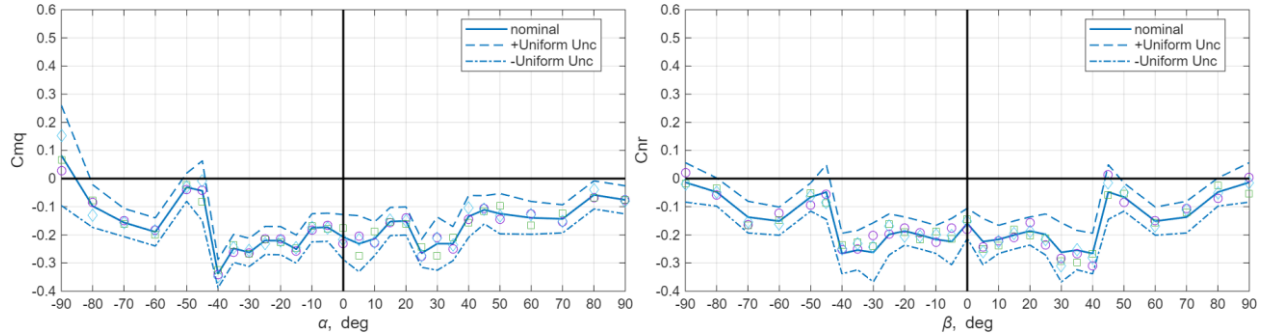


Fig. 25 Nominal with minimum and maximum uncertainty bounds of the dynamic stability derivatives for the Stowed configuration. Repeatability and reproducibility experimental data shown with symbols.

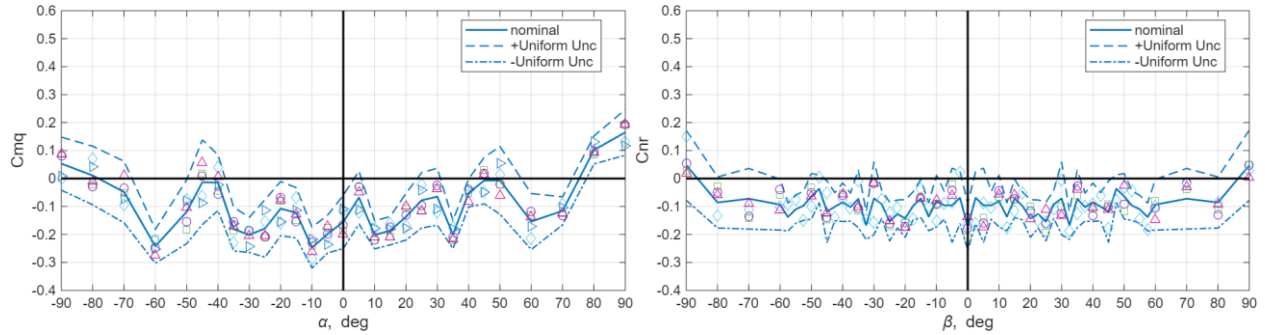


Fig. 26 Nominal with minimum and maximum uncertainty bounds of the dynamic stability derivatives for the Posed configuration. Repeatability and reproducibility experimental data shown with symbols.

V. Summary and Conclusions

NASA's Dragonfly mission will deliver a rotorcraft to Saturn's largest moon, Titan, to enable exploration and search for building blocks of life. The Entry, Descent, and Landing (EDL) phase of the mission will use an aeroshell to deliver the rotorcraft Lander to an above surface release altitude. The paper discusses the dynamic stability characterization of the Entry Vehicle during the final phase of EDL called Preparation for Power Flight (PPF). This phase of flight under the main parachute is particularly challenging with its very low free-stream velocities and multiple configuration changes along with the rotors spooling up. The dynamics stability characterization was obtained by conducting static and forced oscillation tests in the NASA LaRC 20FT Vertical Spin Tunnel on 7.78% and 15.56%-scale models of various PPF configurations.

The test showed that the dynamic aero coefficients, C_{mq} and C_{nr} , are highly dependent on the reduced frequency similitude parameter. Matching the reduced frequency parameter was the largest challenge of the tests. The challenge included using a model size much larger than prior EDL models and at extremely low freestream velocity and dynamic pressure values. The effect of the spinning rotors at idle speed, modeled by a geometrically scaled disk with porosity to match the drag, had a stabilizing effect on the dynamic aero coefficients. The effect of β on C_{mq} and the effect of α on C_{nr} has no significant effect at the $k = 1.1$ flight similitude value. Also, for $k = 1.1$ and near trim conditions, the non-dimensional angular rate similitude parameters had only a minor effect on the dynamic stability derivatives, so it was not included in the final dynamic aero model. This effect can be modeled with additional forced oscillation runs at conditions away from trim.

It was shown that the dynamic stability of the EV in the Posed configuration is dependent upon the Lander orientation relative to backshell. Further evidence of this conclusion was observed in the data showing the effect of adding a simulated rotor disk representing the flow field of idling rotors in the yaw plane upstream of the backshell. The effect of frequency results showed a significant difference in the dynamic stability derivatives between the Stowed and Posed configurations. With these results it was qualitatively concluded that the backshell surface pressures produce the aerodynamic moments responsible for the dynamic stability of the EV, but it is the shape and rigid-body oscillation frequency of the “forebody” induced flow field onto the backshell that drives these surface pressures.

The outcome of this test were separate dynamic aero models for the Stowed and Posed configurations. Each dynamic aero model consists of a nominal with uniformly dispersed uncertainties for C_{mq} and C_{nr} . The nominal and uncertainty are only a function of α for C_{mq} and β for C_{nr} . The nominal values for C_{mq} and C_{nr} are stable for all α and β with a few exceptions near α and $\beta = \pm 90^\circ$. The upper bound uncertainty values are near zero with some positive values based on α or β . The model was suitable for direct use in the POST2 simulation of the PPF sub-phase of the Dragonfly EDL on Titan. The results of the POST2 MC studies using this dynamic aero model, showed that even with maximum dispersed values the vehicle remains dynamically stable for almost 100% of the cases. Additionally, unpublished results of the drone drop tests of dynamically scaled models of the unpowered Stowed and Posed configurations showed they are dynamically stable.

Finally, the drop tests showed the expected coning and pendulum motion of the PPF configurations while descending under the main parachute. The center of rotation of these motions is at the confluence of the suspension lines. To quantify the dynamic aero associated with these motions in captive wind tunnel test techniques requires the rig to move the vehicle with constant rate and rotary motion. It was mentioned in the paper that the PPF configurations were undergoing rotary testing using the RBS when the VST ceased operations. Unfortunately, the rotary testing was not completed before the RBS was moved to the new FDRF (operations expected to begin mid-2026). With the favorable results of the drop tests and with EDL Critical Design Review complete, tests using the constant rate and rotary techniques are on indefinite hold.

VI. Acknowledgements

The dedicated effort of the following people contributed to the success of this test: Clinton Duncan, Rick Thorpe, Earl Harris, Lee Pollard, Wes O’Neal, Zoe Hughes, Karl Edquist, Cole Kazemba, Mike Wright, Tom Fajardo, Peter Lorber, and Patrick Bowles. Special recognition goes to Caleb Thompson and Gary Wainwright for their above and beyond efforts to design and fabricate the numerous models when I asked for them “yesterday”.

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