This presentation discusses the requirements for and the ramifications of including unsteady aerodynamics and structural flexibility in the computation of stability and control derivatives for modern flight vehicles.

APPLICATION OF COMPUTATIONAL STABILITY AND CONTROL TECHNIQUES INCLUDING UNSTEADY AERODYNAMICS AND AEROELASTIC EFFECTS

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The motivation behind the inclusion of unsteady aerodynamics and aeroelastic effects in the computation of stability and control (S&C) derivatives will be discussed as they pertain to aeroelastic and aeroservoelastic analysis. This topic will be addressed in the context of two applications, the first being the estimation of S&C derivatives for a cable-mounted aeroservoelastic wind tunnel model tested in the NASA Langley Research Center (LaRC) Transonic Dynamics Tunnel (TDT). The second application will be the prediction of the nonlinear aeroservoelastic phenomenon known as Residual Pitch Oscillation (RPO) on the B-2 Bomber. Techniques and strategies used in these applications to compute S&C derivatives and perform flight simulations will be reviewed, and computational results will be presented.

Within the LaRC Aeroelasticity Branch (AB), there are two primary objectives supporting the computation of stability and control derivatives. The first is to support free-flying cable-mounted aeroelastic and aeroservoelastic wind tunnel investigations in the TDT. The second is to support full-scale aeroelastic and aeroservoelastic analyses of modern flight vehicles. In the former case, since wind tunnel models are often conceptual in nature, a large database describing the model's flight characteristics, as is usually assembled for full-scale aircraft, is not available. Therefore, we rely virtually exclusively on empirical, analytical, and computational methods to predict the S&C performance of the model. This includes a requirement to predict both static and dynamic derivatives as well as the impact of structural flexibility on the model's performance. Since the TDT is a transonic facility, nonlinear aerodynamics is also an important

contributor to the analysis. The widespread use of automated flight controls on virtually all modern commercial and military aircraft has introduced a new class of problems where the vehicle control system can interact with the aerodynamics and structural flexibility of the system. The discipline investigating these interactions is known as aeroservoelasticity and is rapidly growing in importance for prediction of on- and off-design vehicle performance. To effectively predict aeroservoelastic problems, accurate computation of control effectiveness is a must.

The first application to be discussed is the prediction of S&C derivatives for a SST wind tunnel model tested in the LaRC TDT. The model is an aeroelastically scaled model of a 1970's SST concept. It was developed to investigate control laws for the aircraft. The cable system employed in the TDT provides a five-degree-of-freedom mount for the model. A single vertical cable runs from the wind tunnel ceiling to the wind tunnel floor through a pair of vertically-mounted pulleys installed in the model just forward of the center of gravity. Similarly a single cable runs between the sidewalls of the wind tunnel through a horizontally mounted pair of pulleys aft of the center of gravity. In addition, four snubber cables run from the corners of the tunnel to the model near the C.G. These four cables can be interactively tightened and loosened. In the tight configuration, they are used to hold the model at the center of the tunnel during wind

off conditions, and they are slack during "free-flight" testing. They can also be rapidly tightened when the vehicle encounters an instability to attempt to stabilize the aircraft. The model also includes hydraulically actuated wing and horizontal tail control surfaces. Control effectiveness derivatives, including flexibility effects are required to design the flutter-suppression control laws that are the subject of the test. In addition, the precise position and tension on the cables is defined using a computer program known as GRUMCBL, which requires S&C derivatives for the model.

This slide discusses the wind tunnel test objectives and requirements for S&C derivatives to support the test, emphasizing the importance of COMSAC techniques for this type of testing.

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This slide shows a video clip of the SST testing in which an aggressive flutter suppression control law is activated on the model. The model experiences a severe upset and the tunnel bypass valves and snubber support cables are activated. Unfortunately the model upset is too severe, and nonlinearity in the cable mount system and/or aerodynamics slowly drive the model to destruction. While it is unreasonable to blame the destruction of the model on poor predictions of S&C derivatives, this is a stark example of the importance of accurate predictions of these types of derivatives for this type of testing.
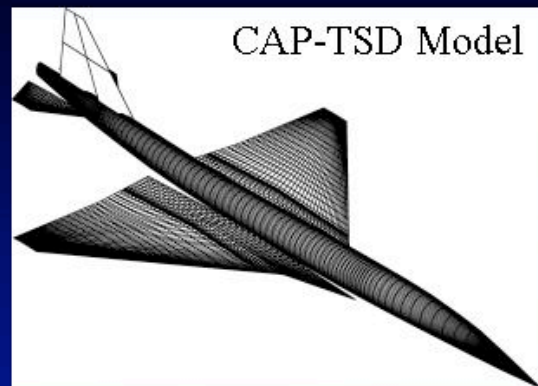
S&C derivative predictions for the SST model came from four primary sources, Stability and Control DATCOM, linear doublet lattice, transonic small disturbance potential flow (CAP-TSD), and wind tunnel balance data. Static, dynamic, rigid and flexible derivatives were developed for this configuration. Analyses using the Computational Aeroelasticity Program – Transonic Small Disturbance (CAP-TSD) are the focus of this presentation. Using this methodology, static derivatives were computed using a finite difference technique, but are not the main focus of this discussion. Dynamic derivatives were estimated by pulsing the configuration in pitch, plunge, yaw, and spanwise translation. Roll rate derivatives were computed using a steady analysis and imposing specialized boundary conditions to the lifting surfaces which represent the rolling motion of the aircraft.

This slide describes the essential features of the inviscid and viscous/inviscid interaction versions of CAP-TSD.

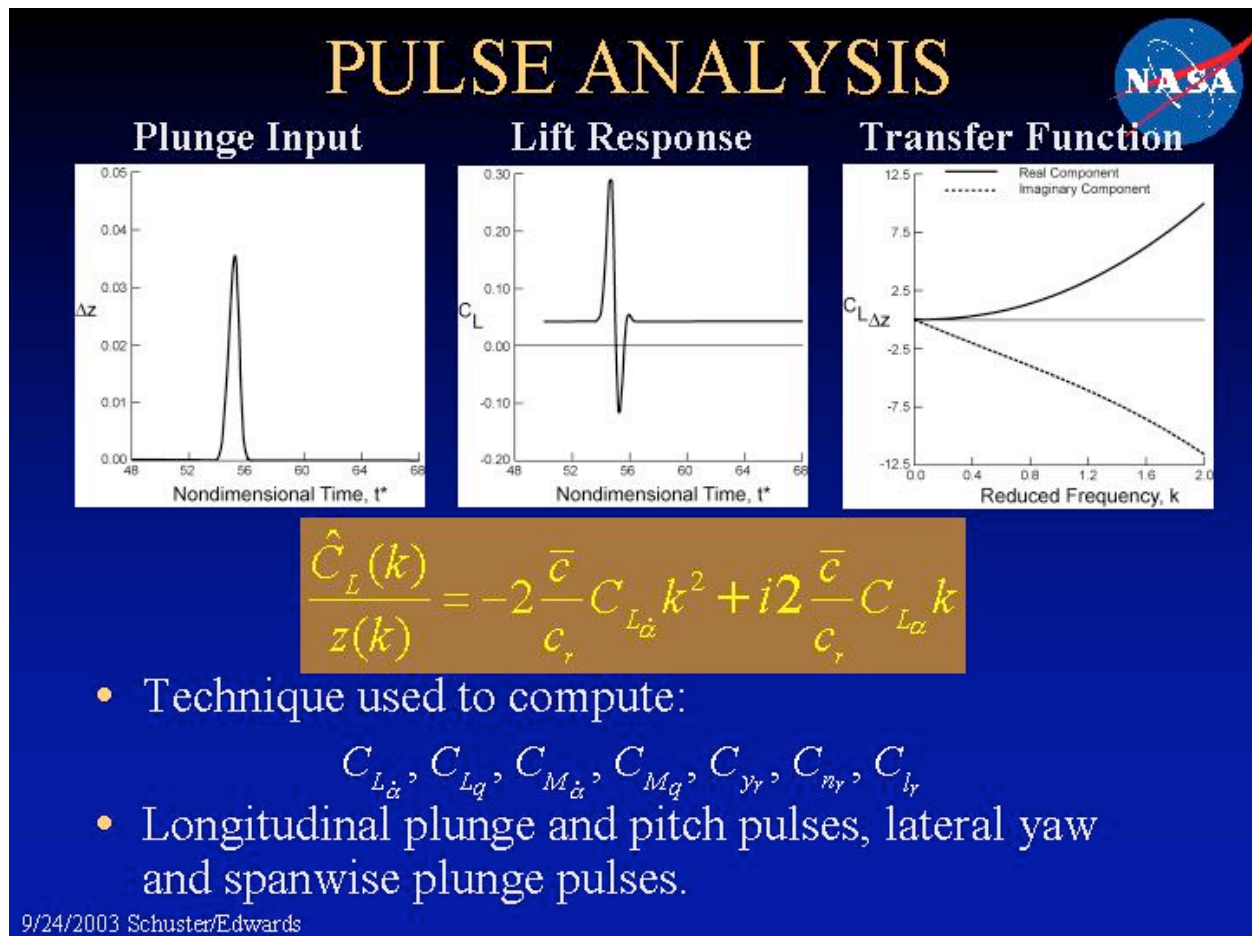Longitudinal and lateral rate derivatives were computed using a pulse analysis. This slide represents a configuration plunge pulse, the lift coefficient response to the pulse, and the transfer function computed from the input and response. The transfer function is derived by dividing the complex Fourier transform of the response by the transform of the input. The character of the transfer function at zero frequency defines the static lift curve slope and the dynamic S&C derivative due to angle-of-attack rate. A pitch pulse of the configuration results in a combined pitch rate and angle-of-attack rate derivative, which in conjunction with the plunge pulse can be used to extract the pitch rate derivative. A similar procedure is used to compute the lateral derivatives due to yaw rate and sideslip rate.

This slide shows the longitudinal and lateral rate derivatives computed by CAP-TSD and compared with results from doublet lattice and DATCOM. While the various method show a general agreement in magnitude and sign between the methods, one is hard-pressed to say the correlation for this case is good. In general, CAP-TSD tends to over predict the magnitude of the rate derivatives, with the exception of pitching moment. There are several modeling assumptions inherent in each of the methods which could have a profound impact on the results, but given the time constraints and objectives of the analysis, it was impossible to investigate these issues. Certainly, further investigation of techniques for computing these derivatives is warranted before widespread acceptance of the methodology can be anticipated.
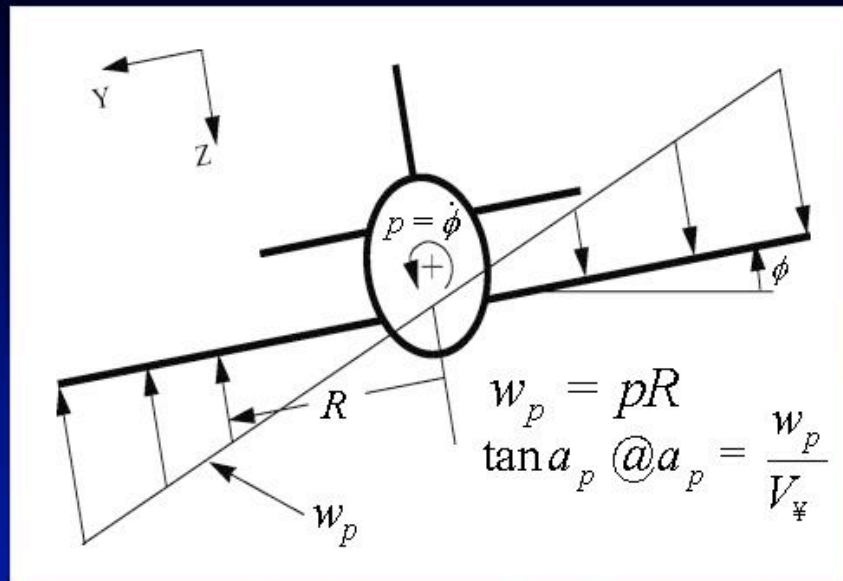
SST Dynamic Derivatives
$M = 0.50$

Derivative	Method		
	CAP-TSD	Doublet Lattice	DATCOM
$C_{L_{\dot{\alpha}}}$	1.080	n/a	0.606
C_{L_q}	4.596	n/a	3.655
$C_{M_{\dot{\alpha}}}$	-0.610	n/a	-0.962
C_{M_q}	-1.193	n/a	-2.354
C_{y_r}	0.952	0.467	n/a
C_{n_r}	-0.688	-0.290	-0.288
C_{l_r}	0.135	0.063	0.056

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Roll rate derivatives were computed using CAP-TSD by modifying the lifting surface boundary conditions used in the code to represent a steady rolling motion of the vehicle. Incorporation of the rolling motion in this manner allows roll rate derivatives to be computed using a steady analysis as opposed to a time-accurate computation.

The roll rate derivatives computed by CAP-TSD using this technique are in much better agreement with doublet lattice and DATCOM than were the previous longitudinal and lateral rate derivatives. The exception being yawing moment due to roll rate, which is a historically-difficult derivative to estimate.

Roll Rate Derivatives
M = 0.50

Derivative	Method		
	CAP-TSD	Doublet Lattice	DATCOM
C_{l_p}	-0.206	-0.232	-0.207
C_{y_p}	-0.032	-0.022	0.014
C_{n_p}	0.025	0.014	-0.002

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Structural flexibility effects were also investigated for the aircraft by adding structural modes to the CAP-TSD model and performing an aeroelastic analysis of the SST configuration. This slide shows the first six structural modes and frequencies included in the aeroelastic analysis.

Lift curve slope, elevator effectiveness and outboard aileron effectiveness as computed by CAP-TSD are compared with balance data on the model acquired in the TDT prior to cable-mount testing. Due to aeroelastic deformations, these derivatives are a function of the dynamic pressure. Since the wind tunnel model is inherently flexible, no rigid data for the model on the balance is available. In general, the magnitude and trends in the data as compared to experiment are very good with the exception of the lift curve slope. CAP-TSD does not compute the wing and horizontal tail carry-over lift across the fuselage making the CAP-TSD lift cure slope lower than that of the experiment. An important feature to note is the loss in elevator and aileron control effectiveness with increasing dynamic pressure predicted by the theory and supported by the experimental data. Both the theory and experiment indicate an elevator reversal for this aircraft at a dynamic pressure between 20 and 30 psf.

Effect of Flexibility on Stability Derivatives, M = 0.50

Derivative	Data Source	Rigid	Dynamic Pressure (psf)		
			20	30	40
C_{L_α}	CAP-TSD	2.590	2.060	1.930	1.810
	Experiment	n/a	2.430	2.270	2.300
$C_{L_{\delta_H}}$	CAP-TSD	0.330	0.079	-0.009	-0.080
	Experiment	n/a	0.077	-0.006	-0.130
$C_{l_{\delta_A}}$	CAP-TSD	0.046	0.024	0.019	0.016
	Experiment	n/a	0.030	0.028	0.025

- CAP-TSD calculates no fuselage or wing carry-over lift.
  - Accounts for discrepancy in lift curve slope due to angle of attack.

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In summary, this analysis represents a pure application of the available methodology with minimal opportunity to effectively research the methods employed or the results obtained. All of the data were used to establish bounds for the input data to the GRUMCBL cable-mount stability program to determine cable positioning and tensions for the free-flying test. There is considerable scatter in the derivatives produced by the various methods, particularly for the longitudinal and lateral dynamic derivatives. Structural flexibility was a significant player in this analysis, and both CAP-TSD and the experimental data indicated an elevator reversal at a relatively low dynamic pressure.
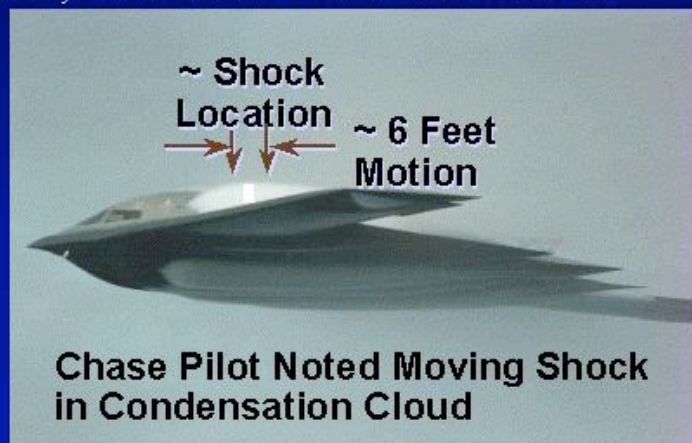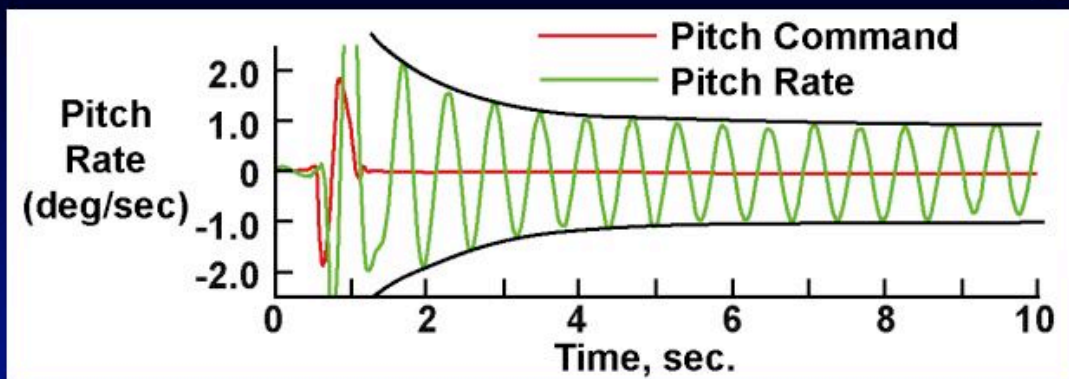
B-2 Residual Pitch Oscillation

- CAP-TSDV modified to investigate problem.
  - Rigid body short period dynamics and trim added.
  - Flight control simulation added.
- Accurately modeled the heavyweight RPO event, but the lightweight event was not as accurately predicted.
- Reported in AIAA–98-1805, "Residual Pitch Oscillation (RPO) Flight Test and Analysis on the B-2 Bomber" and NASA/CP-199-209136 "Simulation of Non-Linear Transonic Aeroelastic Behavior on the B-2"

~ Shock Location ~ 6 Feet Motion

Chase Pilot Noted Moving Shock in Condensation Cloud

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Typical RPO Event

- Pitch command doublet results in an oscillatory pitch response that decays over time to a Limit Cycle Oscillation (LCO).

- Event involves shock motion and separated flow at transonic flight conditions, rigid body DOF, structural flexibility and nonlinear flight control system (servo-valve hysteresis).

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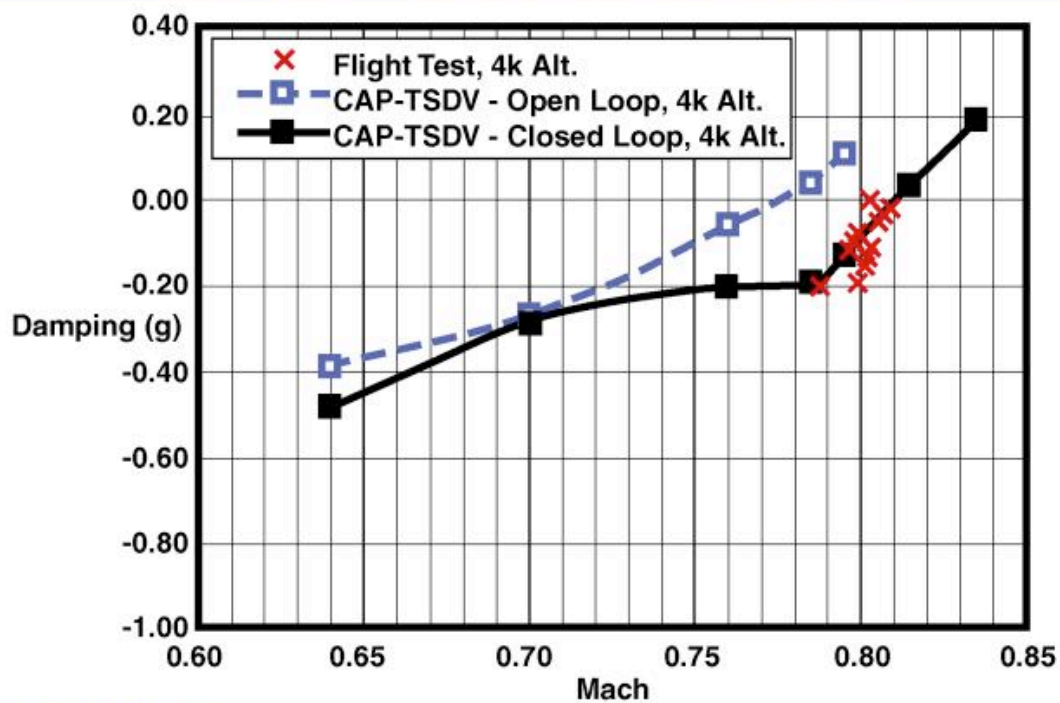
CAP-TSDV B-2 RPO Analysis

Longitudinal Control Layout

Flight Article   CAP-TSDV Model

Split Drag Rudder   Elevons   GLAS
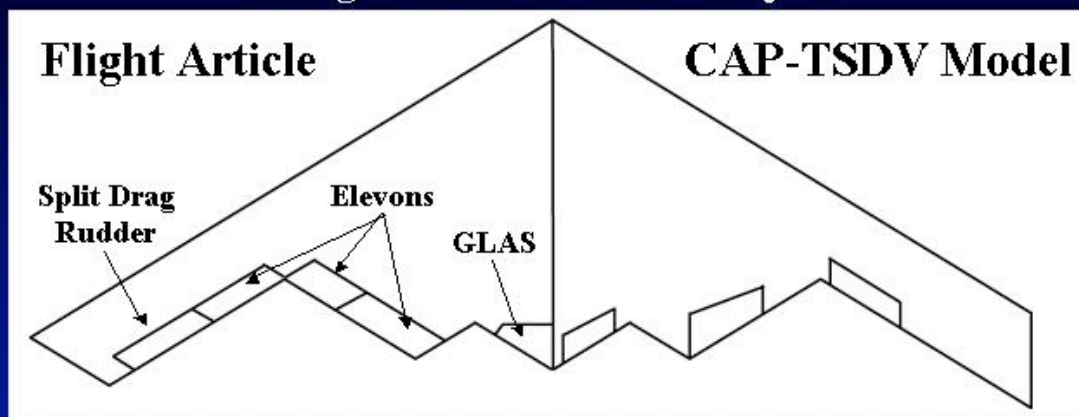
- Gust Load Alleviation System (GLAS), inboard elevon and outboard elevon primary control surfaces attempting to control the RPO during flight.
- CAP-TSD modeling restrictions impact the modeling of these control surfaces as well as the wing tip.

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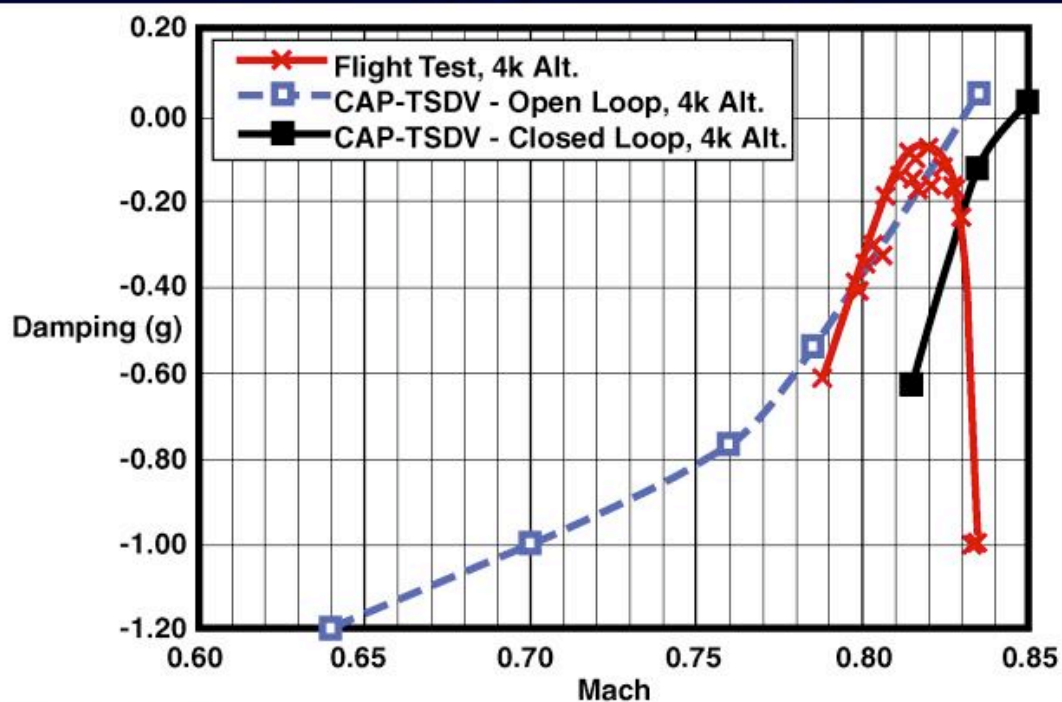
B-2 RPO Summary

- Probably the most comprehensive analysis of a modern flight vehicle ever attempted.
    - Transonic, separated flows.
    - Rigid body motion, structural flexibility and vehicle mass effects included in the analysis.
    - Nonlinear flight control system integrated with hysteresis.
    - CAP-TSDV in complete longitudinal control of the vehicle during the analysis.
- Prediction of the heavy weight RPO is very encouraging, but improved transonic/separated flow analysis required to accurately predict the light weight RPO events.

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