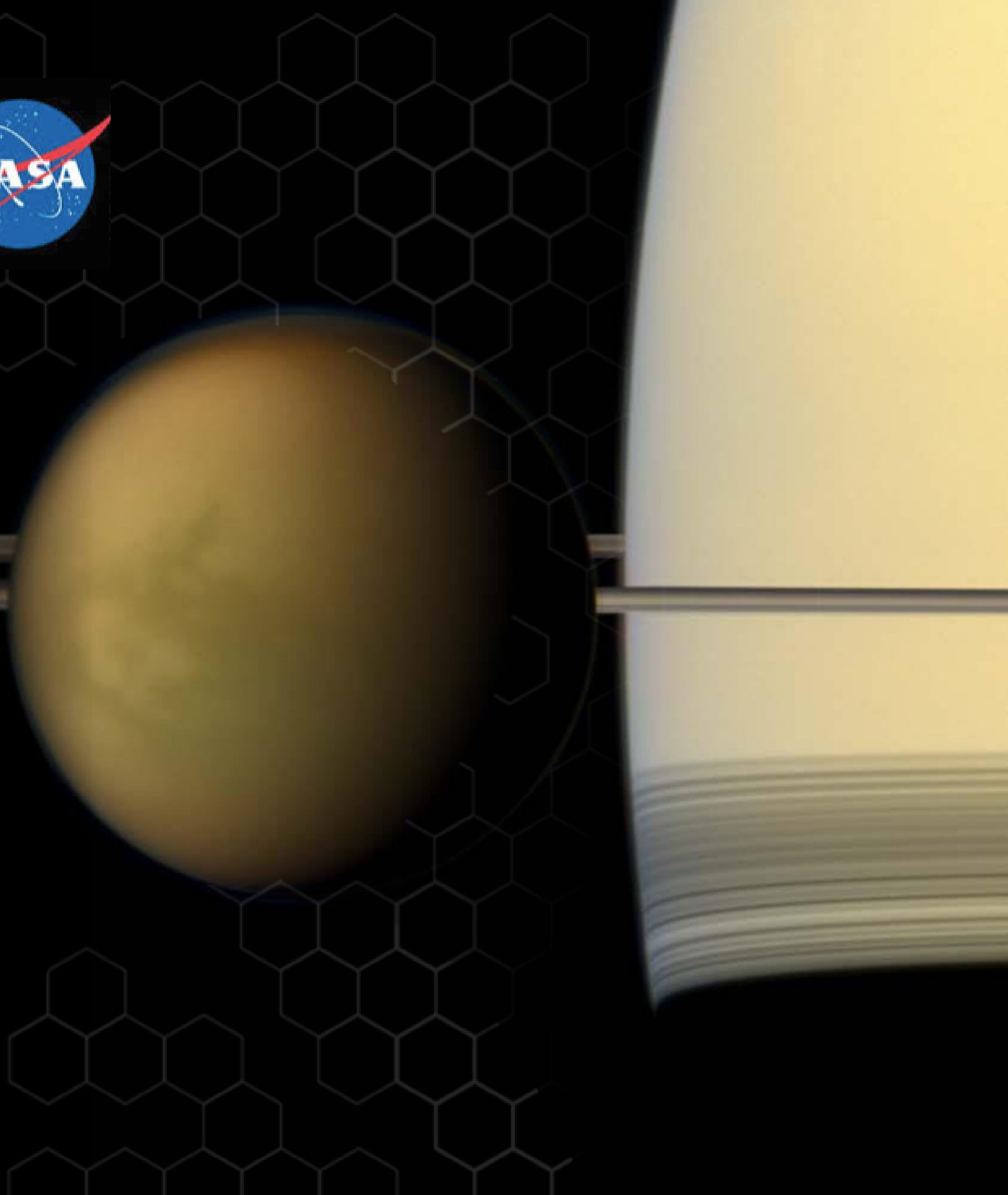
DRAGONFLY

A relocatable lander to explore Titan's prebiotic chemistry and habitability

JOHNS HOPKINS APPLIED PHYSICS LABORATORY

NASA



Aerodynamic Stability of the Dragonfly Aeroshell in the Transonic Dynamics Tunnel (Invited)

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Dragonfly Entry and Flight Dynamics
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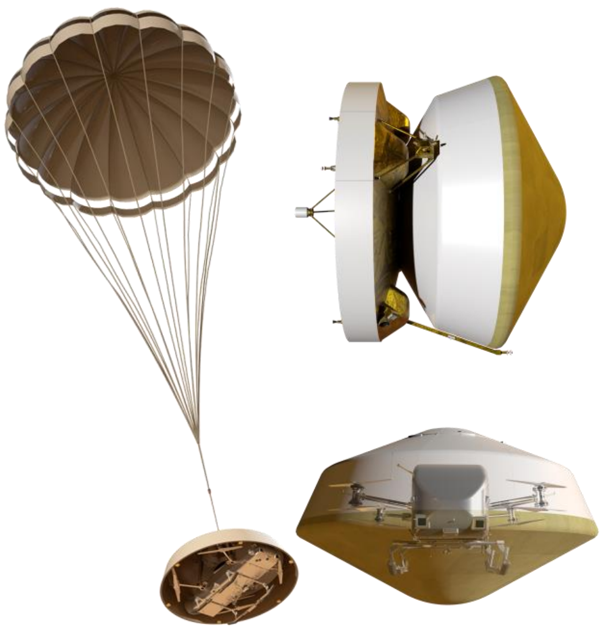
Dragonfly Mission Overview

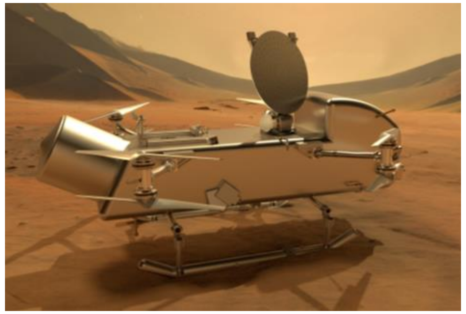
CRUISE AND DIRECT ENTRY SYSTEMS

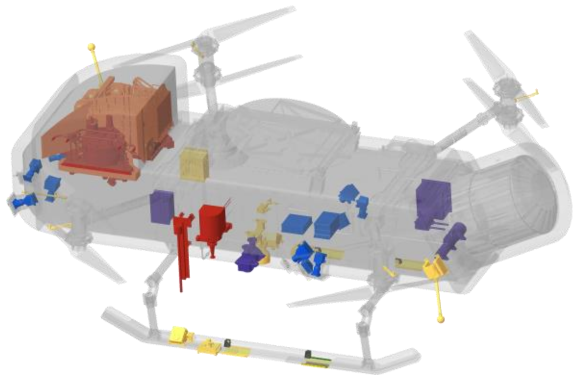


Mission Elapse Time ~ 13 yrs:
10 enroute, 3 surface

Heavier-than-air mobility highly efficient at Titan

- Atmospheric density 4x higher than Earth's reduces wing/rotor area required for lift
- Gravity 1/7th of Earth's reduces power required





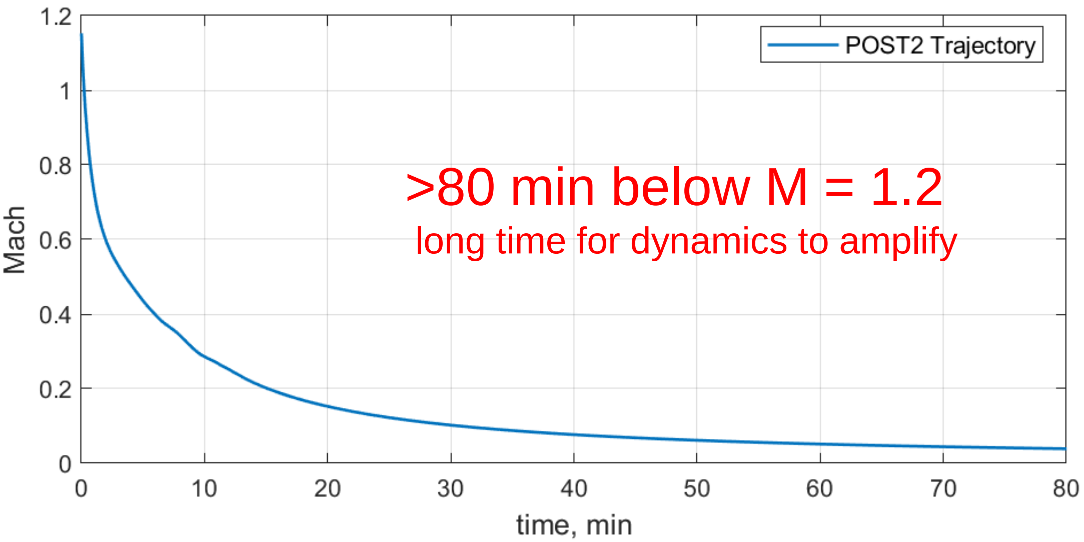
LANDER INSTRUMENTS

- DraGMet: Geophysics & Meteorology Package (APL, JAXA)
- DraMS: Mass Spectrometer (GSFC, CNES)
- DrACO: Drill for Acquisition of Complex Organics (Honeybee Robotics)
- DragonCam: Camera Suite (MSSS)
- DraGNS: Gamma-ray Neutron Spectrometer (APL, LLNL, GSFC, Schlumberger)

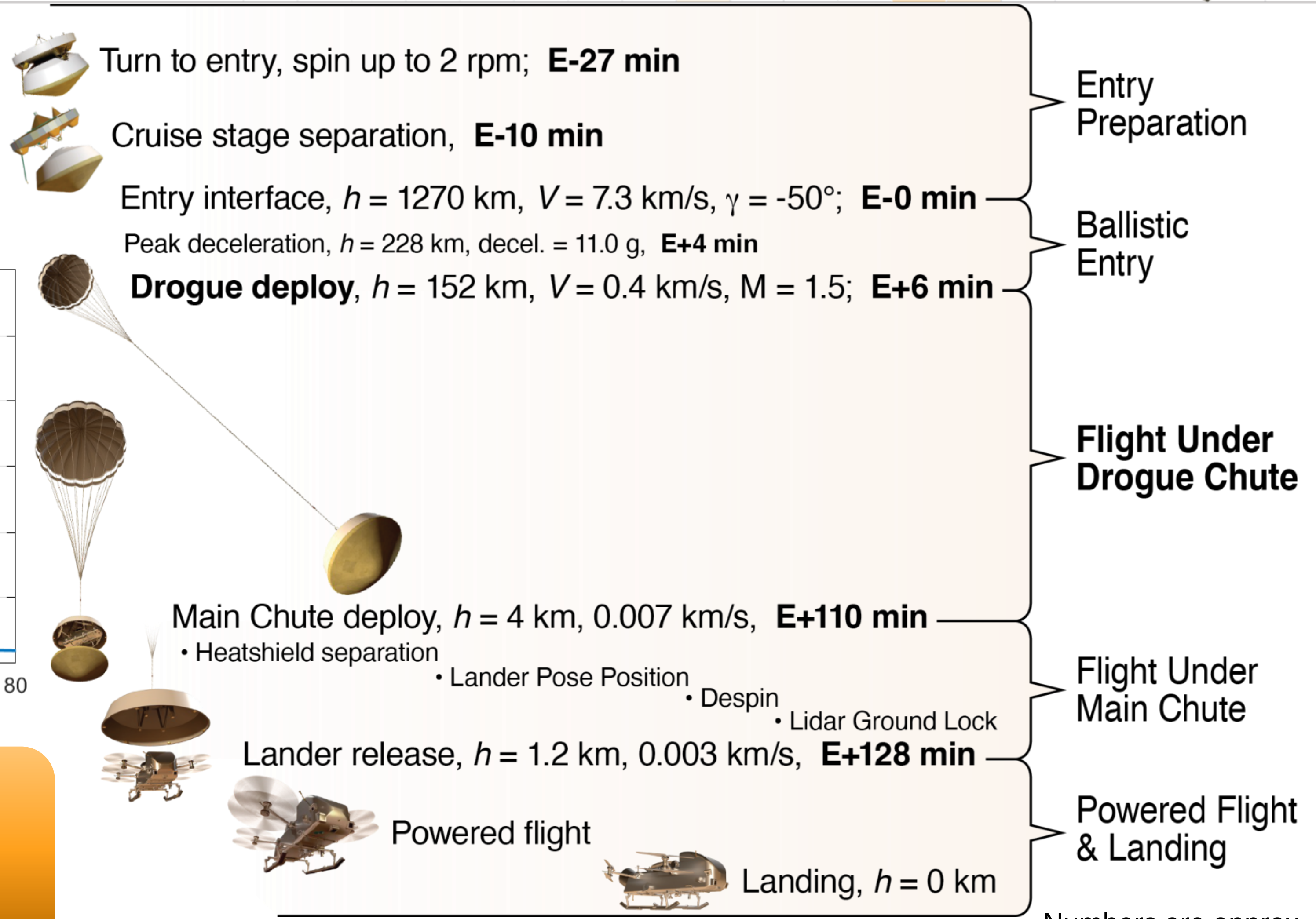
The Dragonfly mission will deliver a rotorcraft Saturn's largest moon, Titan, to enable exploration and search for building blocks of life.

Entry, Descent, & Landing (EDL) CONOPS

- Titan EDL time ~ 2 hours
  - Earth EDL (lifting) ~ 12 min
  - Mars EDL ~ 7 min



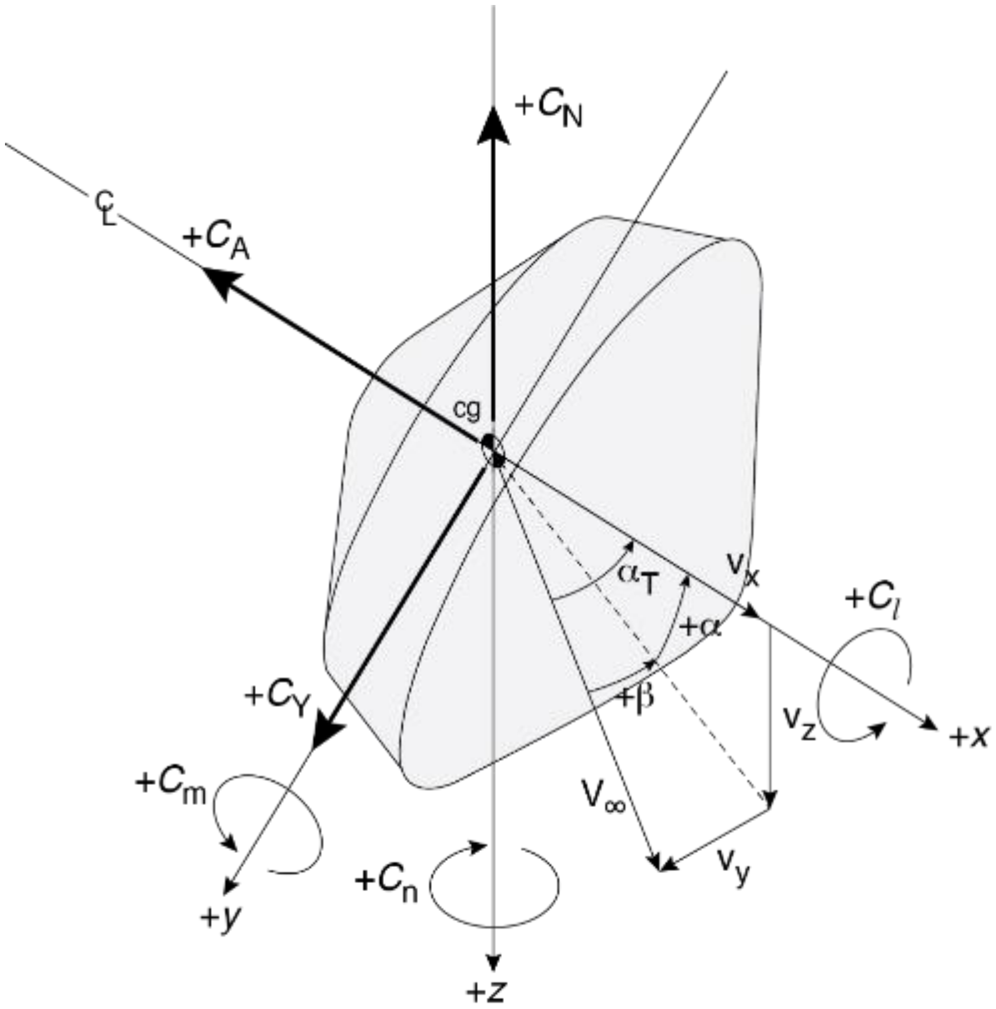
Characterizing the aeroshell aerodynamics is critical to ensure a successful EDL



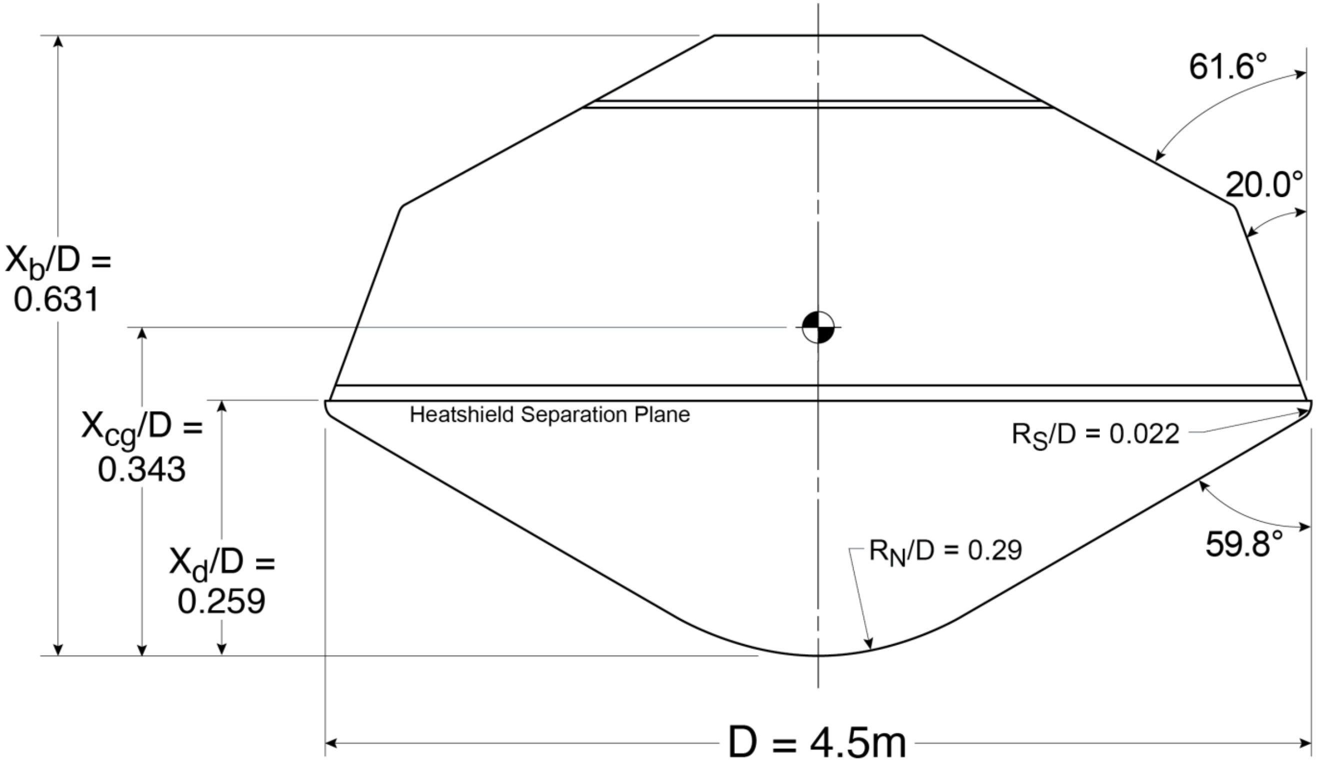
Numbers are approx.

Objective: Conduct aeroshell aerodynamic stability test in the NASA LaRC Transonic Dynamics Tunnel (TDT) to provide requisite data for flight mechanics simulation studies

Dragonfly Aeroshell Physicals for Aero Stability Characterization



Aerodynamic Coordinate System



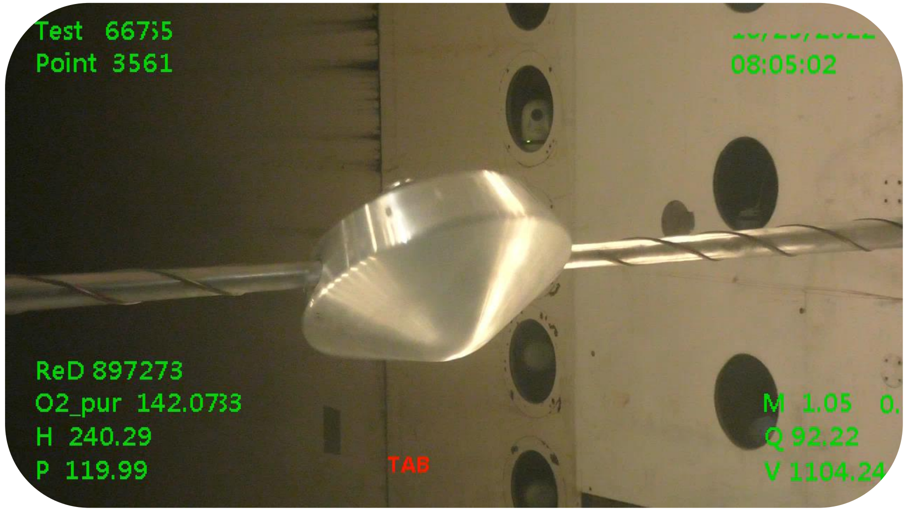
<u>Nominal Mass Properties</u>

- Mass: 2500 kg
- Mass moment of inertia: 3589 kg-m^2

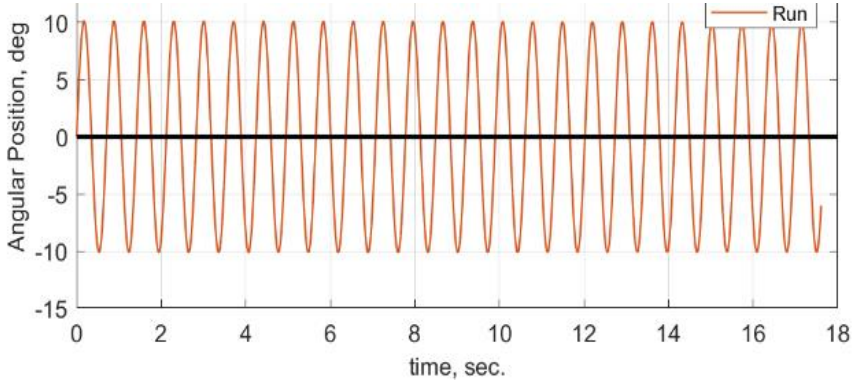
Transonic Dynamics Tunnel Test Description

- **Tunnel Characteristics**
  - Large test section: 16- X 16-ft
  - Sub-atmospheric pressure tunnel
  - Test mediums: Air and R134A
- **Test Techniques**
  - Static Force & Moment
  - Dynamic Test Techniques (1-DOF):
    - Sinusoidal Oscillation
    - Constant Rate
    - Multi-Sine Orthogonal
- **Data Acquisition**
  - 6-component strain gauge balance
  - Angular position
  - Tunnel flow conditions
  - Steady Surface Pressures
- **Test Parameters**
  - Mach numbers: 0.1 to 1.1
  - α-range: -90 to +90 deg.
  - Non-dimensional angular rate, $\hat{q}$
  - Reduced frequency, *k*
  - Reynolds Number, *Re*
- **Test Dates**
  - June 17-24, July 11, Oct. 24-31, 2022; Feb. 14-15, 2023

Dynamic Test Tech: Sinusoidal Oscillation



Sinusoidal Oscillation Position Signal

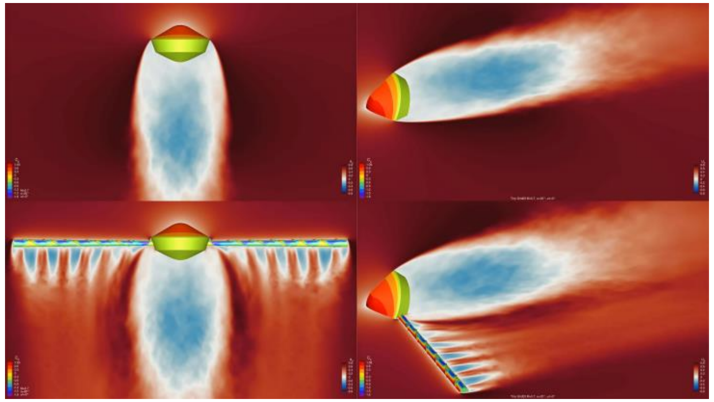


Aero data satisfy *all* similitude requirements for *Mach* $\geq$ 0.2

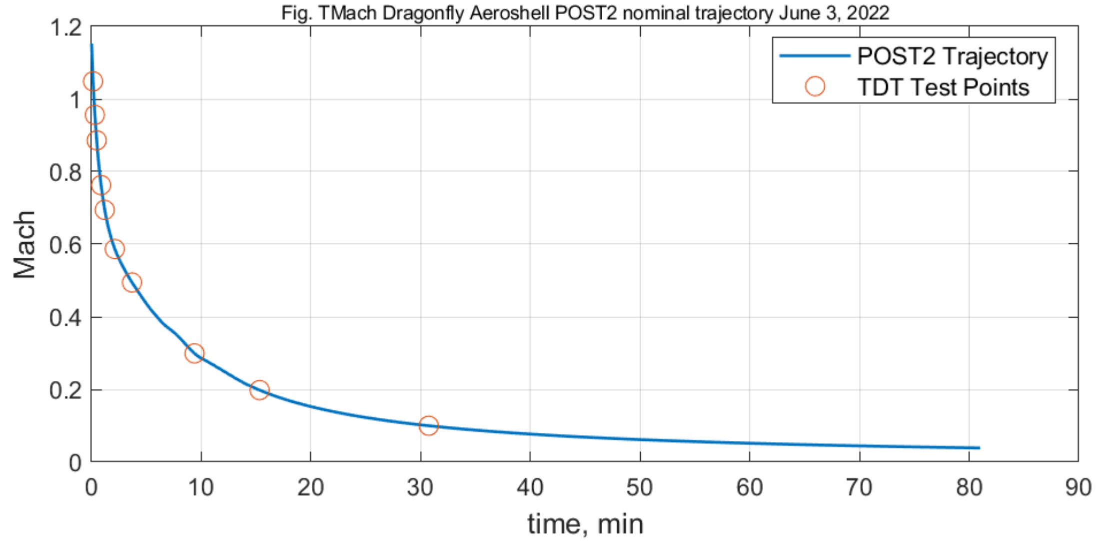
Sting Effects

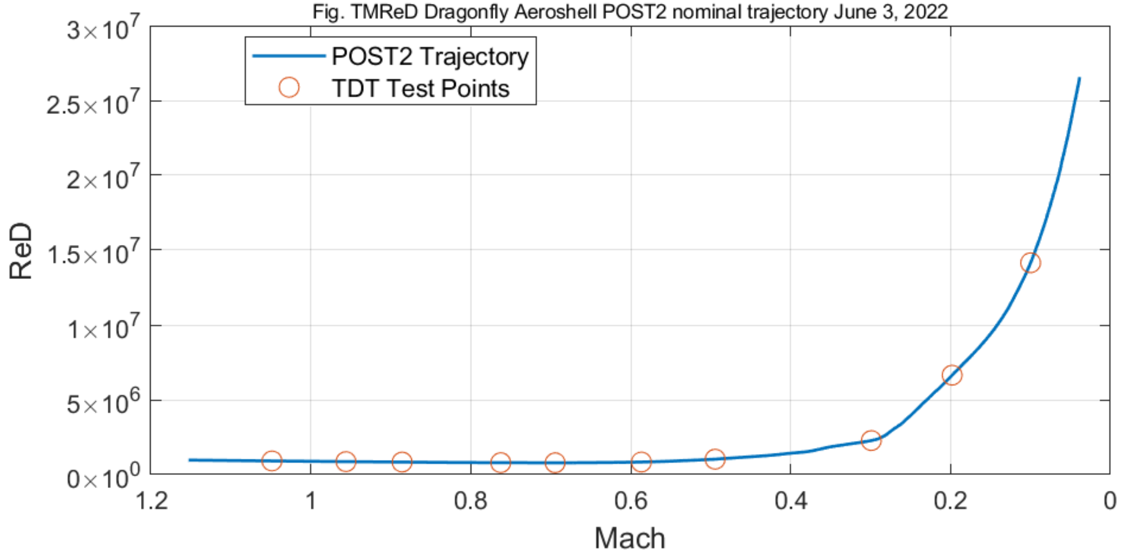
- Model Scale: 12.42%
- Sting-to-Model Diam. Ratio: 9%

NASA Engineering and Safety Center (NESC)
CFD Dragonfly Dynamic Stability Assessment
TI-21-01709



Parameter Space and Similitude Requisites

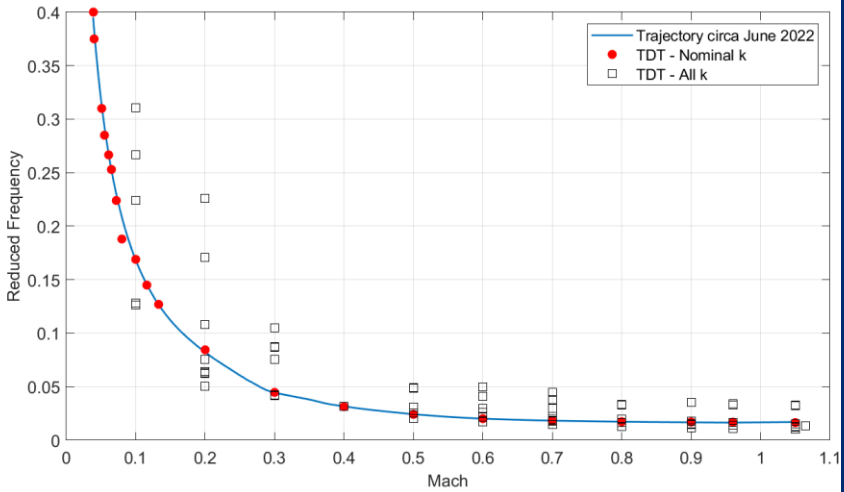




Similitude Requisites for Oscillatory Dynamic Aero

Reduced Frequency

$$k = \frac{\omega L_{ref}}{2V_\infty}$$



Non-dimensional Angular Pitch Rate

$$\hat{q} = \frac{q L_{ref}}{2V_\infty}$$

Sinusoidal Forced Oscillation Motion with Amplitude, A, and oscillation frequency ω

$$\alpha = \theta = A \sin \omega t$$

$$\dot{\alpha} = q = A\omega \cos \omega t$$

$$\hat{q} = 2kA \cos \omega t$$

Aerodynamic Modeling For POST2 6-DOF MC Simulation

- POST2 models the Dragonfly Aeroshell trajectory using Newton's second law for translational and rotational equations of motion
  - Aerodynamics modeled as instantaneous with first order Taylor series expansion
- Static aero dispersions impact trajectory performance (drag), nonzero trim, and dynamics due to static stability
- Dynamic aero coefficients modeled as a derivative, C_{m_q}, C_{n_r} and C_{l_p}
  - Contribute to vehicle dynamics as a time integral response to perturbations from trim. Sources of perturbations:
    - winds, parachute release & deployment, mass properties, etc.
  - Uniform Uncertainties
    - most positive value of will *always* provide the maximum contribution to vehicle dynamics (this is not true for static aero coeff. and some other models)
- Large parameter space to prevent early termination of POST2 MC simulation runs
- Physically realizable uncertainties

Equations of Motion

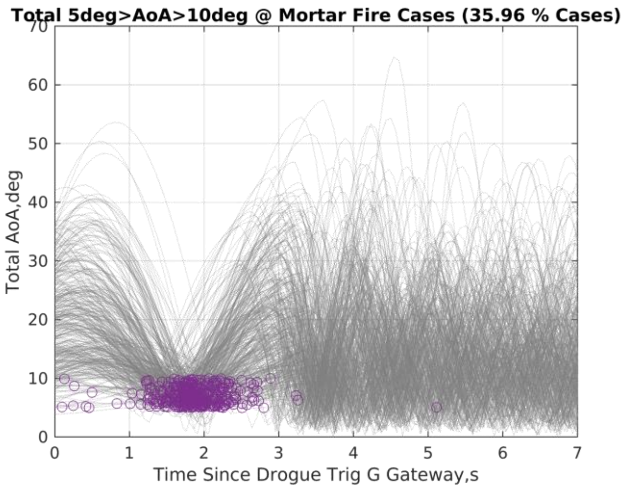
$$\begin{bmatrix} m\dot{u} \\ m\dot{v} \\ m\dot{w} \end{bmatrix} = \begin{bmatrix} m(rv - qw) + \bar{q}SC_X - mg\sin\theta \\ m(pw - ru) + \bar{q}SC_Y + mg\cos\theta\sin\phi \\ m(qu - pv) + \bar{q}SC_Z + mg\cos\theta\cos\phi \end{bmatrix}$$

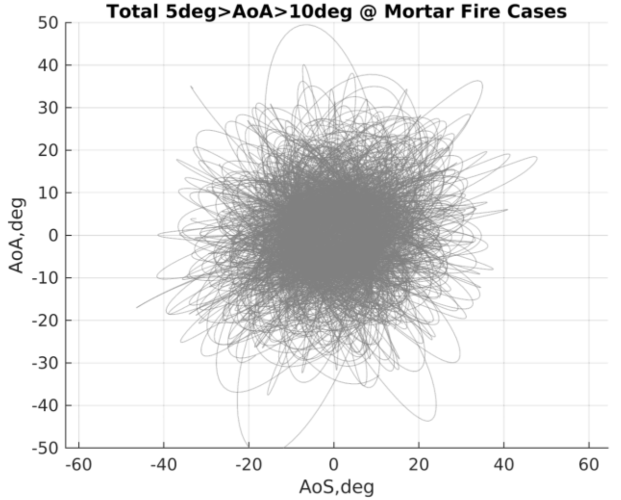
$$\begin{bmatrix} \dot{p}I_x - \dot{r}I_{xz} \\ \dot{q}I_y \\ \dot{r}I_z - \dot{p}I_{xz} \end{bmatrix} = \begin{bmatrix} \bar{q}SbC_l - qr(I_z - I_y) + qpI_{xz} \\ \bar{q}S\bar{c}C_m - pr(I_x - I_z) - (p^2 - r^2)I_{xz} \\ \bar{q}SbC_n - pq(I_y - I_x) - qrI_{xz} \end{bmatrix}$$

Linear Taylor Series Expansion

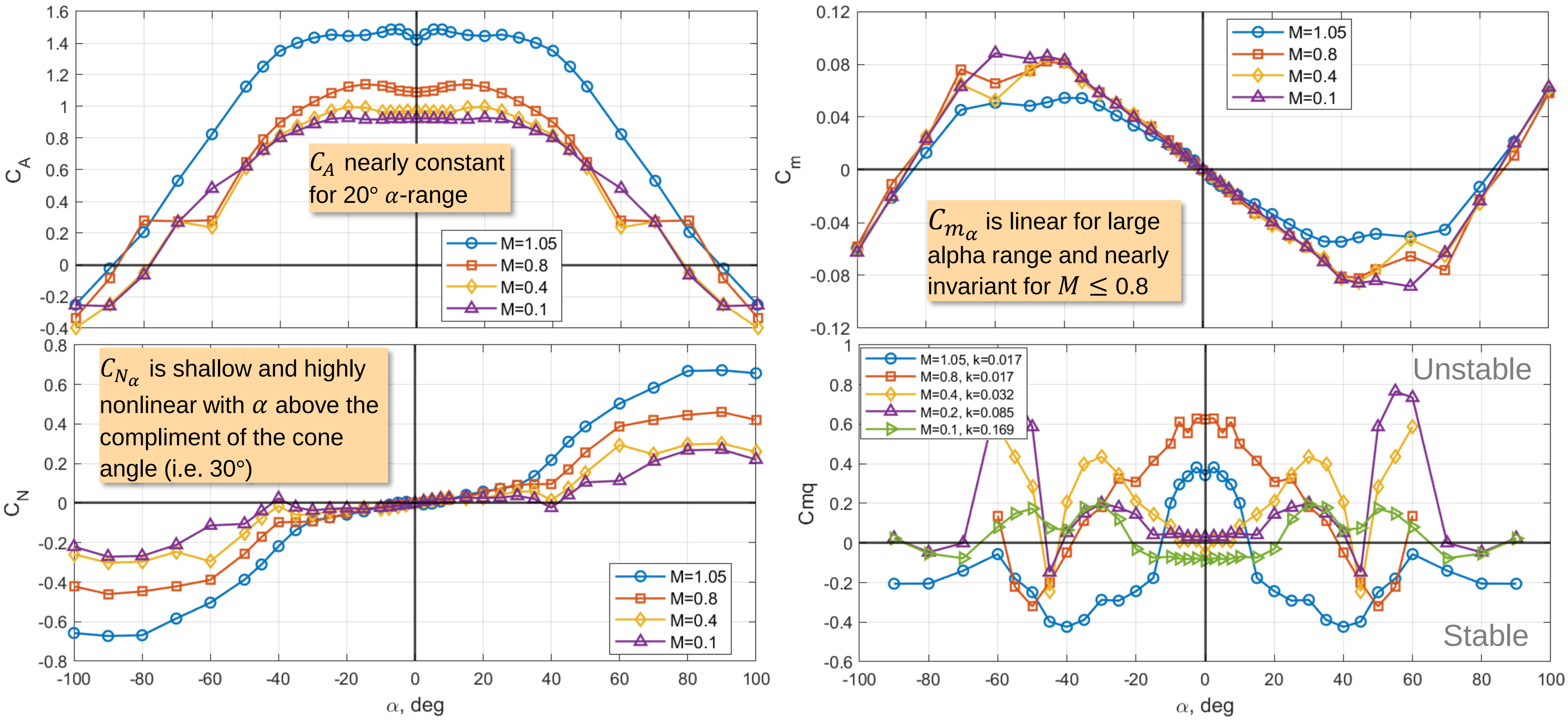
$$C_m = C_{m_0} + C_{m_\alpha}\alpha + C_{m_q}\hat{q}$$

$$C_{m_q} \equiv \frac{\partial C_m}{\partial\left(\frac{qL_{ref}}{2V_\infty}\right)} + \frac{\partial C_m}{\partial\left(\frac{\dot{\alpha}L_{ref}}{2V_\infty}\right)}$$



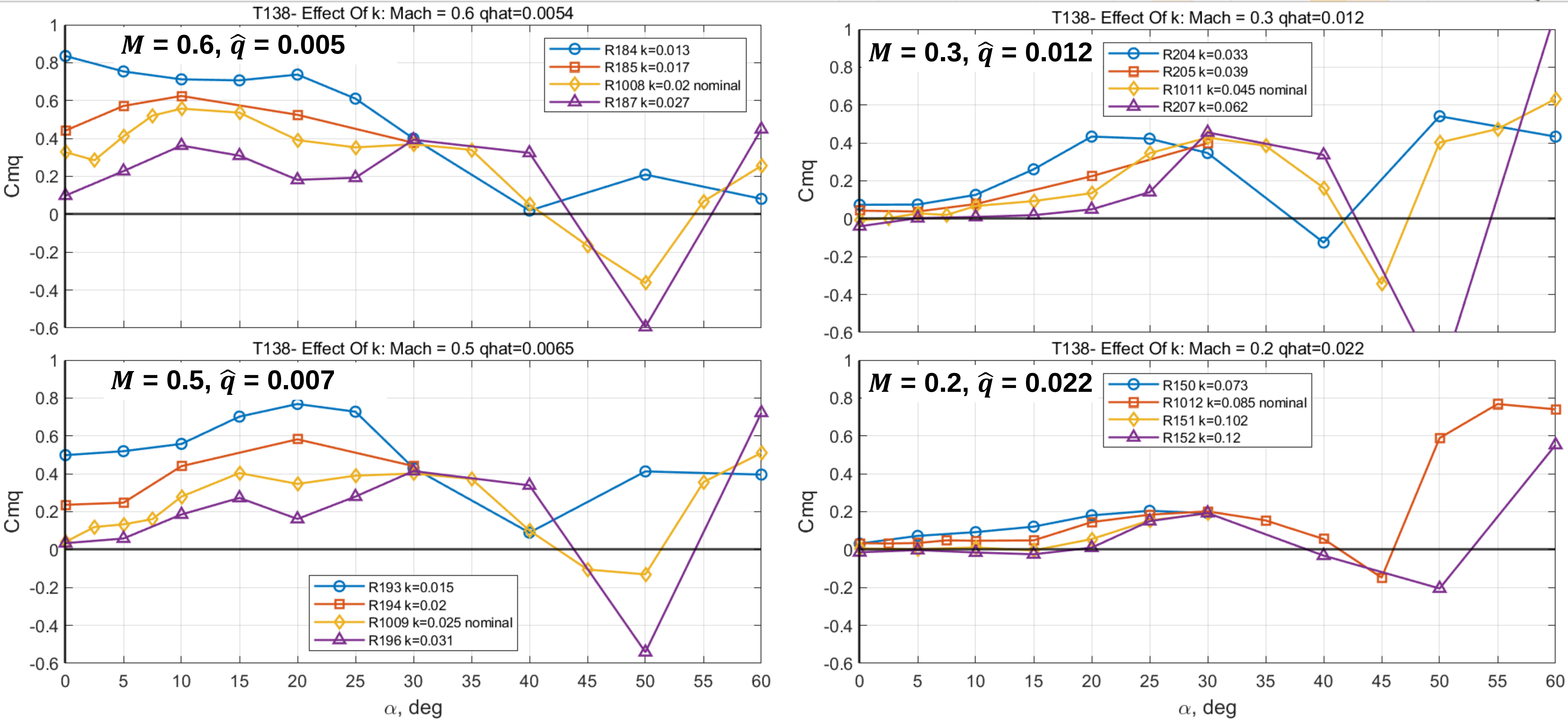


Effect of Mach on Static and Dynamic Aero Coefficients



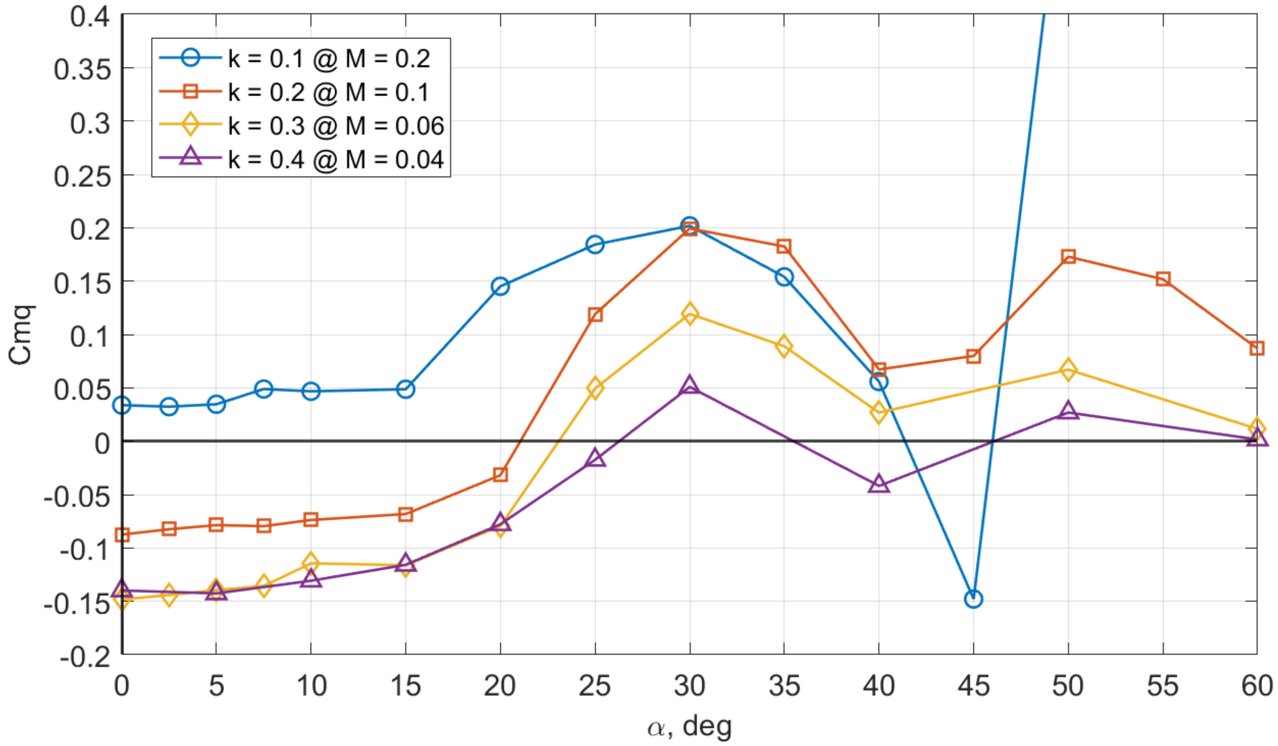
C_{m_q} unstable for $M \geq 0.2$, near trim

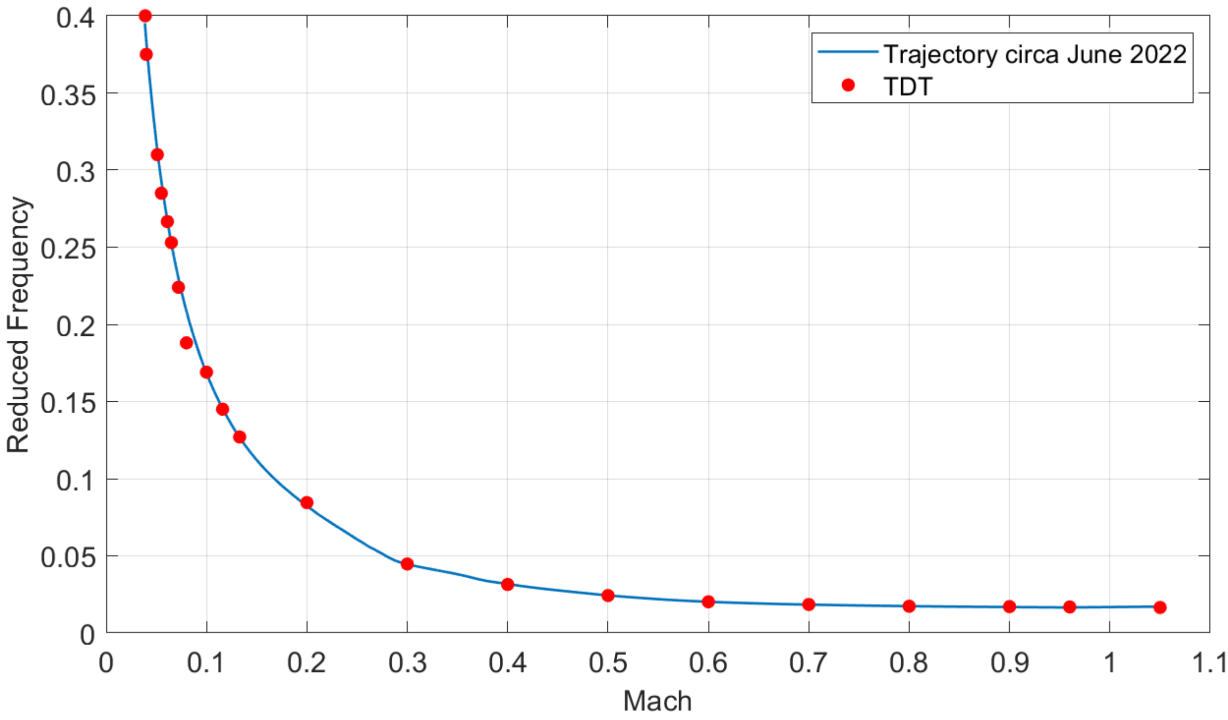
Effect of Reduced Frequency for Subsonic Mach Numbers



- Nonlinear with M, α, and k
- No effect of k at $\alpha = 30°$

Effect of Reduced Freq. for Incompressible Mach Numbers





- Drogue release at $M = 0.04$
- Significant incremental effect
- Nonlinear with k
- For $k > 0.3$ and $\alpha < 20°$, effect is saturated
- ADB accounts for k using Mach number

Summary & Conclusions

Summary

- Dynamic stability is one of the major concerns for meeting Dragonfly EDL requirements exacerbated by a long flight time, >2 hours.
- Monte Carlo simulation assessments require static and *dynamic* test techniques:
  - cover a large parameter space
  - physically realizable uncertainties
- Extensive aerodynamic data for M < 1.1
  - M = 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 0.97, 1.05
  - α-range: -90° to +90°
  - Reduced frequencies for flight under drogue
  - Satisfies all similitude requirements for M < 1.1
    - exception: Reynolds number is only matched for $M \geq 0.2$
  - Uncertainties cover all Mach and α
    - repeatability
    - reproducibility

Conclusions

- **Effect of Mach and α**
  - C_N and C_m are linear over large α-range
  - C_{m_q} highly nonlinear
    - $M \geq$ 0.2: Unstable
    - $M <$ 0.2: Stable
- **Effect of Reduced Frequency on C_{m_q}**
  - For $M < 0.8$, nonlinear with α except α = 30° where there is no effect.
    - compliment of cone angle = 30°
  - Significant incremental effect for M < 0.2
    - ADB accounts for k effect with Mach number breakpoints

QUESTIONS

DRAGONFLY

http://dragonfly.jhuapl.edu