Preliminary Characterizations of Altair Lunar Lander Slosh Dynamics and Some Implications for TVC Design

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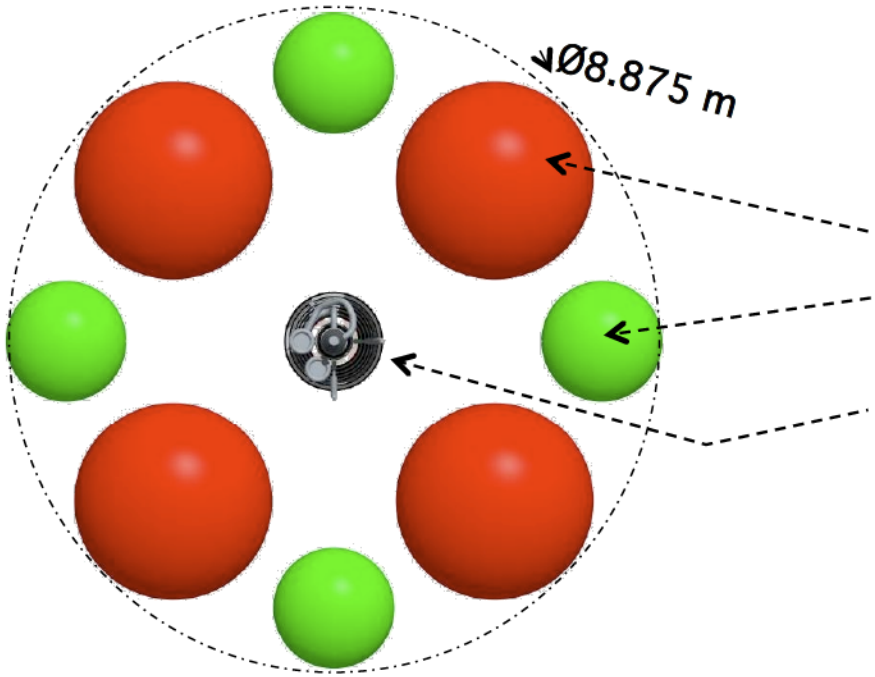
Impacts of Fuel Slosh on Thrusting Maneuvers

- Lessons learned from past missions:
  - A fuel slosh instability in the booster contributed to the failure of the first U.S. attempt to place a satellite (Vanguard-1, Navy) into orbit in 1958
    - See A. Bryson, Control of Spacecraft and Aircraft, Princeton University Press, Princeton, 1994
  - Loss of the ATS-V spacecraft in 1969
  - Loss of Intelsat IV in 1977
  - NEAR (Near Earth Asteroid Rendezvous, launched on 2/17/96):
    - During a critical orbital correction maneuver on 12/20/98, the spacecraft experienced unexpected motion one second after ignition and was “safed” by Fault Protection
  - Apollo-11 experienced TVC/Slosh interactions during powered descent and the entire duration of the trans-Earth injection burn
  - Others

Topics to Cover

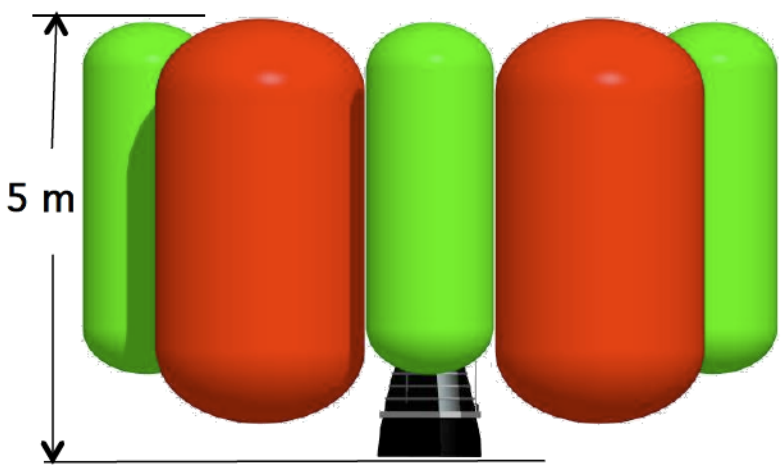
- Modeling fuel slosh during spacecraft thrusting maneuvers
- Placement of fuel tanks to guarantee stable interactions between fuel slosh mode and the S/C rigid-body mode
- Estimation of slosh frequencies (as a function of mission phases):
  - Estimation of slosh mode damping
- Some implications for Thrust Vector Control design:
  - Selection of TVC controller bandwidth
  - Adequacy of the excursion range of engine gimbal actuator
- TVC system design: Complex Interactions between GN&C, Propulsion, Structure, and Other Subsystems

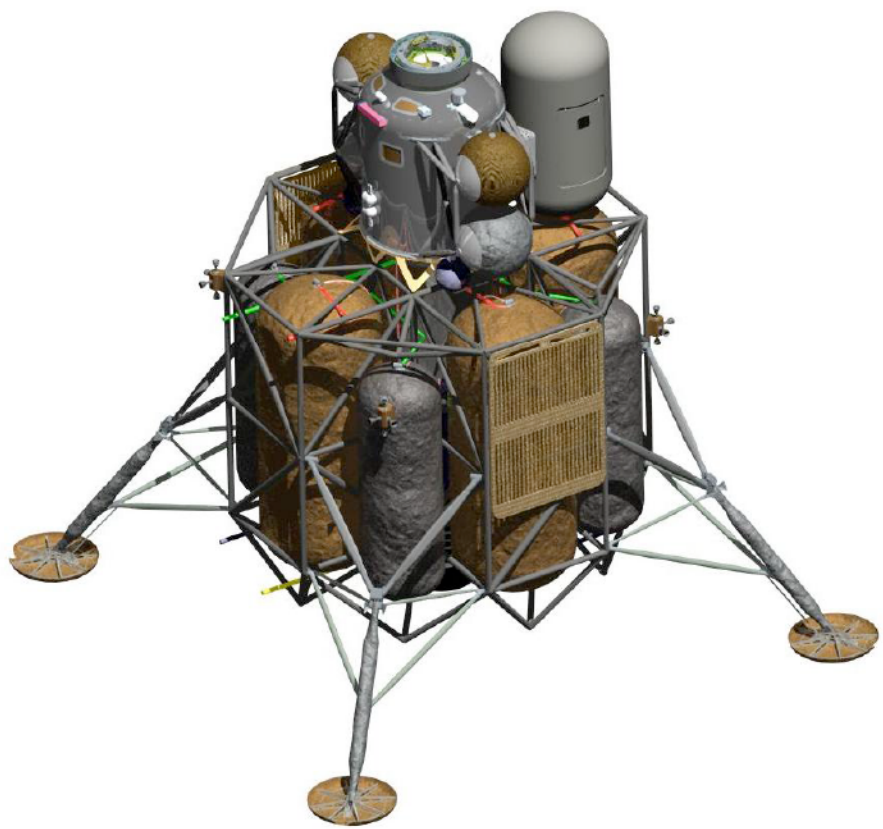
Altair Descent Module Tank Baseline



LOX tanks are in red
LH2 tanks are in green

Descent module engine



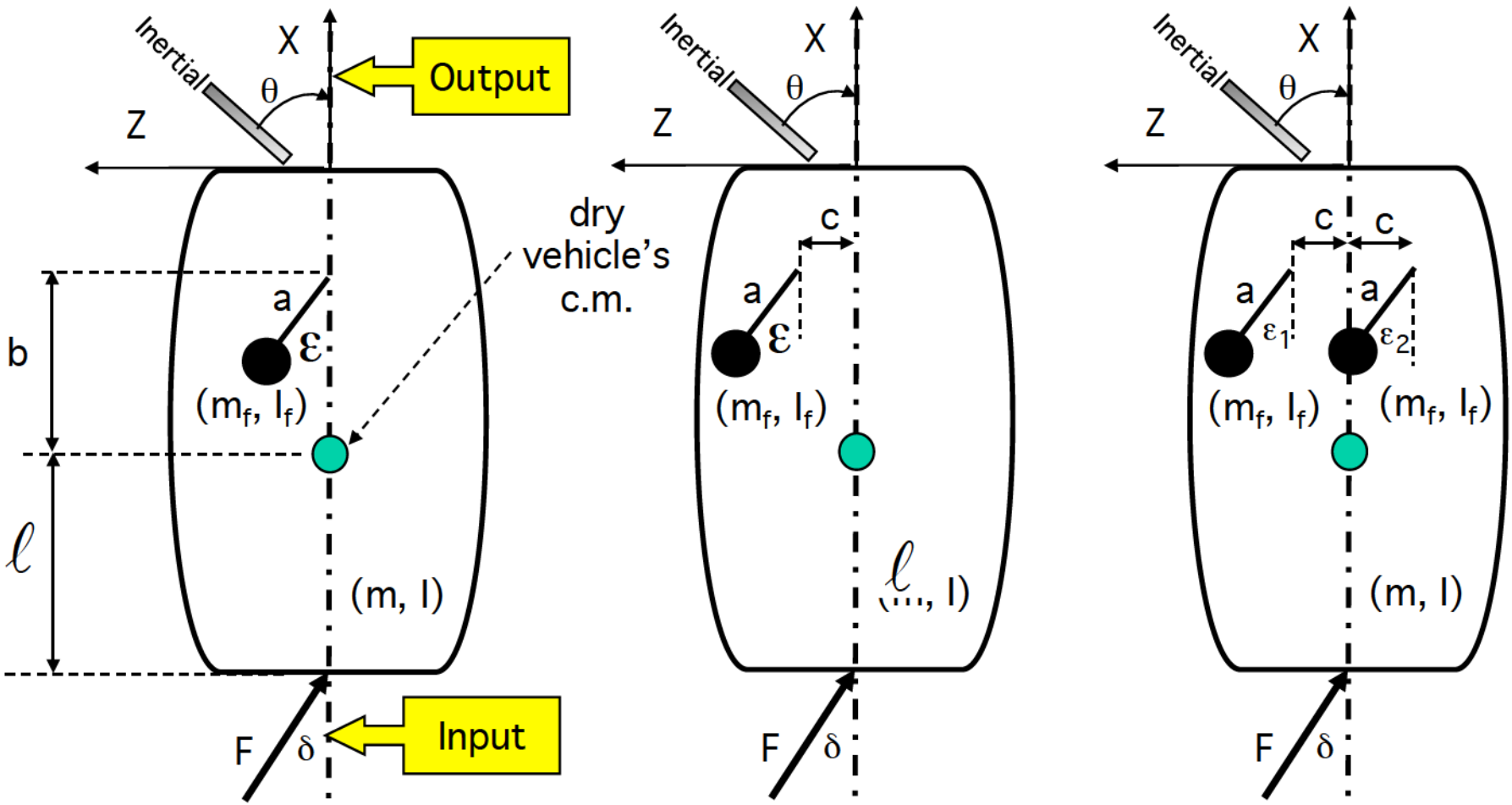


Modeling Fuel Slosh: Simplification Assumptions

- To fix ideas, and for simplicity, the motion of the S/C, with sloshing fuel lumps, about a <u>single</u> axis is considered
- Altair has many fuel tanks. But our simplified analyses have only one or two tanks
- The gross effect of lateral fuel slosh is commonly represented by a mechanical equivalent <u>pendulum</u> model:
  - This approach was used in the TVC autopilot designs of numerous JPL spacecraft: Voyagers (1966), Mariner-9 (1969), Vikings (1970), Cassini (1993), and others
- Dynamics associated with the structures (e.g., bending), sensors (e.g., gyroscope), engine (e.g., “tail wags dog”), gimbal actuators, and others are neglected

Spacecraft with Fuel Slosh "Pendulum"

- Three tank configurations were studied. The simplest configuration, on the left, is addressed here



Transfer Function with Slosh Mode

$$\frac{\theta(s)}{\delta(s)} = -\frac{K}{s^2}\frac{\{1+\frac{s^2}{\Omega_Z^2}\}}{\{1+\frac{s^2}{\Omega_P^2}\}}$$

Slosh mode is represented by a Pole-Zero pair: $[\Omega_P, \Omega_Z]$

Where:

Control effectiveness parameter = Gain factor =

$$K\ (\sec^{-2}) = \frac{F(\ell + \frac{m_f}{M}b)}{I + \frac{mm_f}{M}(b^2 - ab)} = \frac{F\ell}{I} \quad \text{(if } m_f \text{ is very small)}$$

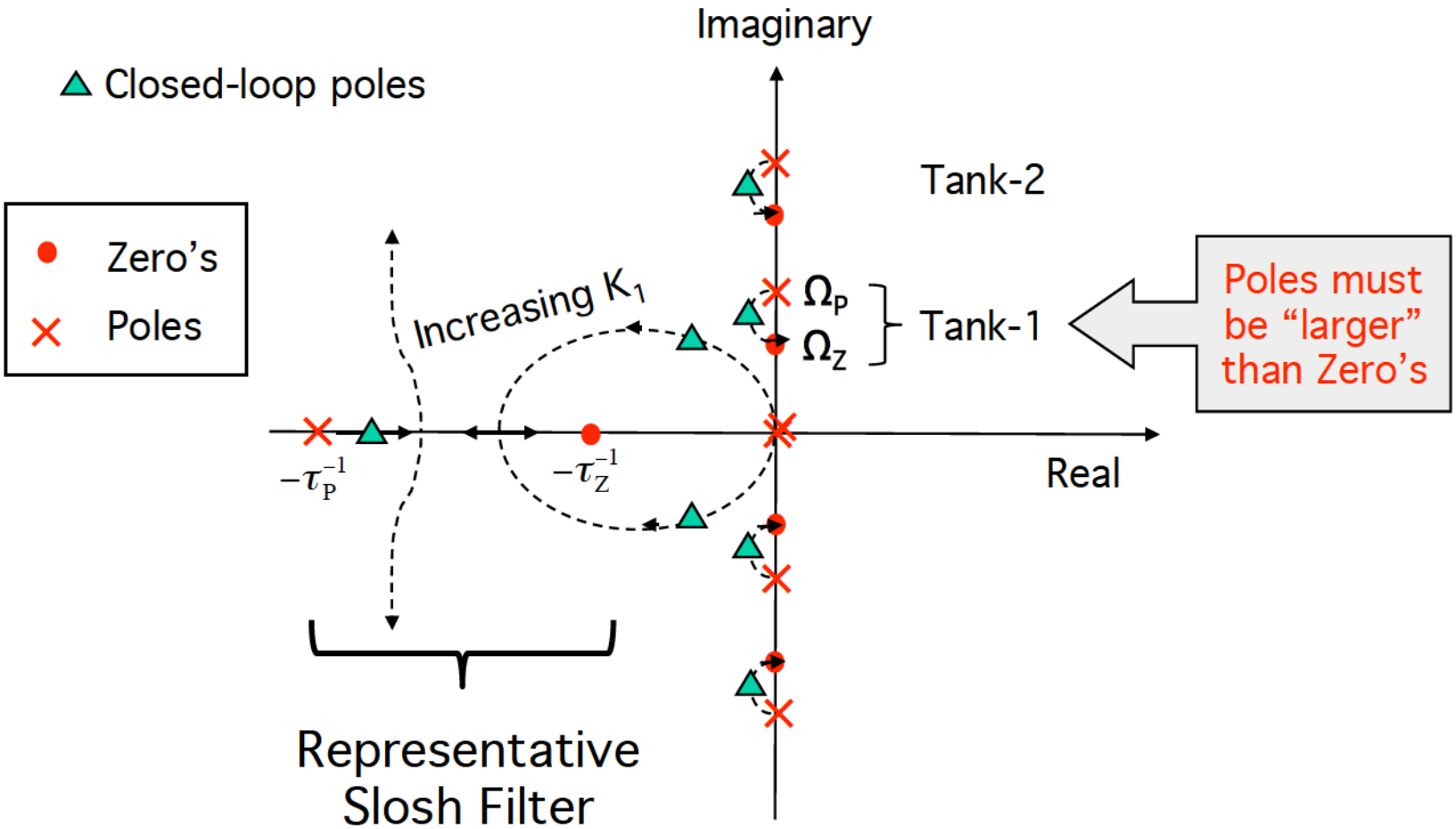
$$\Omega_Z^2\ (\sec^{-2}) = \frac{aF(\ell + \frac{m_f}{M}b)\frac{m_f}{M}}{(\ell + \frac{m_f}{M}b)I_f + \frac{\ell a^2 m m_f}{M}}$$

$$\Omega_P^2\ (\sec^{-2}) = \frac{aF\frac{m_f}{M}\{I + \frac{mm_f}{M}(b^2 - ab)\}}{II_f + \frac{mm_f}{M}(I_f b^2 + Ia^2)}$$

$$M = m + m_f$$

Stability of TVC Control Loop: *Stable* Configuration

Representative Root Locus



Stable Interaction: Pole above Zero

$$\Omega_P^2 - \Omega_Z^2 = G\frac{A}{BC},$$

where :

$$G = \frac{aFmm_f^2}{M^2} > 0$$

$$A = -ab(\ell + \frac{m_f}{M}b)I_f + \frac{a^2bmm_f}{M}\{(-a+b)\ell - k^2\}, \quad \text{where } I = mk^2$$

$$B = II_f + \frac{mm_f}{M}(a^2I + b^2I_f) > 0$$

$$C = (\ell + \frac{m_f}{M}b)I_f + \frac{\ell a^2mm_f}{M} > 0$$

- To avoid undesirable unstable TVC/ Slosh interaction, Ω_P must be larger than Ω_Z. This is the case if A>0
  - A is >0 if b<0
  - The fuel pendulum pivot must be placed below the dry S/C's c.m.

$$0 > b \quad \}$$

Placement of Altair Fuel Tanks: Is this condition met?

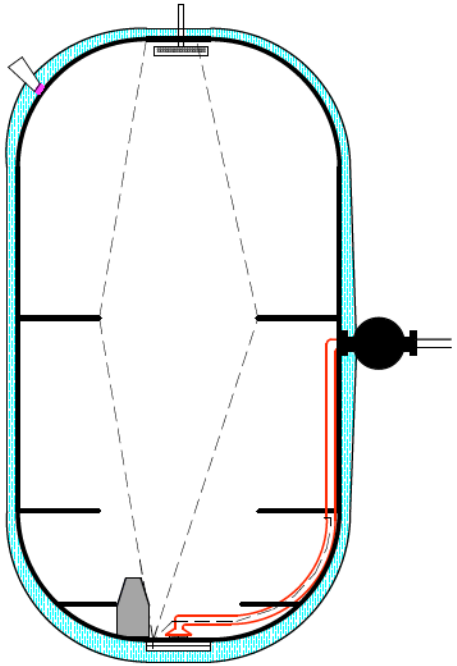
Estimation of Fuel Slosh Frequencies As Functions of Mission Phases

Slosh Estimation as a Function of Mission Phase

- Basic pendulum modeling techniques exist in literature to define slosh parameters for both spherical and cylindrical tanks
  - Literature includes 1960's era NASA and more recent Southwest Research Institute (SwRI) publications
  - Primary slosh characteristics: Slosh frequency, participating slosh mass, equivalent pendulum length, and pendulum attach point

- Like Altair, Apollo LEM tanks were cylindrical with hemispherical end caps. The robotic Saturn orbiter Cassini have tanks with identical shape
  - For Apollo LEM, a <u>hybrid approach</u> to slosh modeling was used, combining spherical and cylindrical modeling
  - Details are given in paper

- Fuel slosh characteristics are related to tank geometry, fill fraction, and longitudinal acceleration (thrust level/mass):
  - Mass and thruster change with mission events



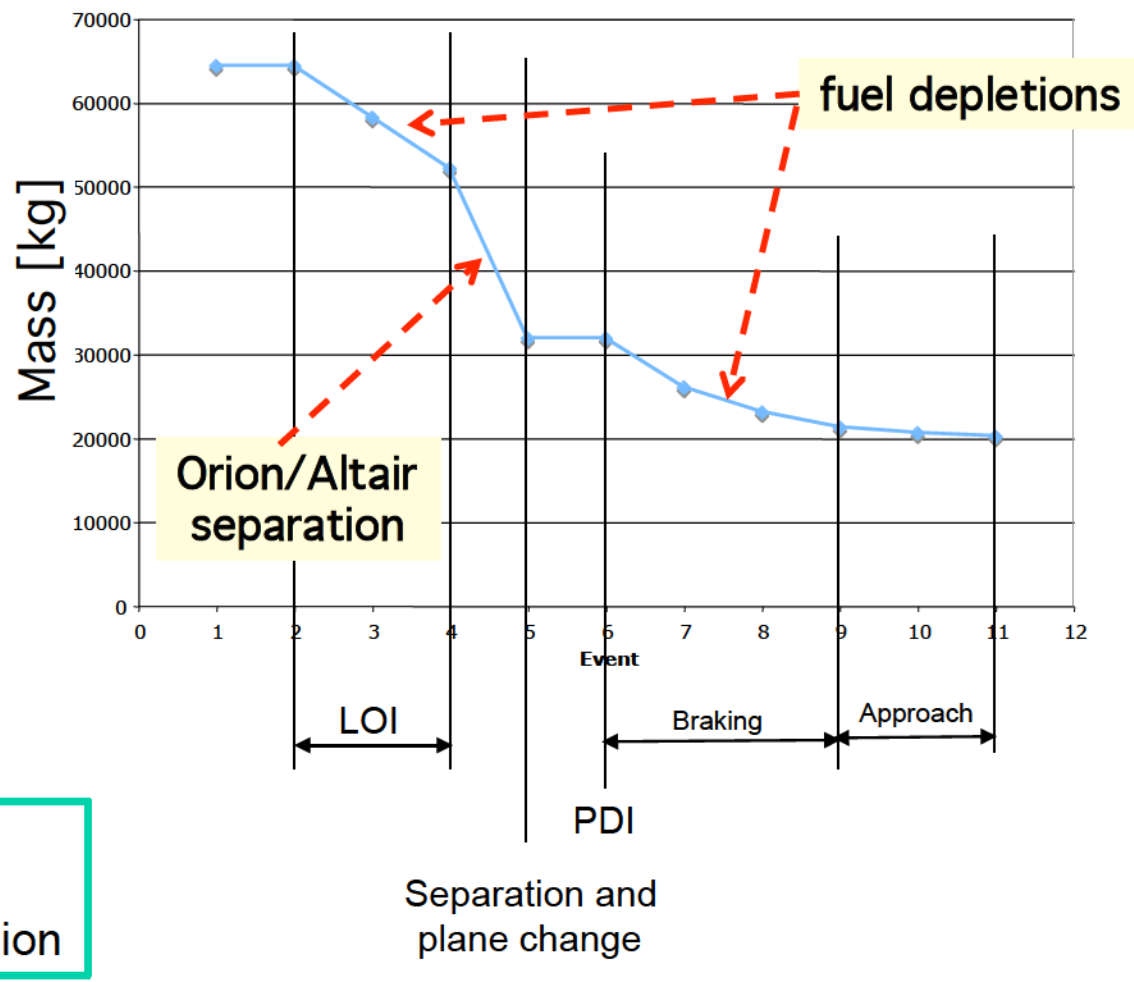
Events and Mass change

Events

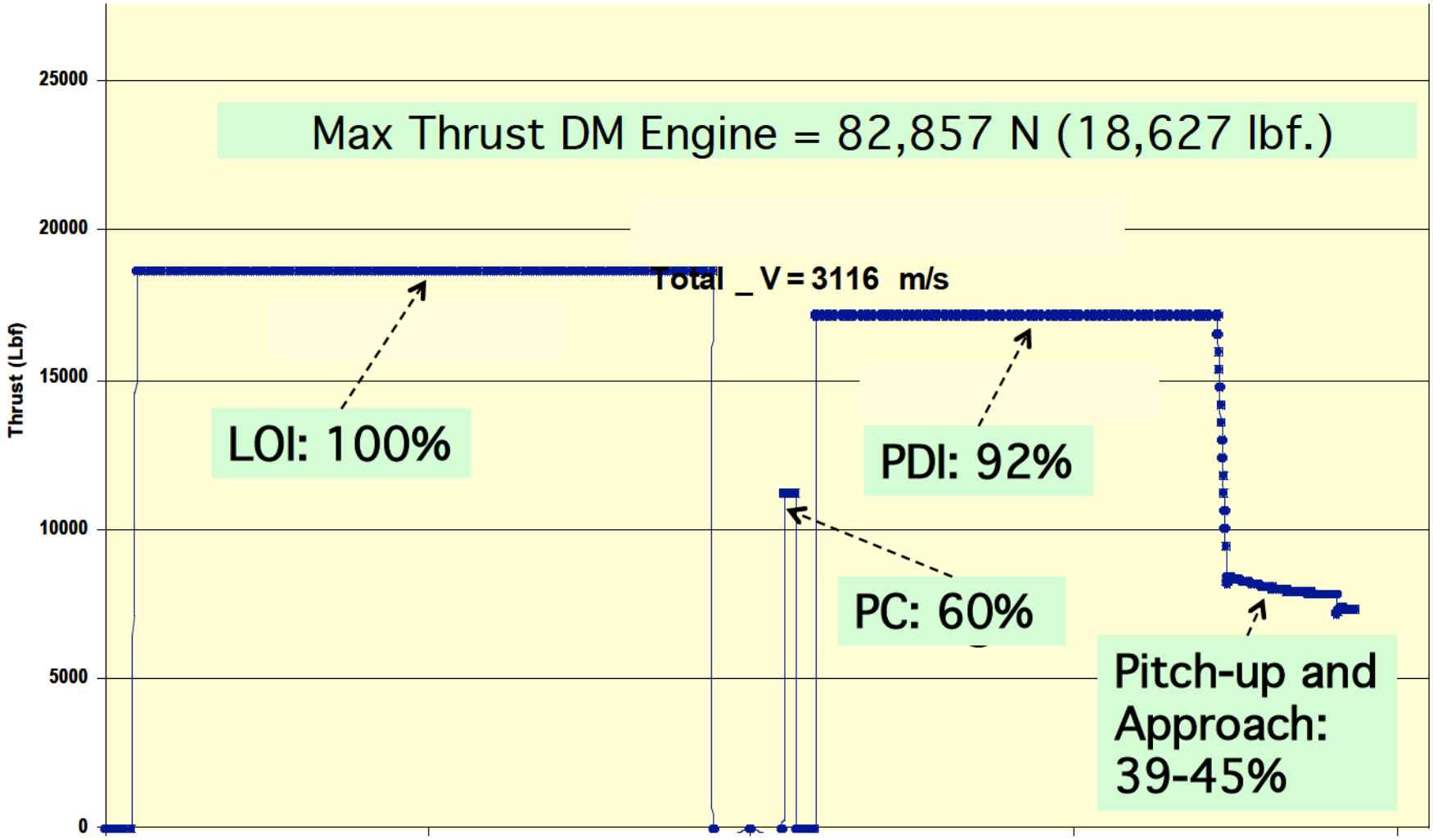
1 Post TLI
2 Start LOI
3 Mid LOI
4 LOI complete
5 Post separation (plane change)
6 Start PDI
7 Mid PDI
8 1/4 burn to go
9 Start Pitch-up and Approach
10 Final Descent
11 Touch down

TLI= Trans-Lunar Injection
LOI= Lunar Orbit Insertion
PDI= Powered Descent Initiation

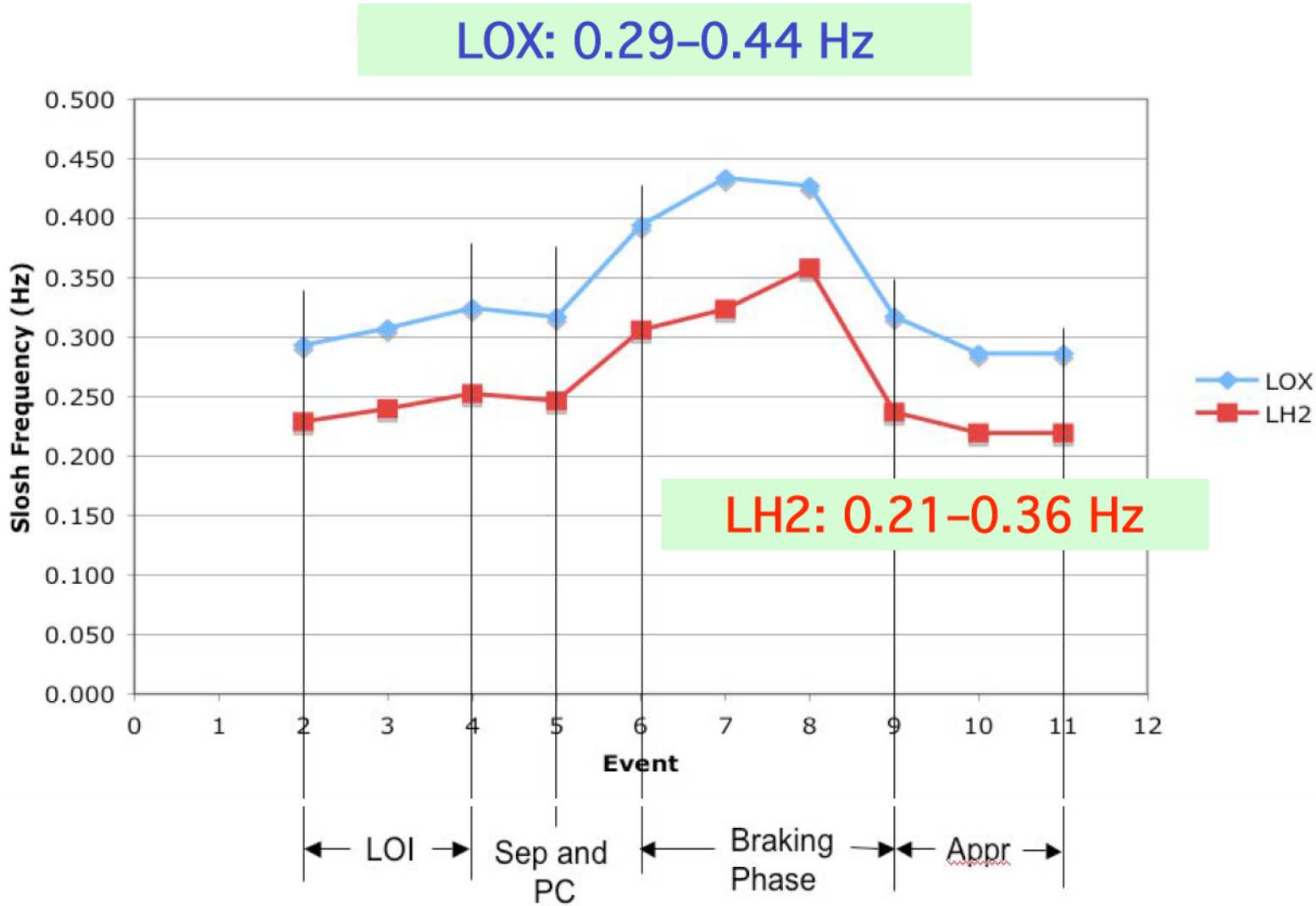
Varying Vehicle's Mass



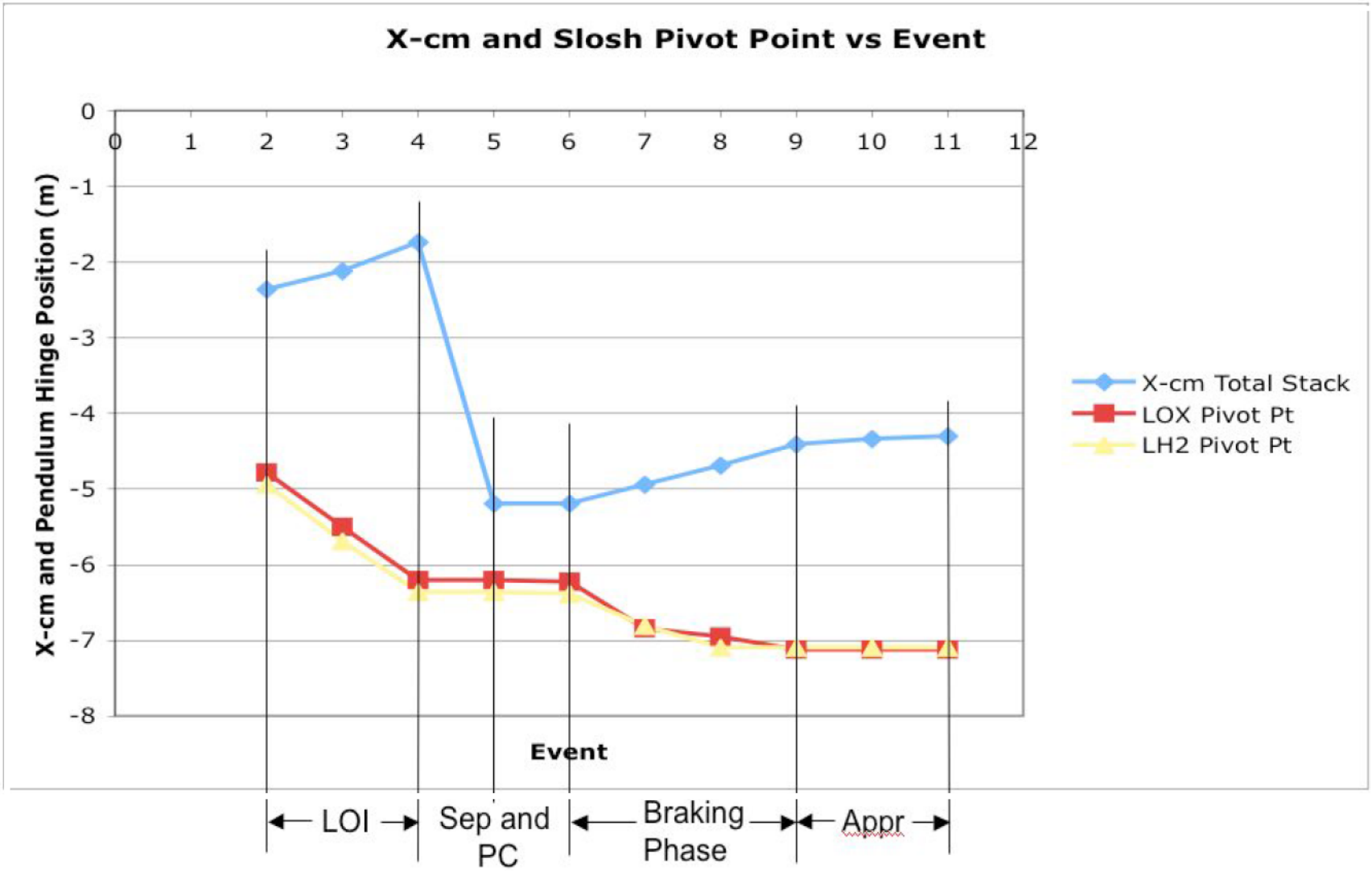
Assumed Mission Thrust Profile



Estimated Slosh Frequencies

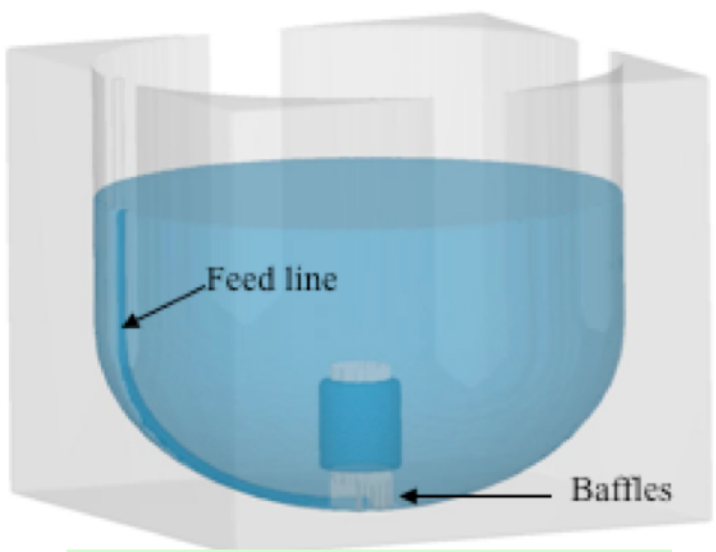


Location of Slosh Pivot Point relative to Vehicle's c.m. (Is b < 0 ?)

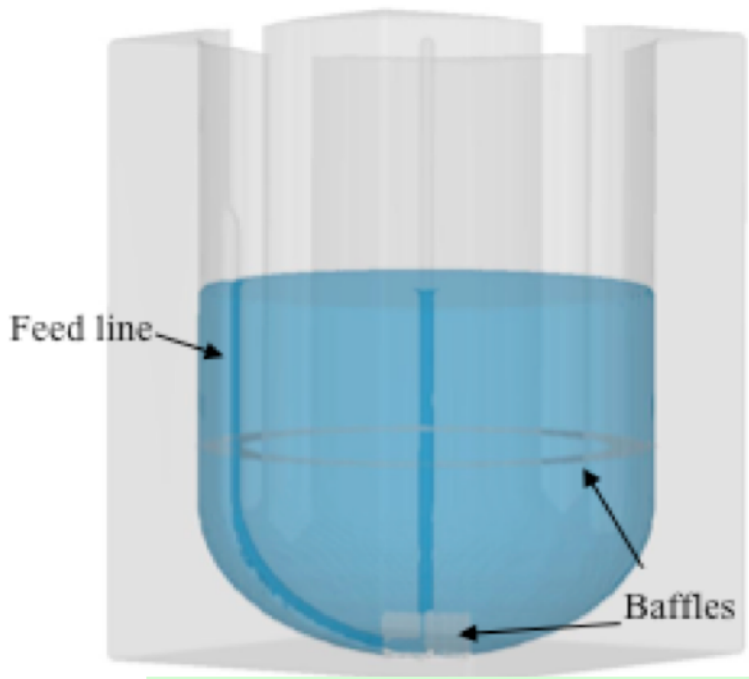


CFD-based Slosh Frequency Estimations

- Slosh frequencies were also estimated via the commercially available CFD code, Flow3D™
  - A CAD model of the internal volume of the tank was directly imported into the CFD model and a Cartesian grid was created to discretely resolve the fluid area into 2×2×2 cm elements
  - Two models were created and run for each tank, one with the internal structures and one without it
  - Results are close to those estimated analytically (see paper)



Altair LH2 tank in Flow3D™



Altair LOX tank in Flow3D™

Viscous Damping of Sloshing Liquid

- Viscous Damping is a function of tank radius L (in m), longitudinal acceleration a_X (in m/s^2), and kinematic viscosity of fuel ν (in m^2/s)
- Viscous Damping (ξ) for a "smooth" (no baffle) spherical tank is given approximately by

$$\xi = 0.79\sqrt{\frac{\nu}{\sqrt{a_X L^3}}}$$

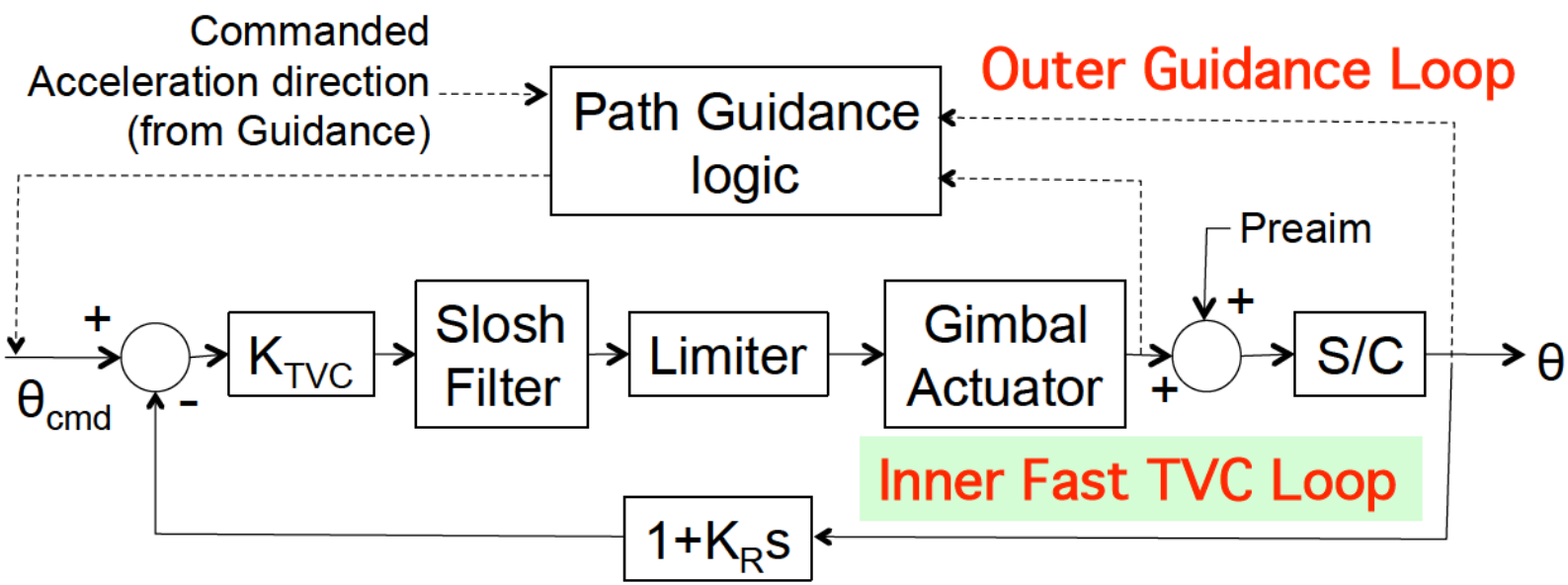
- Viscous damping for a half full spherical tank with different liquids

Liquid	Application	Damping [%]	Relative to water
Water	(reference)	0.0604	1.0
Aerozine-50	Apollo Fuel	0.0576	0.95
N_2O_4	Apollo & Shuttle Oxidizer	0.0323	0.53
LH2	Altair Fuel	0.0258	0.43
LOX	Altair Oxidizer	0.0265	0.44

- Take-away Message
  - Viscous Damping of Altair fuel and oxidizer are less than their Apollo counterparts
  - Baffles will be needed for Altair LOX tanks
    - Ring baffles are added in LOX tanks, with weight penalty

Guidance and Control Loop

- Path Guidance Logic:
  - Its function is to respond to the acceleration command that is computed onboard by the guidance algorithm
  - Its bandwidth is typically low when compared with the inner TVC bandwidth
- Thrust Vector Control:
  - Its function is to achieve the S/C attitude command generated by the outer guidance loop
  - To meet both the stability and performance requirements in the presence of fuel sloshing, structural dynamics, nonlinearities, and other disturbances



Selection of TVC System BW

- Design a TVC system for a S/C in a powered flight is challenging:
  - The TVC controller must compensate for a wide range of system dynamics (e.g., fuel slosh) some of which are poorly damped and others might have frequencies that are relatively close to the natural frequency of the total system
- There is a general desire to select the TVC BW as large as possible
  - To minimize maneuver execution errors
  - To keep both the S/C rate and the corresponding engine gimbal rate to within acceptable levels at ignition
- Guess a TVC BW that is located away from the slosh mode frequencies so as not to excite them:

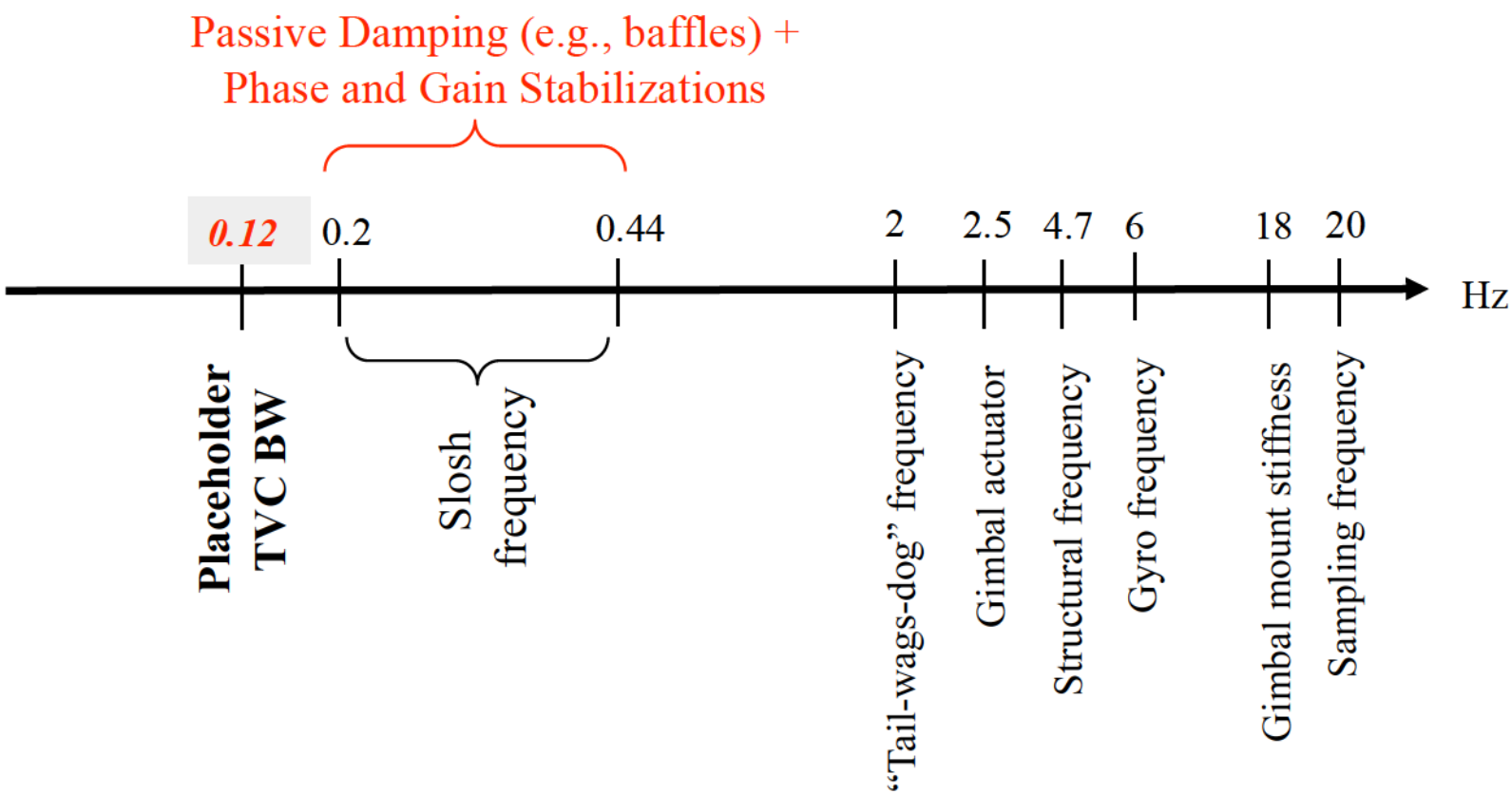
Spacecraft	Apollo*	Shuttle*	Altair
Slosh frequency/BW	2.0	1.94	1.8

- Altair placeholder TVC BW:

Spacecraft	Apollo*	Shuttle*	Altair
Bandwidth [Hz]	0.13-0.18	0.13	0.12-0.15

Stabilization of Under-damped Vehicle Dynamics

- The Altair placeholder TVC BW is an order of magnitude lower than all other system dynamics and "flexibilities":



Time-domain TVC Performance Requirements

- The TVC control engineers must also consider a set of time-domain performance requirements in their selection of the TVC BW
- Ignore high-frequency dynamics and nonlinearities in the TVC loop, we can derive simple expressions for the time histories of the S/C's attitude and gimbal angle when the system is subjected to a step change in the gimbal angle ε

$$\varepsilon\ [\text{rad}] = \text{Gimbal mispointing error}$$

$$\xi = \text{Damping ratio} = \frac{1}{\sqrt{2}}$$

$$\text{Peak S/C rate [rad/s]} \approx \varepsilon\sqrt{\frac{K}{K_{TVC}}}e^{-\frac{\pi}{4}}$$

$$\text{Peak S/C angle [rad]} \approx \frac{\varepsilon}{K_{TVC}}[1+e^{-\pi}]$$

$$\text{Peak gimbal rate [rad/s]} \approx \varepsilon\sqrt{2KK_{TVC}}$$

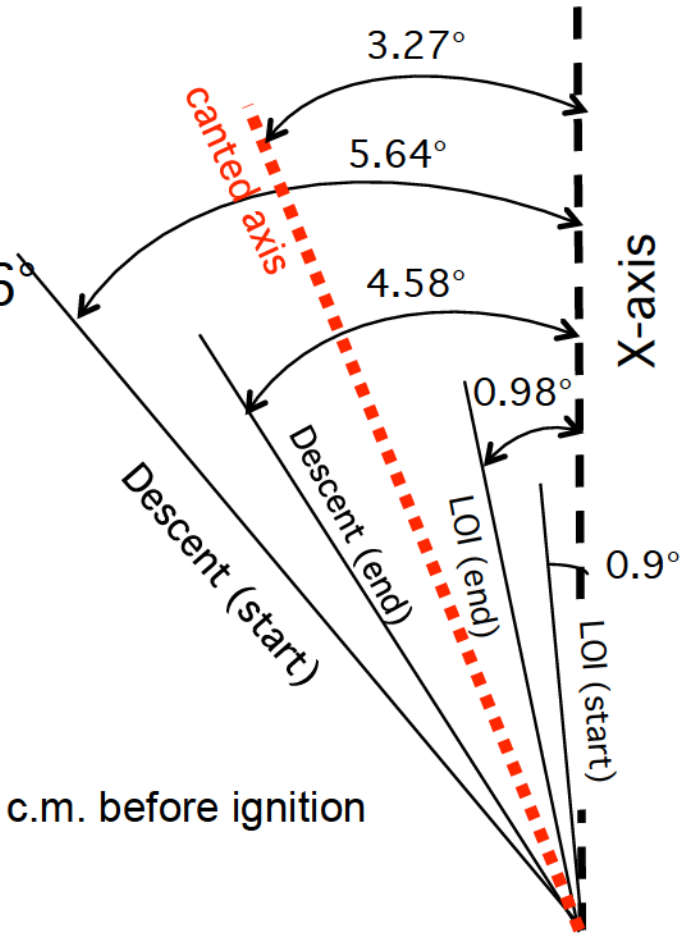
$$\text{Peak gimbal angle [rad]} \approx \varepsilon(1+e^{-\frac{\pi}{2}})$$

For TVC BW = 0.12 Hz, ξ = 0.707, and ε = 1°

Peak S/C's rate	0.2 °/s	Apollo-11, PDI, 0.25 °/s
Peak S/C's attitude	0.6°	
Peak gimbal rate	1.1 °/s	Apollo-11, TEI, 2 °/s
Peak gimbal angle	1.2°	20% of the gimbal range ±6°

Other TVC Considerations

- The descent engine gimbal system must support three ΔV burns on S/C configurations with different c.m. locations:
  - Lunar Orbit Insertion (LOI)
  - Plane Change (PC)
  - Powered Descent and Landing (PD&L)
- Engine gimbal excursion range is only ±6° (same as Apollo-9, 10, 11, and 12)
- Fixes:
  - Cant the DM engine axis: 3.27°±2.37°
  - Build budgets for engine excursions
  - Mission Operations practices:
    - Small fuel settling burn before engine burn
    - Pre-aim gimbal axis at the predicted vehicle's c.m. before ignition
    - Small X-axis dead-band throughout burn
    - others



Summary

- During thrust maneuvers, the sloshing of fuel in partially filled tanks could interact with the controlled system in such a way as to cause the overall system to be unstable

- This failure mode could be a result of poor coordination between systems engineers of Structures, Propulsion, GN&C, Mission Operations, and other subsystems

  Attentions to the following is a minimum:
  - Placements of fuel tanks
  - Tank shapes and baffle designs
  - Separation of TVC BW from slosh mode frequencies
  - Adequacy of excursion range of engine gimbal actuators in all engine burns
  - BW of sensors (e.g., gyroscopes) and actuators (e.g., engine gimbal)
  - Structural frequencies of spacecraft and engine mounts
  - Prediction of S/C's c.m. location, canting of gimbal null axis, others

- Check overall TVC performance via validated simulation test bed