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Neil Dennehy
NASA Technical Fellow for Guidance Navigation & Control
cornelius.j.dennehy@nasa.gov

Launch Vehicle Load Relief: A Historical Perspective and Some New Concepts

Presented by: **Jeb Orr**

Mclaurin Aerospace

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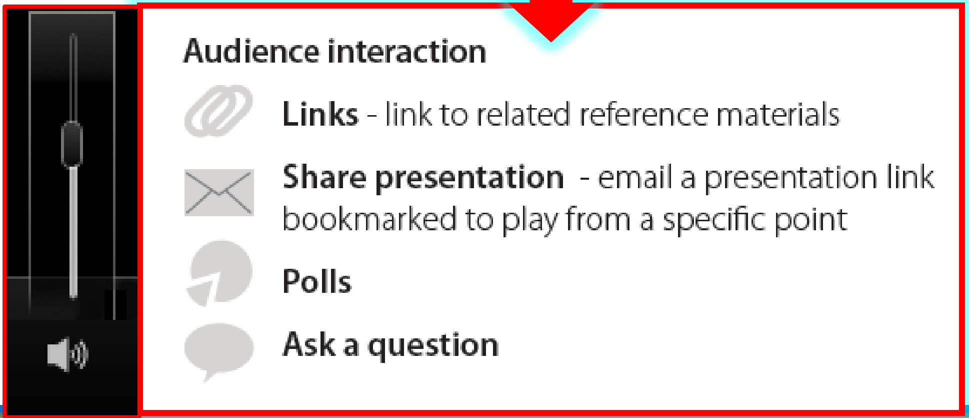

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Launch Vehicle Load Relief: A Historical Perspective and Some New Concepts

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Jeb S. Orr
Colter W. Russell
Abran Alaniz
Mclaurin Aerospace (AMA TEAMS3 Contract)

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Introduction

Ares I Load Relief Example
Fully Coupled Linear Aeroelastic Model (FRACTAL 1)

- ***Load relief*** **is a control technique designed to reduce transient bending loads**
  - For launch vehicles, a primary control goal is to reduce wind induced $\bar{q}\alpha_T$
  - It is noted that reducing $\bar{q}\alpha_T$ does not always imply reduced bending moments
    - Moments due to gimbaling can dominate over aeroelastic loads
    - We will consider only rigid-body load relief approaches.
- **Most approaches to load relief use some sort of acceleration feedback.**
  - Angle of attack is substituted with a surrogate measurement, such as N_Z and filtered angular rate.

Background

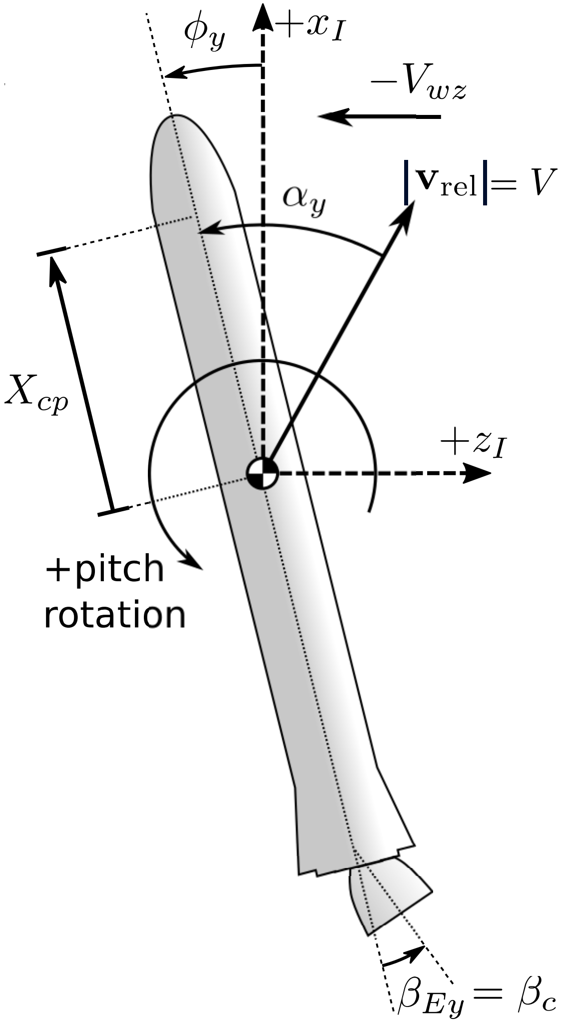
- **For this application we can restrict the discussion to a <u>rigid</u> rocket on a gravity turn.**
  - The gravity turn is by definition the $\alpha = 0$ trajectory.*
  - The control design is a *regulator* problem; i.e., drive the states toward the gravity turn.
- **Near the gravity turn the angle of attack <u>without wind</u> is**

$$\alpha_y = \phi_y + \frac{\dot{z}_I}{V}$$

  - The trajectory-relative velocity (usually not measurable) is related to the body velocity by

$$m_T \ddot{z}_b = m_T \ddot{z}_I + (F - D)\,\phi_y$$

  - The dynamics are written in a "quasi-inertial" or trajectory-relative frame in order to incorporate the angle of attack.
  - This frame is accelerating and anchored to the nominal vehicle center of mass location.



*With no wind.

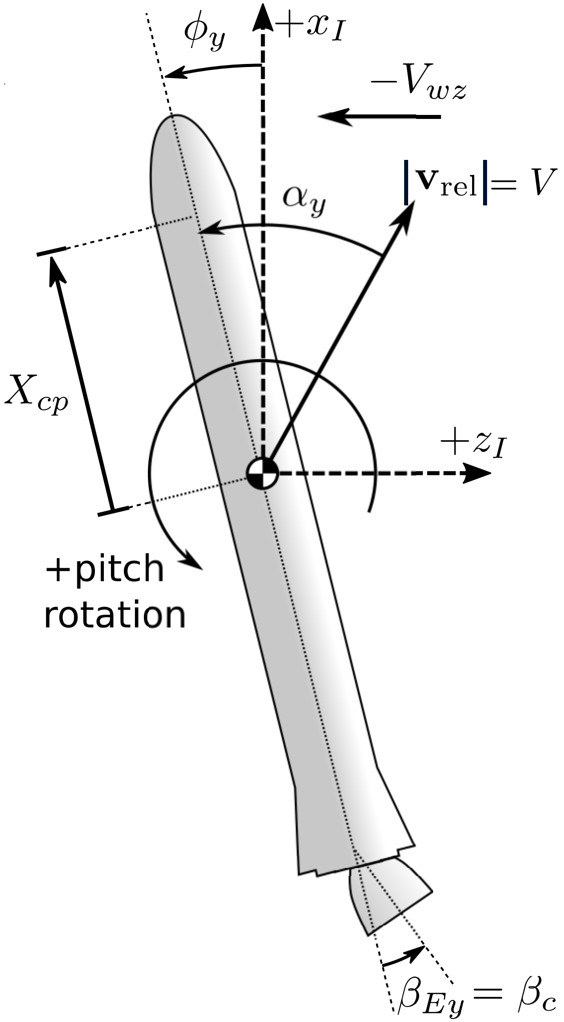
Vehicle Dynamics

- **The vehicle dynamics near the gravity turn are described by two* coupled linear equations:**

Rotation
$$I_{yy}\dot{\omega}_y = C_{N\alpha}\bar{q}S_{ref}X_{cp}\left(\phi_y + \frac{\dot{z}_I}{V}\right) + X_G F_R \beta_c$$

Translation
$$m_T\ddot{z}_I = -m_T\bar{g}\phi_y - C_{N\alpha}\bar{q}S_{ref}\left(\phi_y + \frac{\dot{z}_I}{V}\right) - F_R\beta_c$$

- **The rotation dynamics can be called "short period" although they may be unstable without feedback control.**
  - Most launch vehicles are statically unstable for performance reasons.
- **The translation dynamics are sometimes called a "drift mode" or "plunging mode".**
  - The resultant linear system has 3 poles.
  - We want the 2 rotation poles to be stable and well damped, and the drift root to be at worst neutrally stable.



*The angular rate is also integrated to produce the trajectory-relative attitude angle.

Basic PD Feedback Control

- **We can simplify the dynamics to second order.**
  - Assume no actuator dynamics and no significant plunging velocity.
- **Introducing simple proportional-derivative feedback:**

$$\beta_c = -k_p\phi_y - k_D\omega_y$$

  - An approximately ideal gain set is

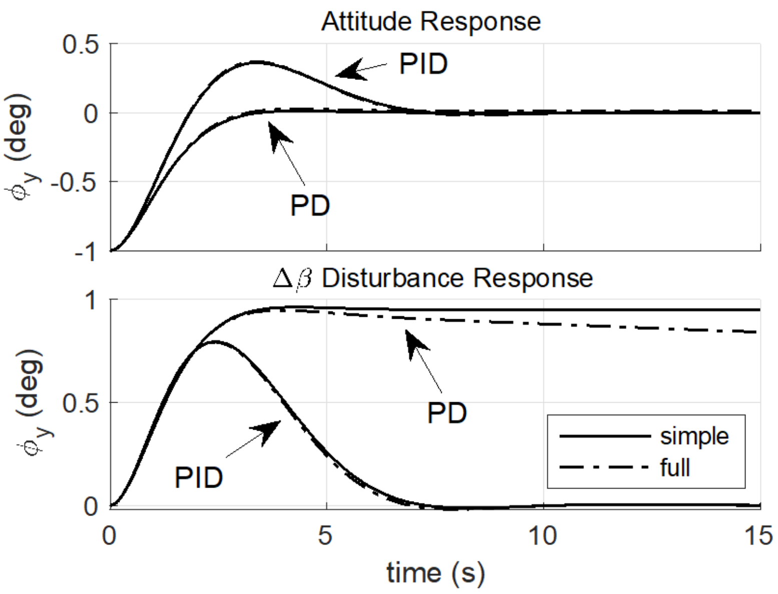
$$k_P = \frac{I_{yy}\omega_c^2 + C_{N\alpha}\bar{q}S_{ref}X_{cp}}{-X_GF_R} \qquad k_D = \frac{I_{yy}2\zeta_c\omega_c}{-X_GF_R}$$

  - The natural frequency and damping are chosen to meet a performance metric, also subject to a lower bound

$$\mathrm{GM}_a \approx 20\log_{10}\frac{X_GF_Rk_P}{C_{N\alpha}\bar{q}S_{ref}X_{cp}} \geq 6\,\mathrm{dB}$$

  - This is the aerodynamic gain margin.
  - Similar closed-form gain expressions can be found for PID control.

Typical launch vehicle attitude response, PD & PID control



Gains can be designed using 2nd order dynamics and then applied to a higher-order model including translation

Simple Alpha-Feedback Load Relief

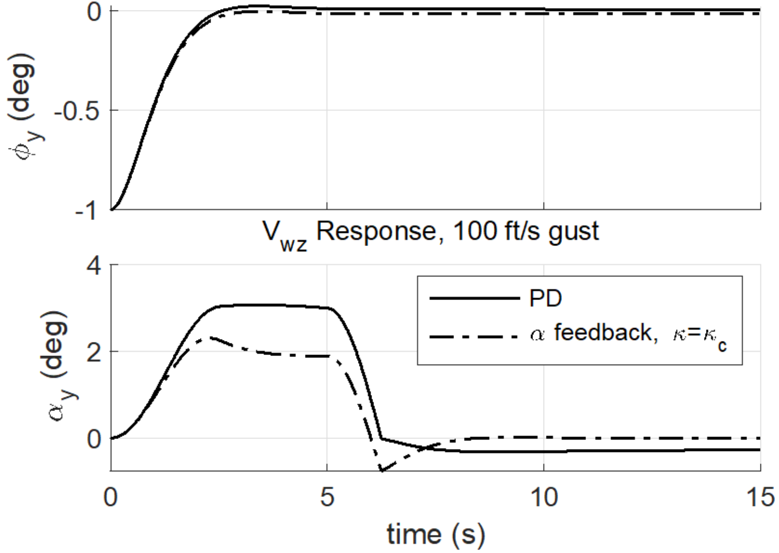
- **In order to reduce $\bar{q}\alpha_T$ one can add pure α feedback.**
  - Pure α feedback can be unstable: vehicle will turn into the wind and deviate from the trajectory
  - Eigenvalue associated with drift root is in RHP

- **Consider a linear combination of attitude and angle of attack feedback:**

$$\beta_c = -(1-\kappa)\,k_P\phi_y - k_D\dot{\phi}_y - \kappa k_P\alpha_y$$

  - There is a critical gain κ_c where the drift root is neutrally stable.[1]
  - A **closed-form expression** can be derived as a function of the control gains, aerodynamics, etc.
  - In this case the response to a gust will be improved but the vehicle will not deviate exponentially from the trajectory.
  - However, angle of attack cannot be easily measured!

PD vs. Alpha Feedback



- PD control response to gust returns attitude error to zero but vehicle has nonzero angle of attack due to drift velocity
- "Ideal" critical-gain alpha control is neutrally stable in drift and reduces loads.
- Equivalent to "**drift minimum**" control.

[1] Barrows, T., and Orr, J., Dynamics and Simulation of Flexible Rockets, Chapter 9, Elsevier, 2021.

Classical (Saturn I/I-B) Load Relief

- **Reliable sensing of angle of attack was determined to be infeasible for early launch vehicle configurations**
  - Alpha sensing had been demonstrated using the X-15 ball nose, but was not reliable in subsonic and transonic conditions
  - Vanes must survive the launch environment and are subject to aeroelastic errors
  - Inertial air data was not available with high accuracy or reliability (also tried on X-15)

- **Early load relief approaches[2,3] used body accelerometer feedback:**

$$\beta_c = -k_p \phi_y - k_D \omega_y - k_z \ddot{z}_b$$

  - There are 3 closed form gain sets that can be derived for *steady state:*
    1. *Attitude error minimum.* Vehicle attitude error is zero. Special case.
    2. *Drift minimum.* Vehicle acceleration normal to trajectory is zero.
    3. *Load minimum (no attitude feedback).* Vehicle angle of attack is zero.
       - *Unstable (long period / "path motion").*

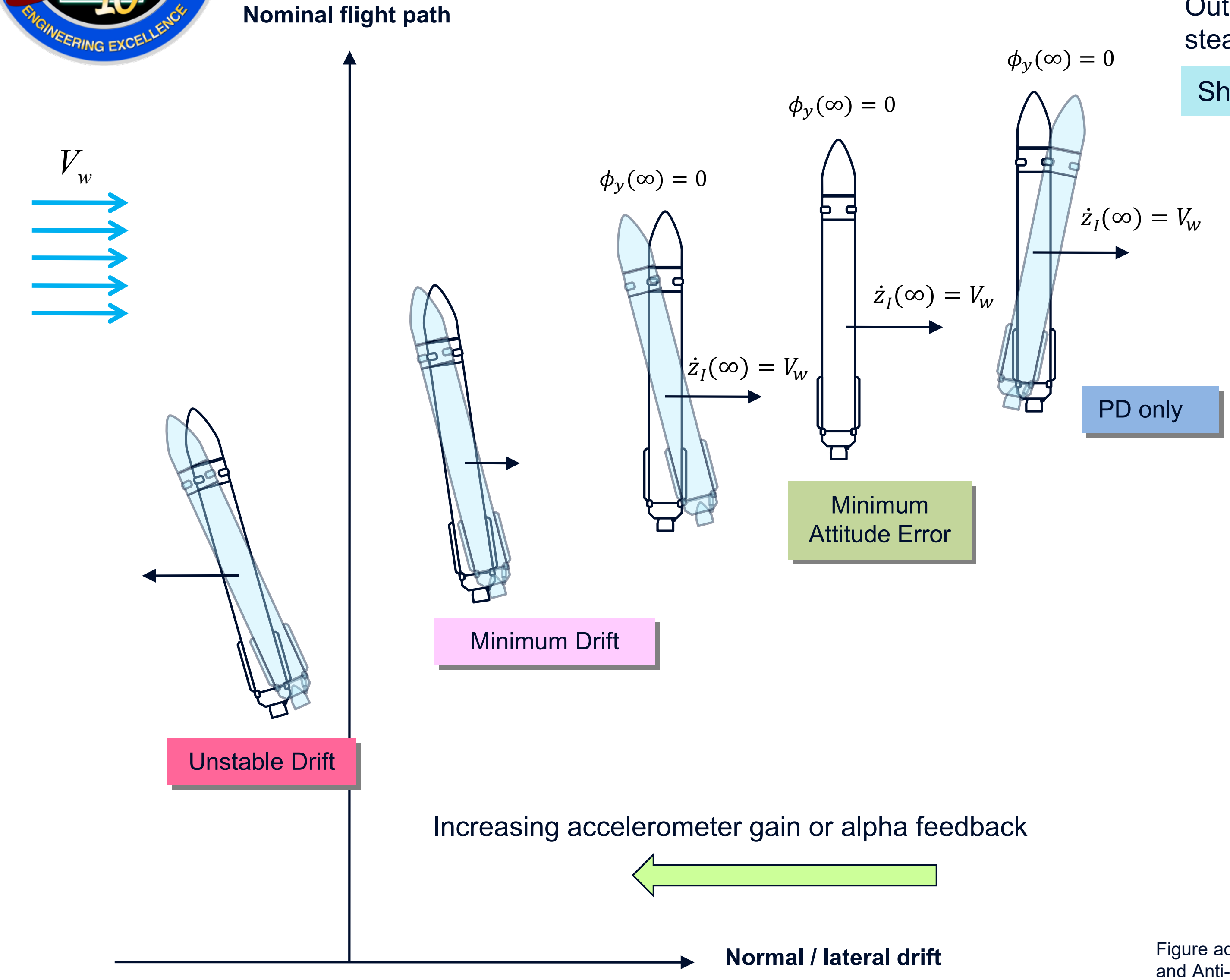
[2] Jaggers, R., "Derivation of a Drift Minimum/Loads Minimum Control Law for Booster, Atmospheric Flight," NASA JSC 5-2950-1-HOU-278, May, 1971.

[3] Haeussermann, W., "Description and Performance of The Saturn Launch Vehicle's Navigation, Guidance, and Control System," NASA TN D-5869, NASA Marshall Space Flight Center, July 1970.

Load Relief Response with PD Control

Outline of vehicle denotes steady-state orientation

Shading denotes transient motion



Nominal flight path

V_w

$\phi_y(\infty) = 0$

$\dot{z}_I(\infty) = V_w$

Unstable Drift

Minimum Drift

Minimum Attitude Error

PD only

Increasing accelerometer gain or alpha feedback

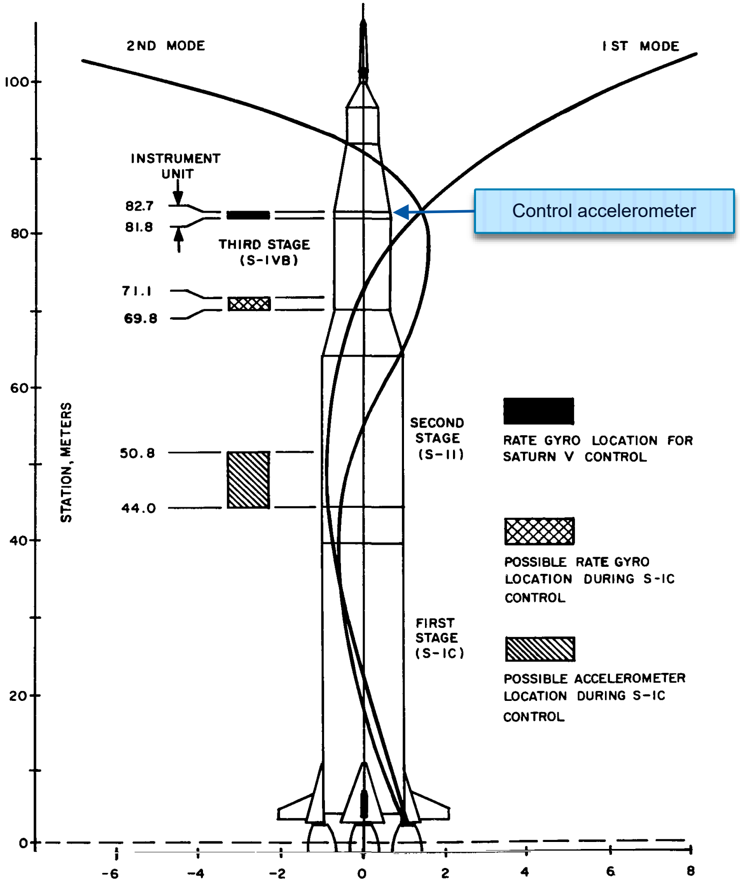
Normal / lateral drift

Figure adapted from Yang, L., "Design of Load Relief and Anti-Drift," Draper Laboratory, 5/23/2009.

Saturn Load Relief

- **Pure accelerometer feedback is difficult to realize in practice.**
    - Bending dynamics couple strongly into accelerometer feedback signal, requiring aggressive low-pass filtering.
    - Angular acceleration couples into accelerometer since instrument is not at CG (requires angular rate compensation).
    - Effective closed-loop bending damping (phase stable 1st mode) can be decreased.
    - Time constants for "steady state" design equations may be on the order of the trajectory.

- **Angle of attack feedback was abandoned in favor of accelerometers.**
- **Load relief was baselined but eventually removed from the Saturn V.[4,5]**
    - Analog component tolerances for low-pass filtering were a contributing factor.



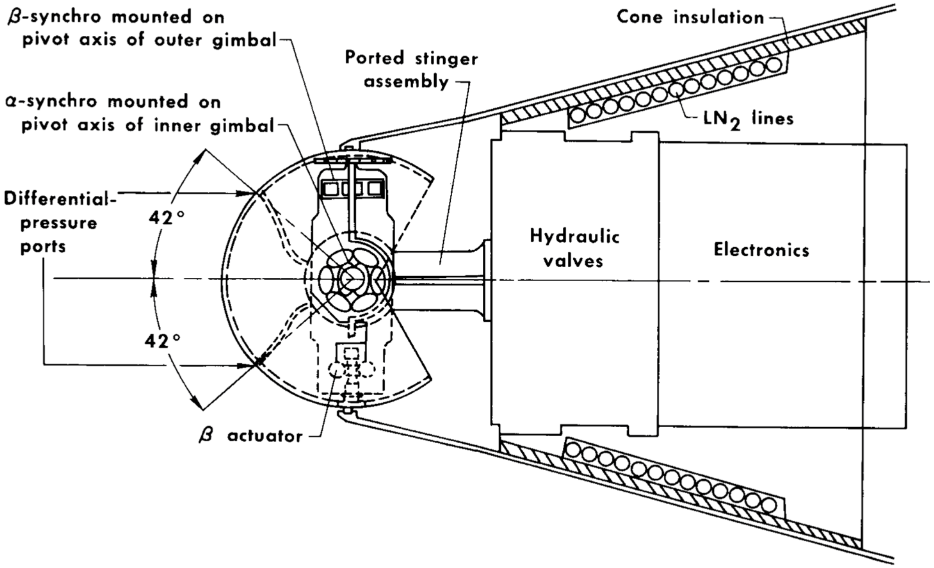
Control accelerometer

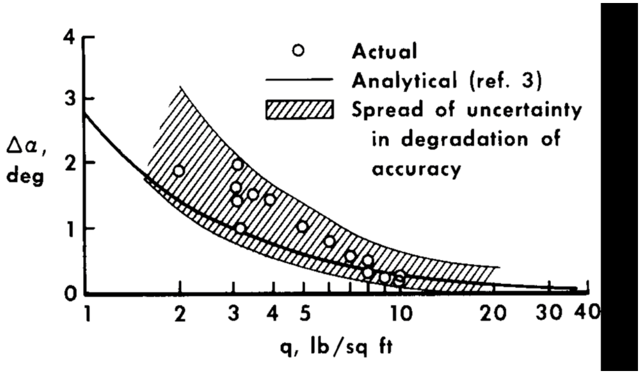
Image: Haeussermann, NASA TN D-5869

[4] Frosch, J. and Vallely, D., Saturn AS-501/S-IC Flight Control System Design," J. Spacecraft, Vol. 4, No. 8, 1967, p. 1003-1009.
[5] Orr, J., Wall, J., and Dennehy, N., "The Enduring Legacy of Saturn V Launch Vehicle Control Design Principles & Practices," 70th International Astronautical Congress, IAC-19-9-D6.2, 21-25 October 2019.

A Sidebar on Air Data and the X-15 (the “q-ball”)

- **A novel angle of attack sensor was developed and demonstrated on X-15**
  - Simple concept – use theoretical pressure distribution over a perfect sphere
  - Analog servocontrol to gimbal the sphere to equalize the differential pressure
  - ~0.1° alignment accuracy to airframe and <0.5° measurement accuracy up to α=22°
  - Excellent performance above Mach 2 except when interacting with RCS plumes at low dynamic pressure (<50 psf)
  - Limited in subsonic & transonic regimes – not useful for launch vehicles.





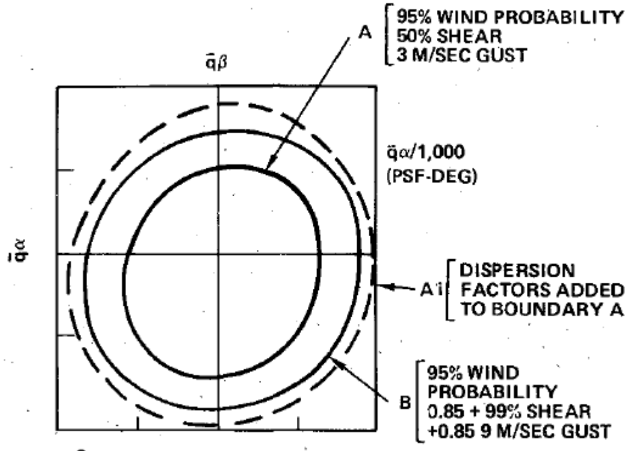
[redacted]

[6] Wolowicz, C.H. and Gossett, T.D., “Operational and Performance Characteristics of the X-15 Spherical, Hypersonic Flow-Direction Sensor,” NASA TN D-3070, November 1965

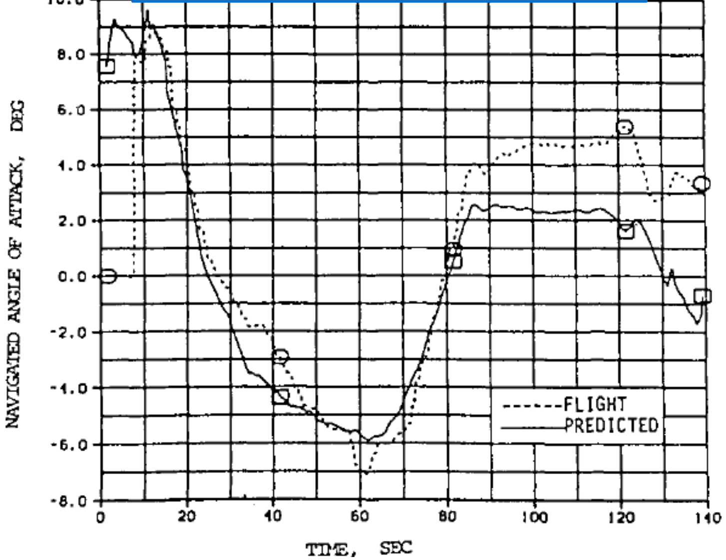
Space Shuttle Ascent Load Relief

- **STS Load Relief combined Ny/Nz feedback with:**
  - Day-of-launch wind biasing (mean monthly wind reference accelerations)
  - Elevon hinge moment load relief (delta-P feedback)
  - Operational design trajectory with zero-lift gravity turn (negative alpha)
- **Complex design approach**
  - Highly coupled loads & dynamics problem due to aerosurfaces and vehicle element interfaces
  - Development of $\bar{q}\alpha_T$ “squatcheloids” over range of Mach numbers
  - Squatcheloids used to develop vehicle loads analysis cases
  - Challenged by bending stability margin throughout the program[8]

Typical aerodynamic angle limit squatcheloid [7]



STS-1 Design and Actual Angle of Attack [9]



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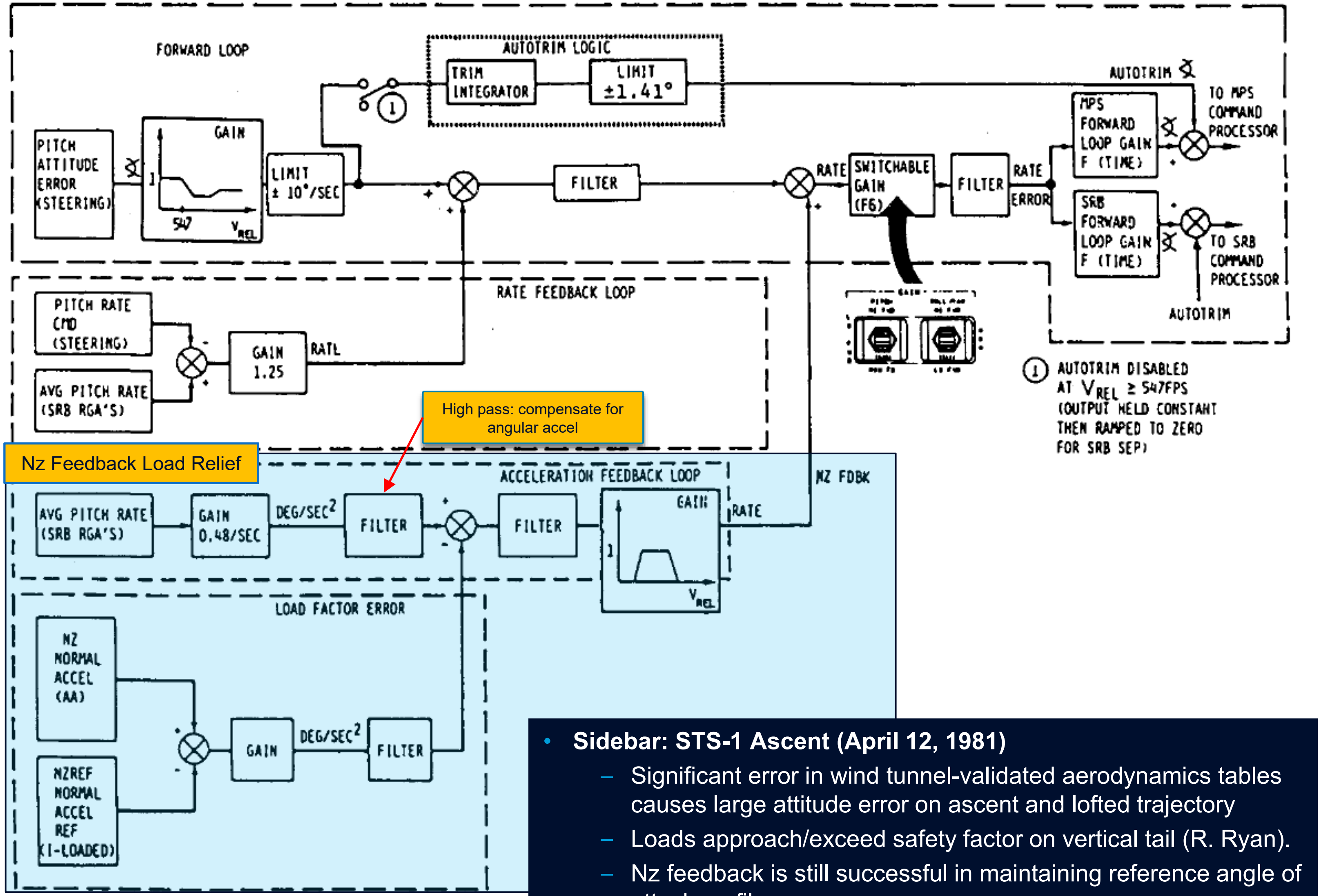
[7] Schleich, W.T., *Shuttle Vehicle Configuration Impact on Ascent Guidance and Control,* J. Guidance, Vol. 7, No. 3., pp. 338-346.

[8] Altenbach, R., NASA STS SSD96D0526, STS Bending Flight Mechanics Data Book, September 1996.

[9] Olsen, L.M and Sunkel, J.W., *Postflight Evaluation of the Shuttle Guidance, Navigation, and Control During Powered-Ascent Flight Phase,* J. Guidance, Vol. 6, No. 6, pp. 418-423.

STS Ascent Pitch Axis FCS Block Diagram



High pass: compensate for angular accel

Nz Feedback Load Relief

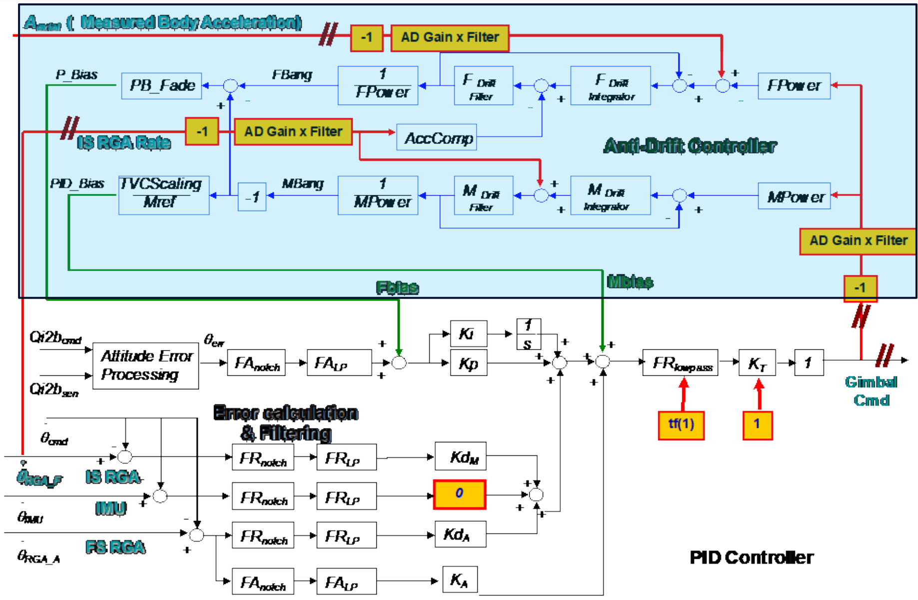
- **Sidebar: STS-1 Ascent (April 12, 1981)**
  - Significant error in wind tunnel-validated aerodynamics tables causes large attitude error on ascent and lofted trajectory
  - Loads approach/exceed safety factor on vertical tail (R. Ryan).
  - Nz feedback is still successful in maintaining reference angle of attack profile.

Figure from Olsen, L.M and Sunkel, J.W., *Postflight Evaluation of the Shuttle Guidance, Navigation, and Control During Powered-Ascent Flight Phase,* J. Guidance, Vol. 6, No. 6, pp. 418-423.

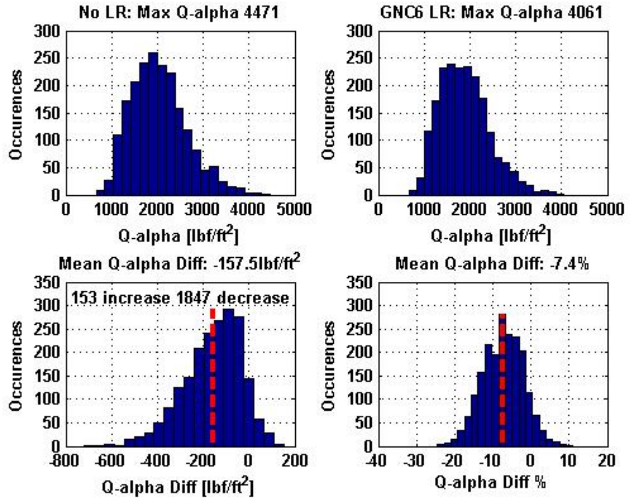
Ares I / I-X / SLS Load Relief

- **Ares I & SLS Load Relief derived from Ares I-X**
  - Ares I-X designed by Bart Bacon et. al (LaRC) and based on concept of external force and moment balance using 1st order Luenberger observers (ignoring drag)
  - Provided an anti-drift function
  - Modified for Ares I to schedule gains and include a load relief function

- **Even with numerical gain optimization, achievable gain was severely limited**
  - Because 1st bending mode is phase stable, bending damping decreases, possibly increasing bending loads over a “no load relief” option
  - Mean rigid-body $\bar{q}\alpha_T$ decreased about 7%.
  - Typical Ares I LR bandwidth was ~0.1 Hz.



Draper PARES MC Analysis [8]



[10] “Control Algorithm and Parameters for the Ares I-X Flight Test Vehicle,” AI1-SYS-CAP-V4.00, NASA ESMD, October 21, 2009.
[11] Jang et al., “Analysis of Ares I Load Relief Controller Design,” MSFC/EV41, January 2009.
[12] Wall, J., “Analytical Presentation of the Ares I Anti-Drift / Load-Relief Flight Control Option,” MSFC/EV41, Nov 9, 2009.
[13] Orr, J., “GNC8 FS Design Rev 2,” MSFC/EV41, April 27, 2010.

Simplified Multi-Loop Load Relief Steering

- **Why? Inner-loop feedback increases the complexity of the inner-loop FCS design**
  - Example: The SLS autopilot has 3 primary control gains (PID), about 64 attitude, rate, and load relief (DCA) filter coefficients, and 4 load relief gains, *per axis*, *per flight condition*

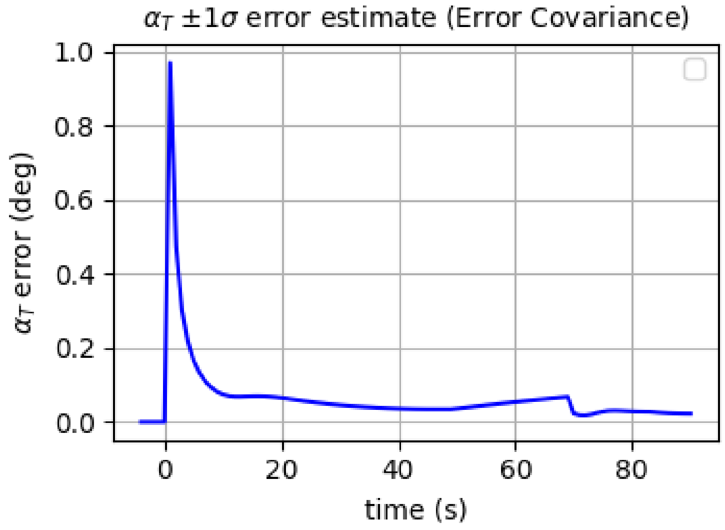
- **Direct air data sensing has not yet been shown to be feasible & reliable for launch vehicles.**
    - FADS, 5-hole probe, etc. have issues with complexity, reliability, and *pre-launch weather*
    - Possibly unacceptable impact to launch availability.
    - However, GPS/INS capability and computing power has markedly improved!

- **INS measurements can be combined with Day of Launch I-Load Update (DOLILU) to construct a synthetic estimate of angle of attack.**

How Has the Situation Changed?

- **Today we have access to good inertial data.**
  - Inertial estimates alone (no wind) can provide angle of attack to sub-degree accuracy using GPS
  - Wind data can be stored online and updated prior to launch (DOLILU)
  - Winds can be determined from DRWP, balloon soundings, and forward-looking sensors
  - New control laws could take advantage of the availability of reliable angle of attack data.

Example Launch Vehicle Navigation Covariance Analysis
- High Tactical-Grade IMU with GPS Aiding
- Inertial Angle of Attack Error Covariance
- GPS SPS + GPS Out



- **Strapdown navigation error states can be used to estimate inertial angle of attack errors.[12]**

Linear Angle of Attack Estimation Errors Depend on Strapdown Navigator Error States

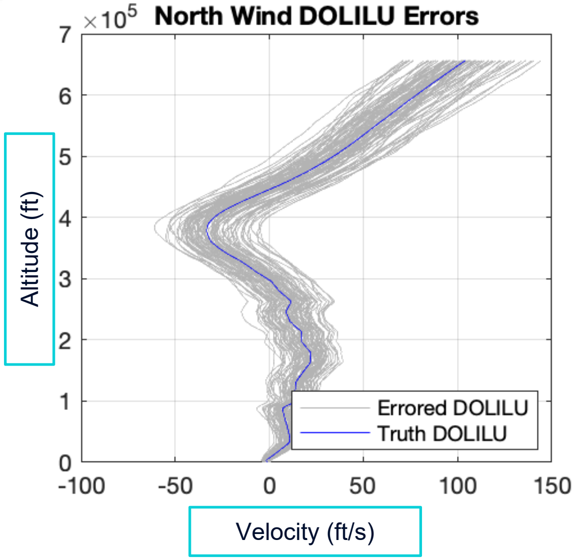
$$\begin{bmatrix} \delta\alpha \\ \delta\beta \end{bmatrix} = \begin{bmatrix} 0 & 0 & \frac{1}{u_0(t)} \\ 0 & \frac{1}{V_0(t)} & 0 \end{bmatrix} \mathbf{T}_0^{BN}(t) \left(\begin{bmatrix} \delta v_N \\ \delta v_E \\ \delta v_D \end{bmatrix} + \mathbf{v}_{N0}^{\times} \begin{bmatrix} \delta\phi \\ \delta\theta \\ \delta\psi \end{bmatrix} \right)$$

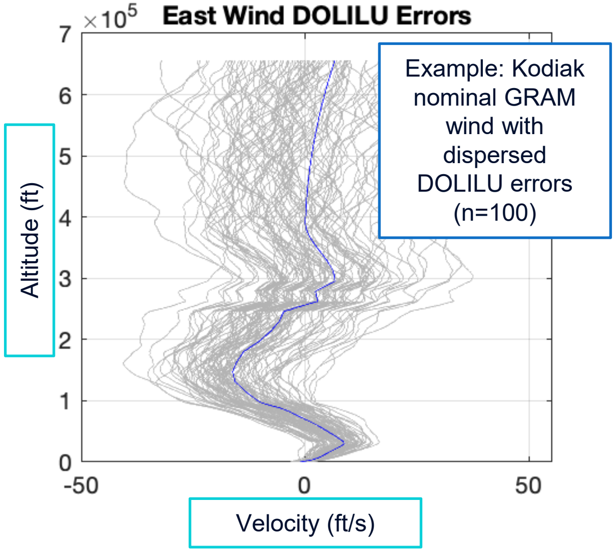
[12] Orr, J., “Aerodynamic Angle Navigation Error Covariance,” Mclaurin Aerospace internal memo, August 10, 2020

DOLILU (Day of Launch I-Load Update)

- **Combining inertial velocity estimates with measured range winds can produce a significantly improved estimate**
  - Actual errors are difficult to know *a priori* due to limited range information (balloon vs. DRWP vs. postflight BET, for example)
    - Some statistical data on CCAFS Jimsphere performance is available from MSFC
    - Limited information at WSMR and elsewhere
  - **Careful: wrong DOLILU is worse than no DOLILU.**

- **Monte Carlo error model**
  - Filtered random walk + GM noise model to account for spatial and temporal error in winds measurements


North Wind DOLILU Errors


East Wind DOLILU Errors

Example: Kodiak nominal GRAM wind with dispersed DOLILU errors (n=100)

New Alpha Feedback Law

- **Revisiting the vehicle pitch dynamics with wind:**

Rotation $$I_{yy}\dot{\omega}_y = N_\alpha X_{cp}\alpha + X_G F_R \beta_c - X_{cp} N_\alpha \frac{V_{wz}}{V}$$

Translation $$m_T \ddot{z}_I = -m_T \bar{g}\phi_y - N_\alpha \alpha - F_R \beta_{Ey} + N_\alpha \frac{V_{wz}}{V}$$

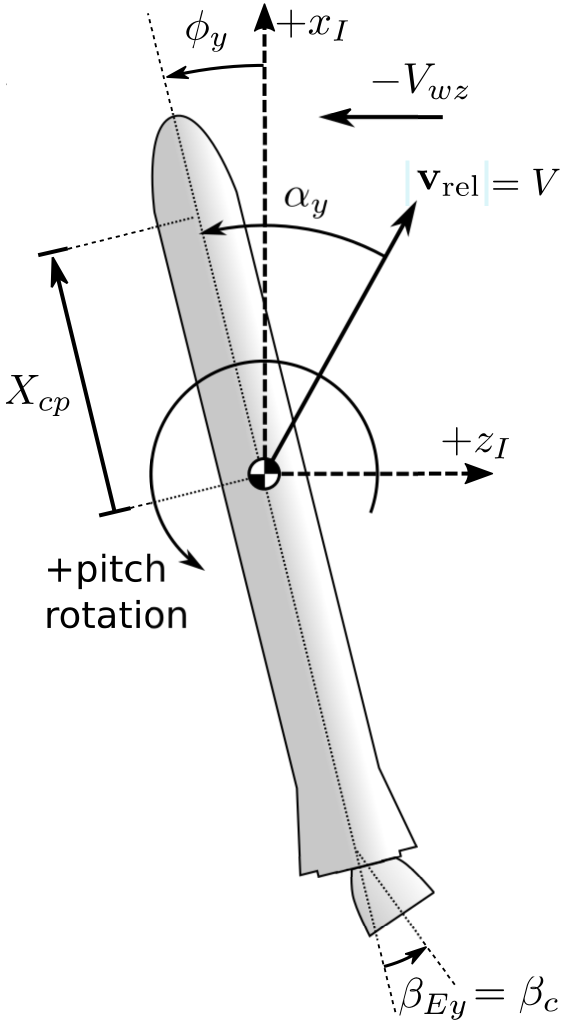
  - Note that the total normal force coefficient $N_\alpha = C_{N\alpha}\bar{q}S_{ref}$
  - The angle of attack with wind is $\alpha = \phi_y + \frac{\dot{z}_I - V_{wz}}{V}$

- **These equations are valid near the gravity turn.**
  - If the forward and wind velocity are approximately constant:

$$\boxed{\dot{\alpha} = \omega_y + \frac{\ddot{z}_B}{V} - \frac{\bar{g}\sin\phi_y}{V}}$$

  - A rate command load relief law can be derived[13]:

$$\boxed{\omega_{yc} = k_{p\alpha}\alpha + \int_0^t k_{i\alpha}\alpha(\tau)\mathrm{d}\tau + \frac{1}{V}\left(\bar{g}\sin\phi_y - \hat{\ddot{z}}_B\right)}$$



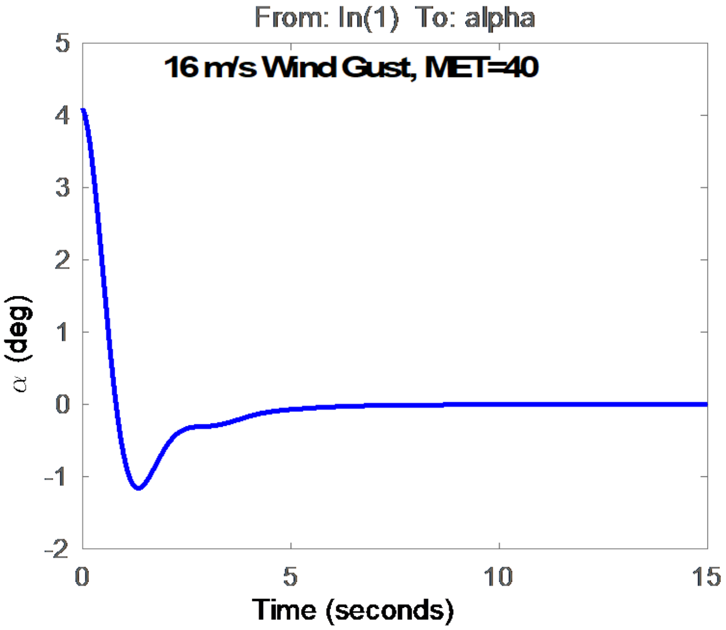
[13] Orr, J., "Booster Alpha Control near a Gravity Turn," Mclaurin Aerospace internal memo, October 18, 2020.

Advantages of Outer-Loop Angle of Attack Control

1. **Inner loop stability margins are not significantly affected by outer loop closure**
2. **Inner loop autopilot structure is simple (PD/PID + bending filters)**
   - Easily accommodate gain-adaptive control
3. **Acceleration feedback can be lower gain / low bandwidth**

- **Challenges**
  - Accelerometer feedback still must be robustly stabilized with bending.
  - Since relative velocity is in the denominator of the feedback law, the effective gain is very high at low velocity.
  - Drift root is still unstable for load minimum condition.

Representative Simplified Linear Model
Truth CG acceleration feedback.

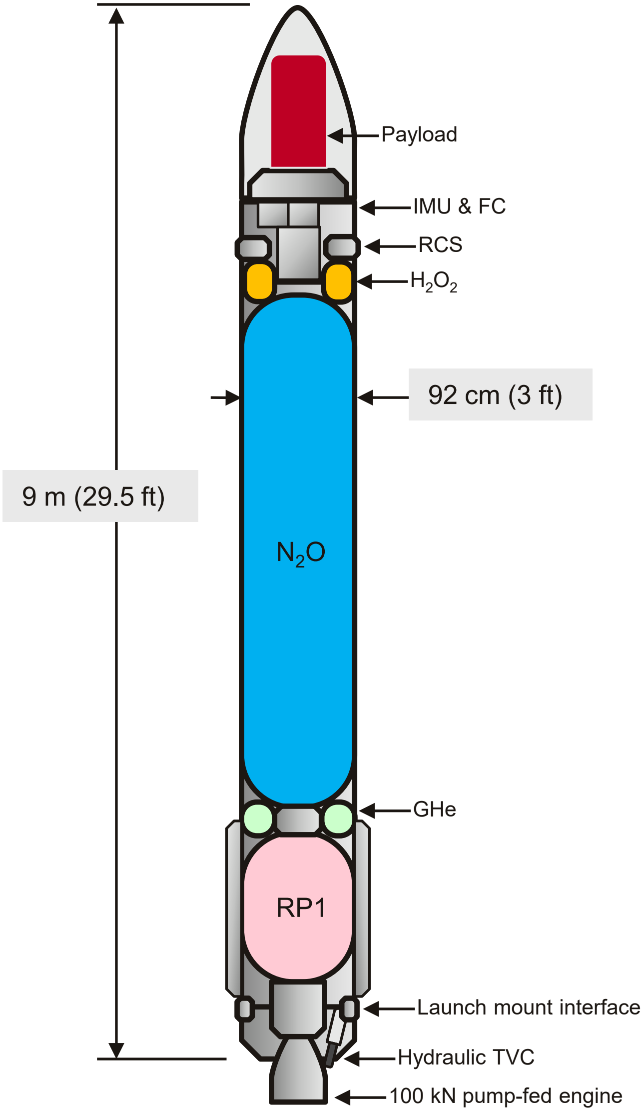


Monte Carlo Analysis in High Fidelity Simulation

- **Representative test using a single-stage boost vehicle concept called SSTV**
- **3 cases considered to evaluate effectiveness of a rate-command algorithm**
  - No load relief (zero wind χ table only)
  - Load relief law with GPS error model but perfect DOLILU table
  - Load relief law with GPS errors and DOLILU errors

  - All runs were performed with flex off
  - Identical seeds for direct comparison of results
- **Simplified set of uniform dispersions used to generate stressing cases with wind**
  - Typical vehicle dispersions (mass properties, thrust, sensors)
  - Environment dispersions to assess winds (GRAM thermo properties)

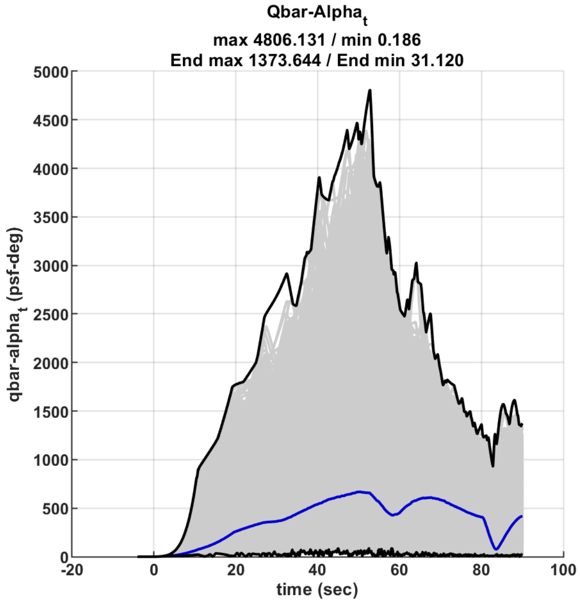
SSTV Synthetic Vehicle Model



Monte Carlo Analysis – Rigid-Body Load Indicators

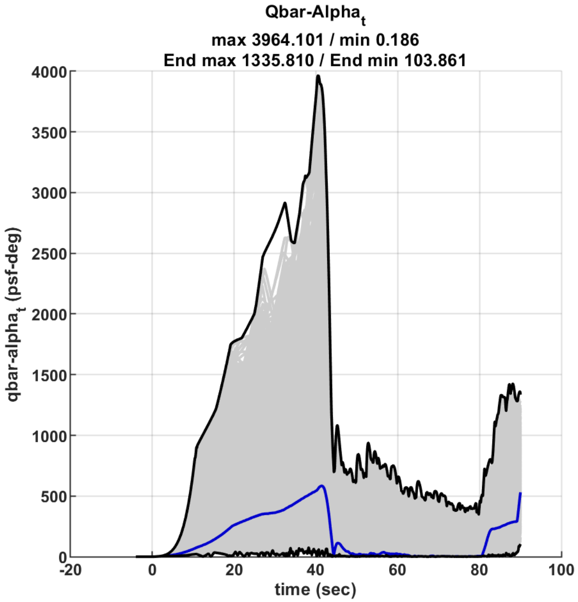
- **Load relief law is enabled at T=40 sec**
  - Load relief is blended in over 5 sec to reduce rate transient at engagement
  - Significant improvement in $\bar{q}\alpha_T$ envelope even with errored winds information
  - Improvements are reflected in 99.865% 10% CR quantiles for loads (not shown)
  - Nominal case is worse with load relief due to nominal wind table errors (expected)

No load relief



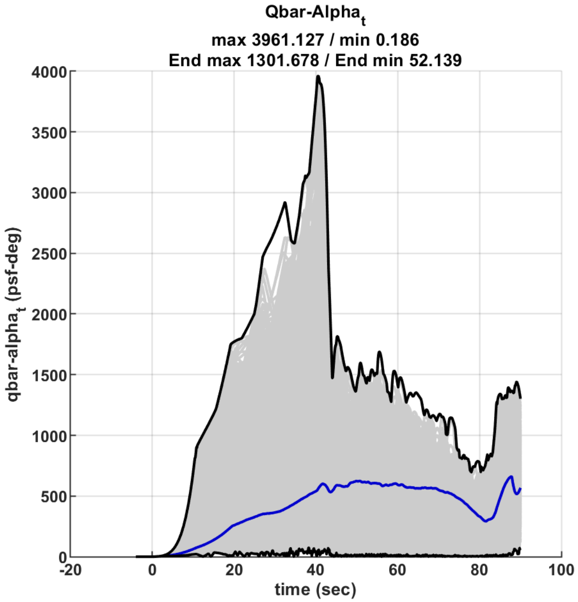
Qbar-Alpha$_t$
max 4806.131 / min 0.186
End max 1373.644 / End min 31.120

Perfect DOLILU (ideal) load relief



Qbar-Alpha$_t$
max 3964.101 / min 0.186
End max 1335.810 / End min 103.861

Load relief with DOLILU errors



Qbar-Alpha$_t$
max 3961.127 / min 0.186
End max 1301.678 / End min 52.139

Summary

- **Launch vehicle load relief is a powerful augmented control technique to reduce vehicle transient loads due to wind.**
  - Fundamental concepts of acceleration and angle of attack feedback have remained unchanged since their advent in the early 1960s.
  - Load reductions can improve launch availability or decrease structural mass.
- **Tradeoffs include:**
    - Placement of accelerometer with respect to CG & bending mode shape/slope OR
    - Feasibility of direct alpha sensing or alpha estimation
    - Control loop complexity / number of parameters
    - Rigid body load metrics ($\bar{q}\alpha_T$) versus transient bending moments due to TVC
    - Robustness/stability margins.
    - Acceptability of marginal or unstable path drift in the presence of wind.

- **Novel methods using modern strapdown GPS/INS combined with near real-time measurements can yield very good performance.**
  - Still a linear control law that can be designed/tuned using classical loop shaping techniques.