Numerical Computations of Dynamic Pitch-Damping Derivatives using Time-Accurate CFD Techniques

TECHNOLOGY DRIVEN. WARFIGHTER FOCUSED.

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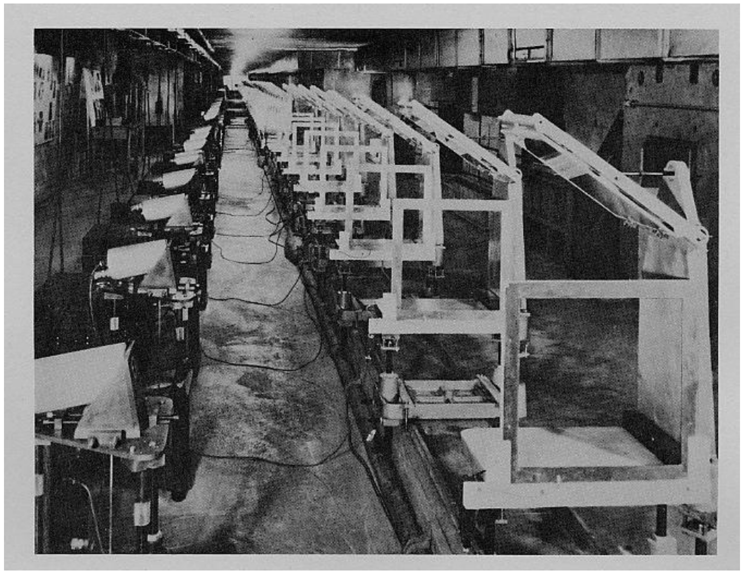
Projectile Aerodynamics

- Wind Tunnel testing
- Actual flight testing
  - Experimental facilities (Aero Range, Transonic Range)
  - Measure the positions and orientations; get Aero from 6-DOF fits
- Empirical codes (AP, DATCOM, PRODAS etc.)
- Computational Fluid Dynamics (CFD)
  - Steady-State Aerodynamics
  - Unsteady Aerodynamics for Magnus, Roll Damping, Pitch Damping using unsteady rolling and imposed pitching motions (Virtual Wind-Tunnel Method)
- CFD and 6-DOF Rigid Body Dynamics Coupling for "Virtual Fly-Outs"
  - Simulate actual free flight (integrated unsteady aero/flight dynamics)
  - Extraction of aerodynamic coefficients (both static and dynamic) from virtual fly-outs
  - Easily extended for computation of dynamic pitch damping moment coefficient using imposed pitching motion– a special case of the virtual fly-out procedure
  - Roll damping and Magnus moment coefficients also are obtained from time-accurate computations of rolling motion, inherently an integral part of the virtual fly-out method

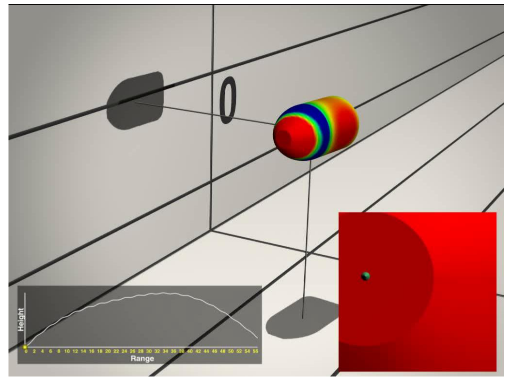
f HPC in the Development of the
tal Virtual Aerodynamic Range

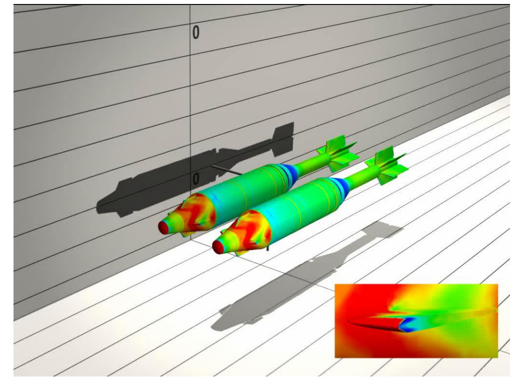
Aerodynamics Experimental Facility



- Measures projectile orientation and position only
  - Pitch, Roll, Yaw
  - X, Y, Z
  - 6DOF fit of range data
  - Limited visualization at a few stations
  - Aerodynamic coefficients determined
  - Characterize observed flight dynamics

Digital Virtual Aerodynamic Range





- Computes entire projectile state
  - Pitch, Roll, Yaw
  - X, Y, Z
  - Linear velocities
  - Pitch, Roll, and Yaw Rates
  - Unlimited flow visualization
  - Integrated Aerodynamics and Flight Dynamics
  - Predictive capability for new geometries
  - Outputs wake and pressure contours

...tidisciplinary Computational Technique

CFD Computational Technique

- 3-D Unsteady Navier-Stokes equations
- Higher order turbulence modeling including hybrid RANS/LES
- Dual Time-Stepping for transient flow computations
  - Two time-steps
  - First (outer) global or physical step –usually set to 1/100th of the period of oscillation
  - Second (inner) step – 5 to 10 inner iterations
- Grid Motion and BC:
  - Grid moves and rotates as the projectile moves and rotates
  - Free stream is preserved for arbitrary mesh and arbitrary mesh velocity

CFD/RBD COUPLING PROCEDURE

- 6-DOF equations solved at every CFD time-step
- CFD provides aerodynamic forces and moments
- 6-DOF provides the response of the body to the forces and moments
- The response is converted to translational and rotational accelerations
- Integrate the accelerations to obtain translational and rotational velocities
- Integrate once more to obtain linear position and angular orientations
- 6-DOF uses quaternions to define angular orientations
- From the dynamic response, grid point locations and velocities are set

e-Accurate CFD Procedures

Complete Virtual Fly-Out Procedure

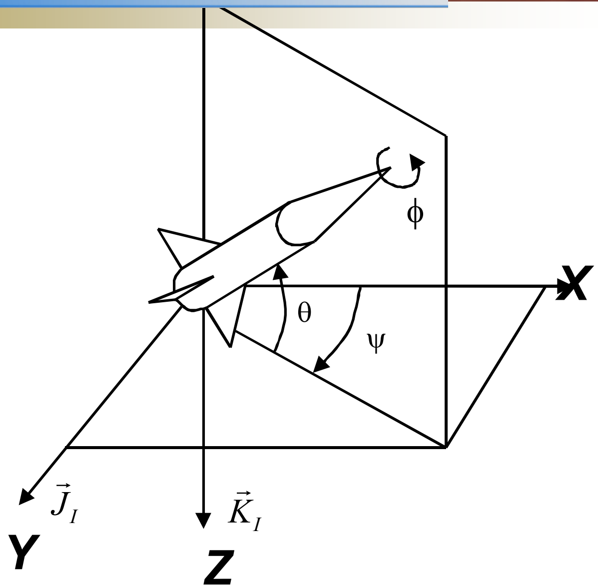
- STEP 1:
  - "Steady-state" mode
  - Grid velocities account only for translational motion
  - Initial conditions also include the angular orientations
- STEP 2:
  - "Uncoupled" mode (Kinematics)
  - Add rotational component in X (spin, p)
  - Compute for a few spin cycles until solution converges
- STEP 3:
  - "Coupled mode"
  - Add the other rotational components (q and r)
  - Full dynamic calculations

Time-Accurate CFD Procedure for Dynamic Derivatives

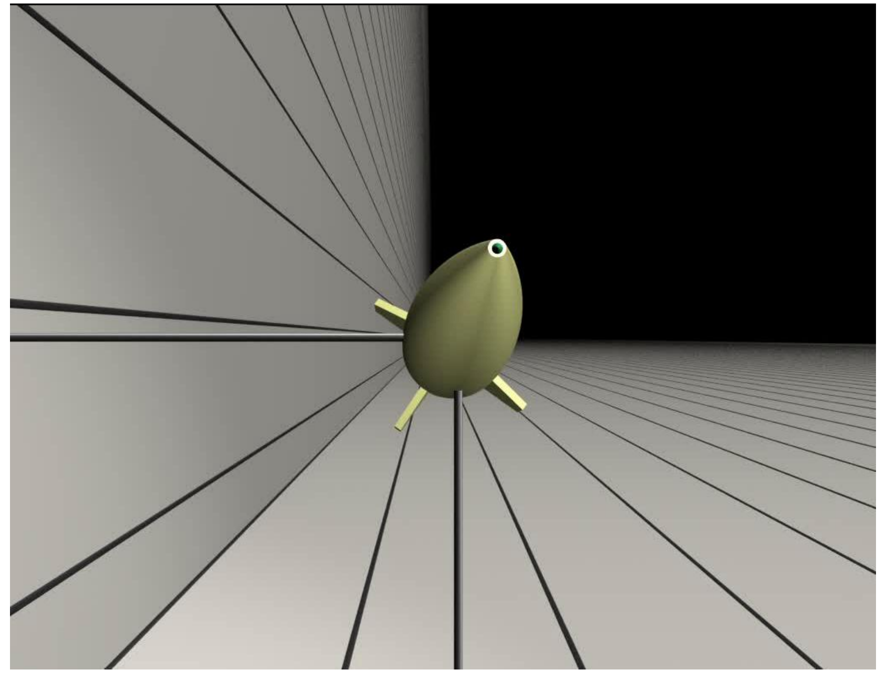
- STEP 1:
  - "Steady-state" mode
  - No translation motion
- STEP 2:
  - "Uncoupled" mode (Rolling Motion)
  - Add rotational component (spin, p)
  - Compute for a few spin cycles until solution converges
- STEP 2:
  - "Uncoupled" mode (Pitching Motion)
  - Add the other rotational component (q) i.e. impose pitching motion
  - Pitching motion can be sinusoidal

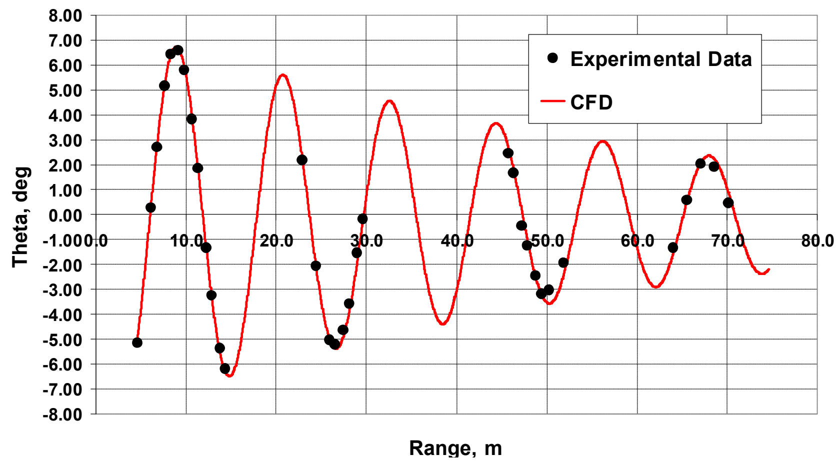
...al Fly-out of a Finned Projectile

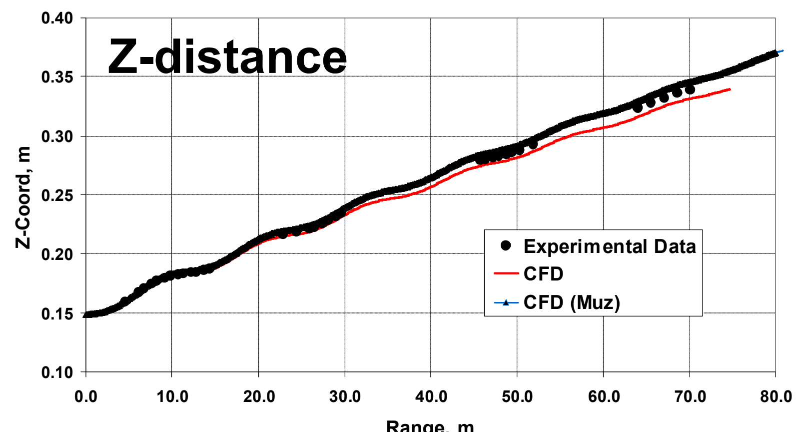
...al Velocity, Mach = 3 (Supersonic)



6-DOF system

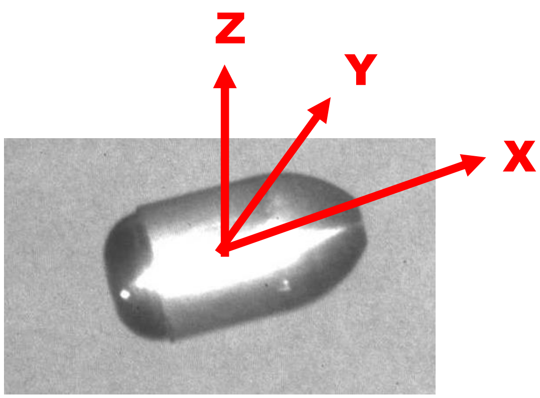


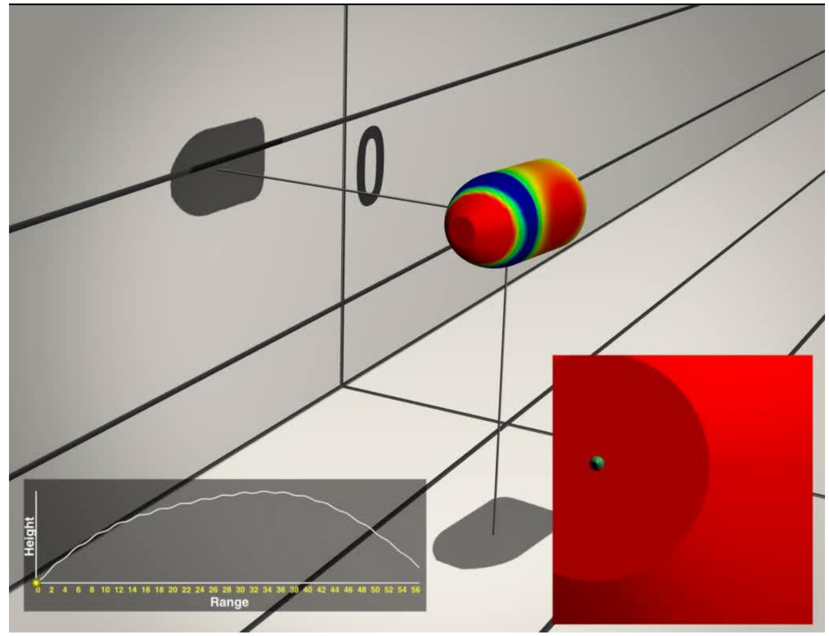


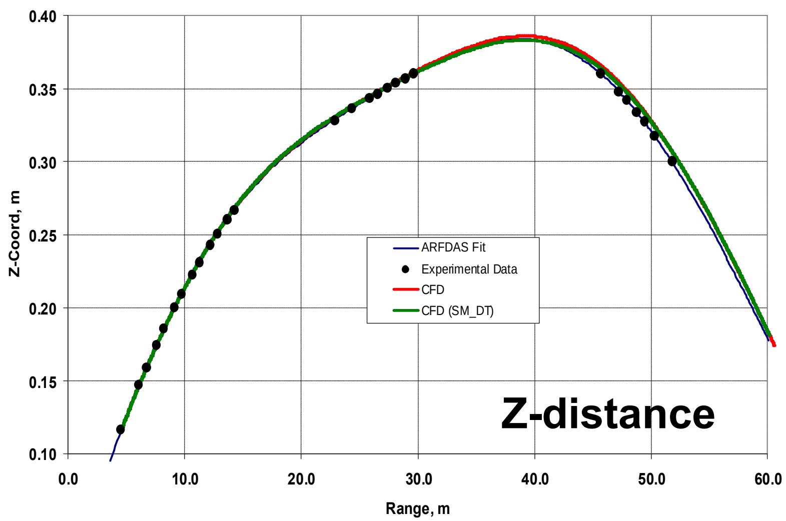


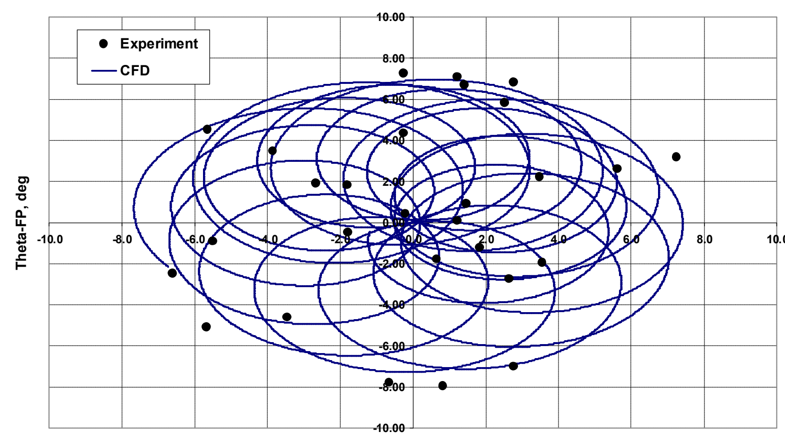
Computed positions and orientations (Euler angles) of the projectile match very well with the data measured in actual free flight tests.

other Example: Spinning Projectile
itial Mach = 0.4 (Subsonic Flight)



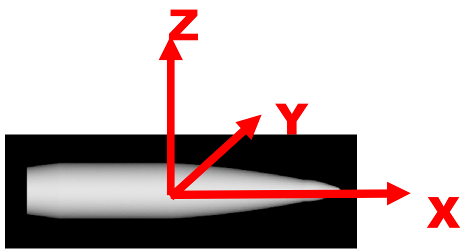


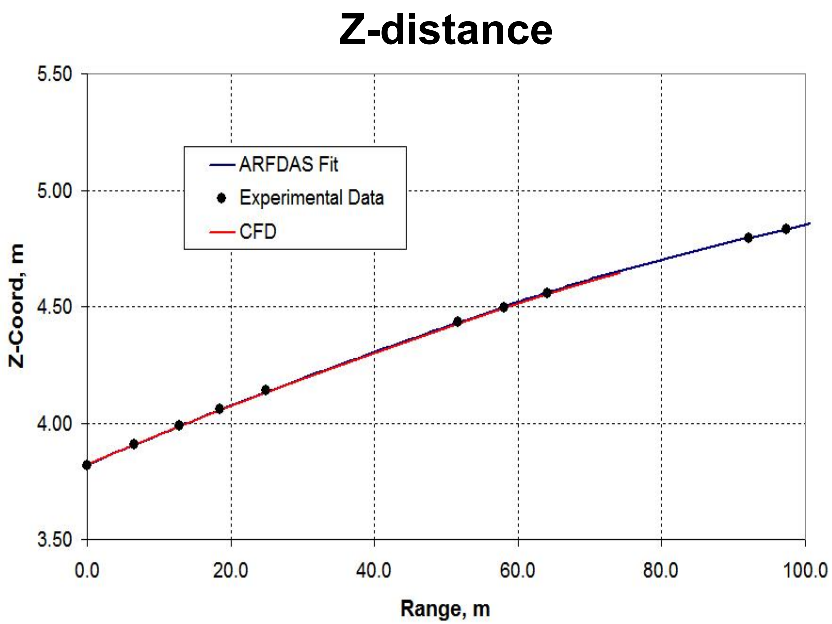


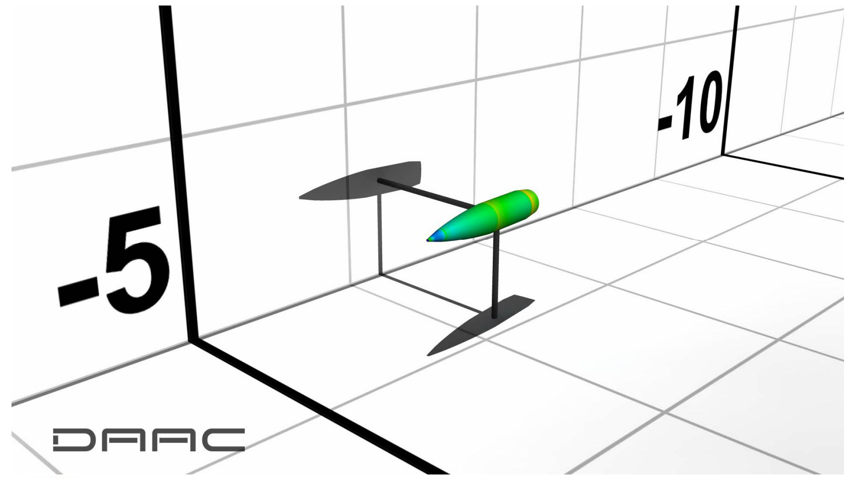


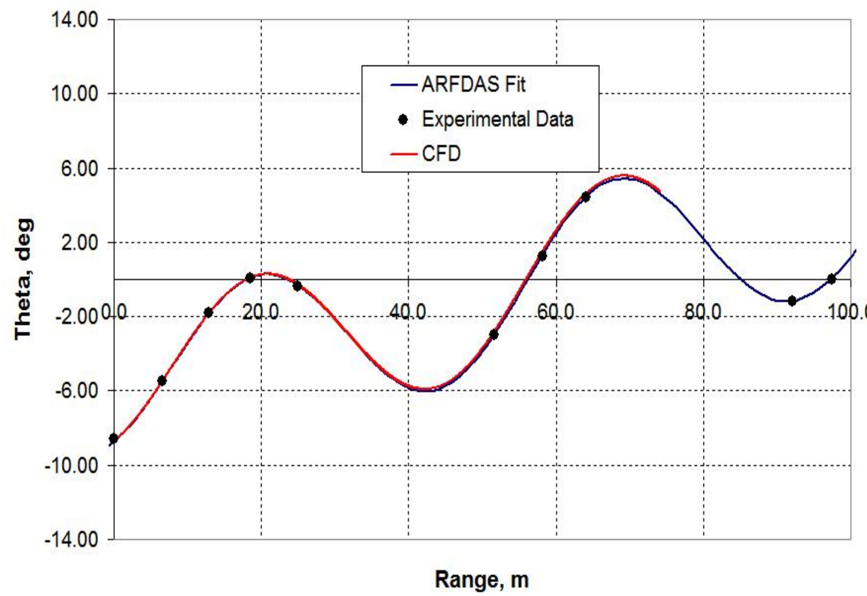
Virtual fly-out technique computes the trajectory of an in-flight spinning projectile; computed results match well with the flight test data

ual Fly-Out of a Spinning Projectile
itial Mach = 1.1 (Transonic Flight)



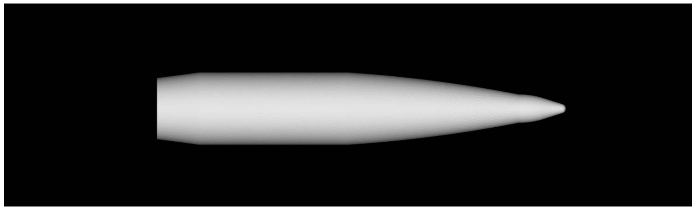






Virtual fly-out technique computes the trajectory of an in-flight spinning projectile; computed results match well with the flight test data.

Extraction of Aerodynamic Coefficients from Virtual Fly-Out Simulations



Spinning Projectile

Pitch-Damping Moment Coeff.

Virtual fly-outs simulations require only the total aerodynamic forces and moments to fly the projectile.

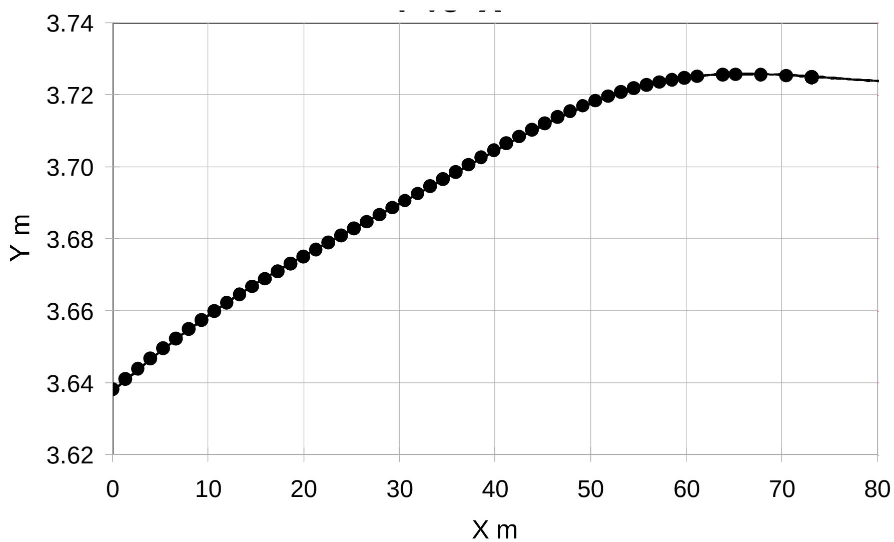
How do we extract the aerodynamic force and moment coefficients from the virtual fly-out simulations? How good are they?

Different Approaches:

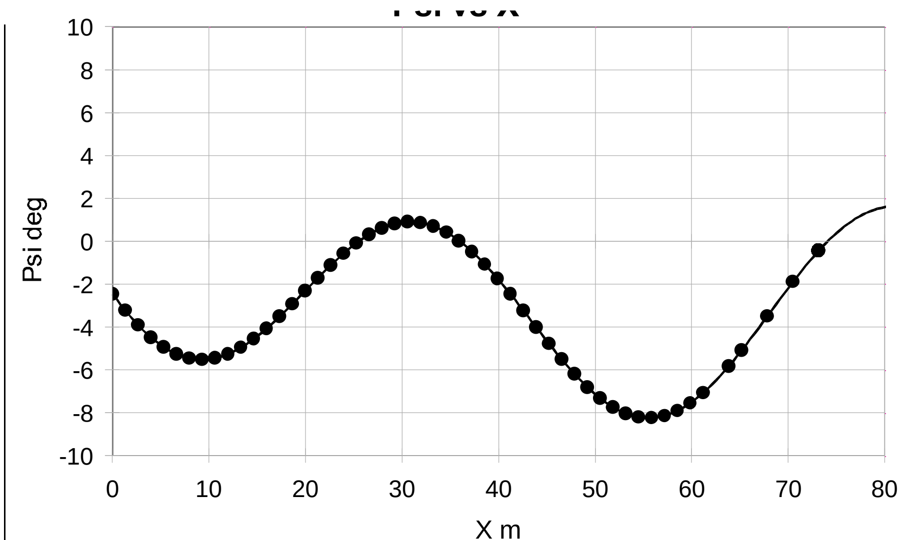
1. Aerodynamic coefficients extracted from CFD/RBD virtual fly-out solutions using range reduction software (ARFDAS, for example).
2. PACE - Simple fitting procedure that require a set of short time-histories (virtual fly-outs) at different Mach numbers.

RFDAS Fit of CFD Generated data Initial M = 1.1

1. Aerodynamic coefficients extracted from CFD using range reduction software, ARFDAS using the virtual fly-out solutions
2. Position (x,y,z) and the orientation (three Euler angles) of the projectile, obtained from the virtual fly-out simulations were provided as input to ARFDAS. ***Same procedure is used for actual flight measured data.***



Y-distance



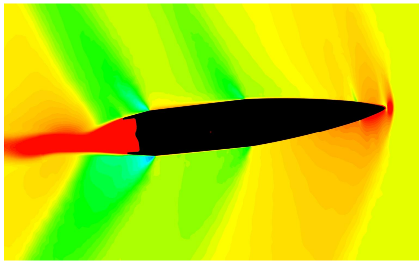
Euler roll angle

Extracted force and moment coefficients (static and dynamic) from virtual fly-out simulation

Data Source	Zero-Yaw Axial Force Coeff., C_{D_0}	Normal Force Coeff. Deriv., C_{N_α}	Pitching Moment Coeff. Deriv, C_{m_α}	Pitch Damping Moment Coeff., Cm_q	Magnus moment Coeff. Deriv., C_{np_α}	Roll Damping Moment Coeff., C_{lp}
Spark Range	0.359	2.081	4.209	-25.3	1.05	-0.019
CFD	0.335	2.362	4.283	-22.9	0.93	-0.019

Aerodynamic coefficients extracted from the virtual fly-out method matches very well with those obtained from free flight tests.

Validate using separate unsteady CFD (Virtual wind tunnel method)



Pitch Damping Moment

$$Pitch\ Damping\ Moment = \frac{1}{2}\rho V^2 S\ d\left(\frac{q\,d}{2V}\right)(C_{m_q} + C_{m_{\dot\alpha}})$$

Pitching motion imposed:

$$\alpha = \alpha_m + \alpha_0 \sin(\omega t)$$

Here,

C_{m_q} = pitch damping moment coefficient due to q

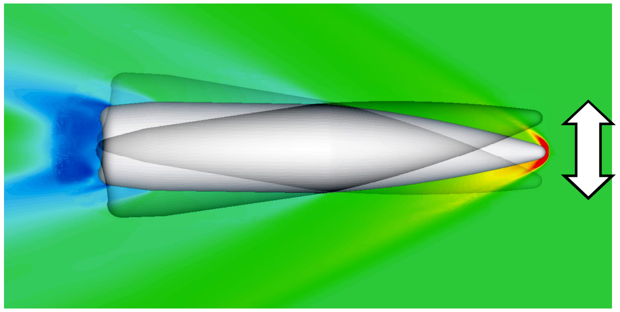
$C_{m_{\dot\alpha}}$ = pitch damping moment coefficient due to $\dot\alpha$

α = instantaneous angle of attack

α_m = mean angle of attack

α_0 = pitch amplitude

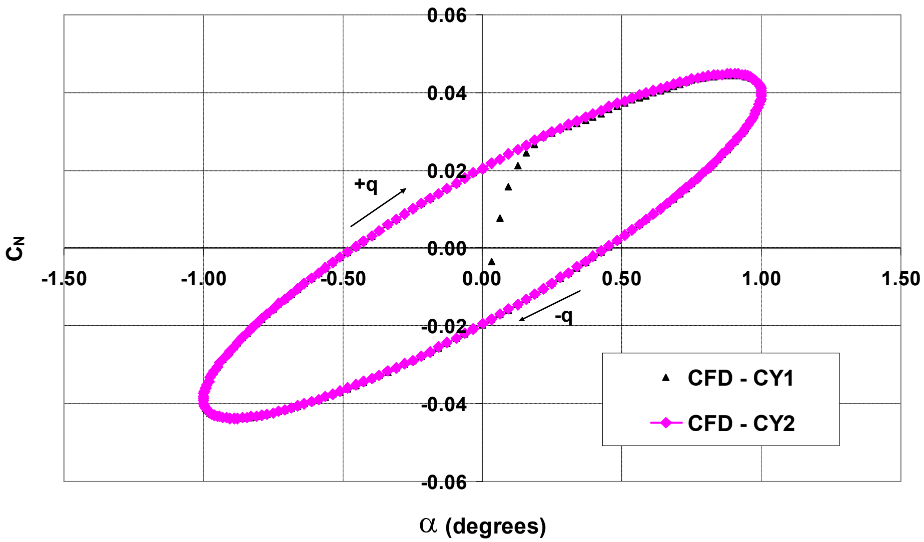
ω = pitch frequency, related to reduced frequency ($k = qd/2V$)



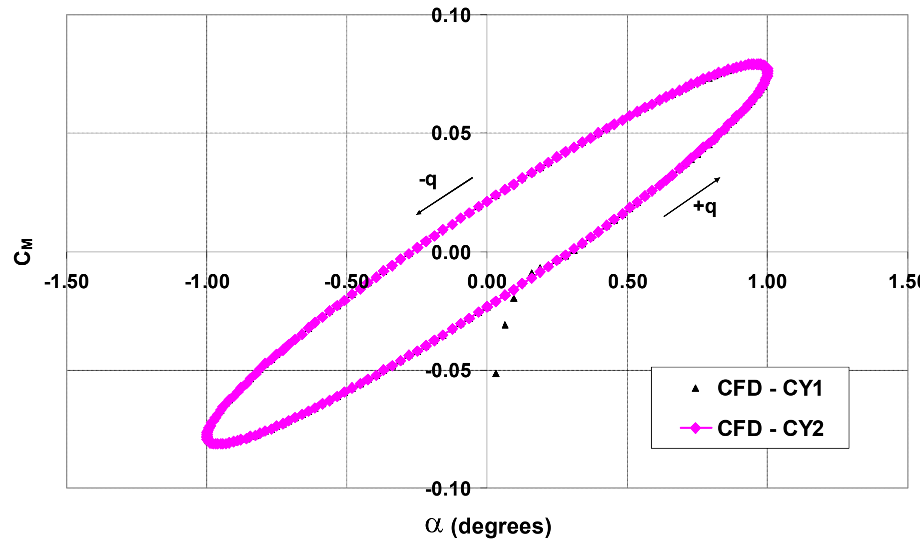
Virtual wind tunnel method (Imposed pitching motion)

-Histories of Normal Force and itching Moment coefficients

Mach = 1.1
α_0 = 1.0, k = 0.1



Normal force



Pitching moment

Pitch damping moment is obtained directly from the time-history plot of the pitching moment coefficient resulting from the imposed pitching motion.

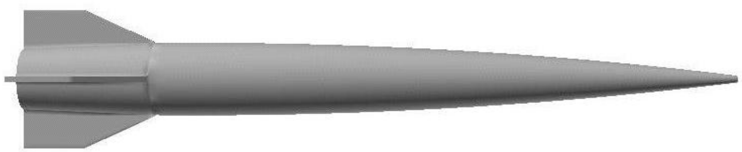
...tracted force and moment ...efficients from virtual fly-out

Data Source	Zero-Yaw Axial Force Coeff., C_{D_0}	Normal Force Coeff. Deriv., C_{N_α}	Pitching Moment Coeff. Deriv, C_{m_α}	Pitch Damping Moment Coeff., Cm_q	Magnus moment Coeff. Deriv., C_{np_α}	Roll Damping Moment Coeff., C_{lp}
Spark Range	0.359	2.081	4.209	-25.3	1.05	-0.019
CFD	0.335	2.362	4.283	-22.9	0.93	-0.019

Pitch damping moment extracted from the virtual fly-out method matches very well with that obtained by a separate unsteady CFD approach with prescribed pitching motion.

Computed C_{Mq}= -24.0 using virtual wind-tunnel approach

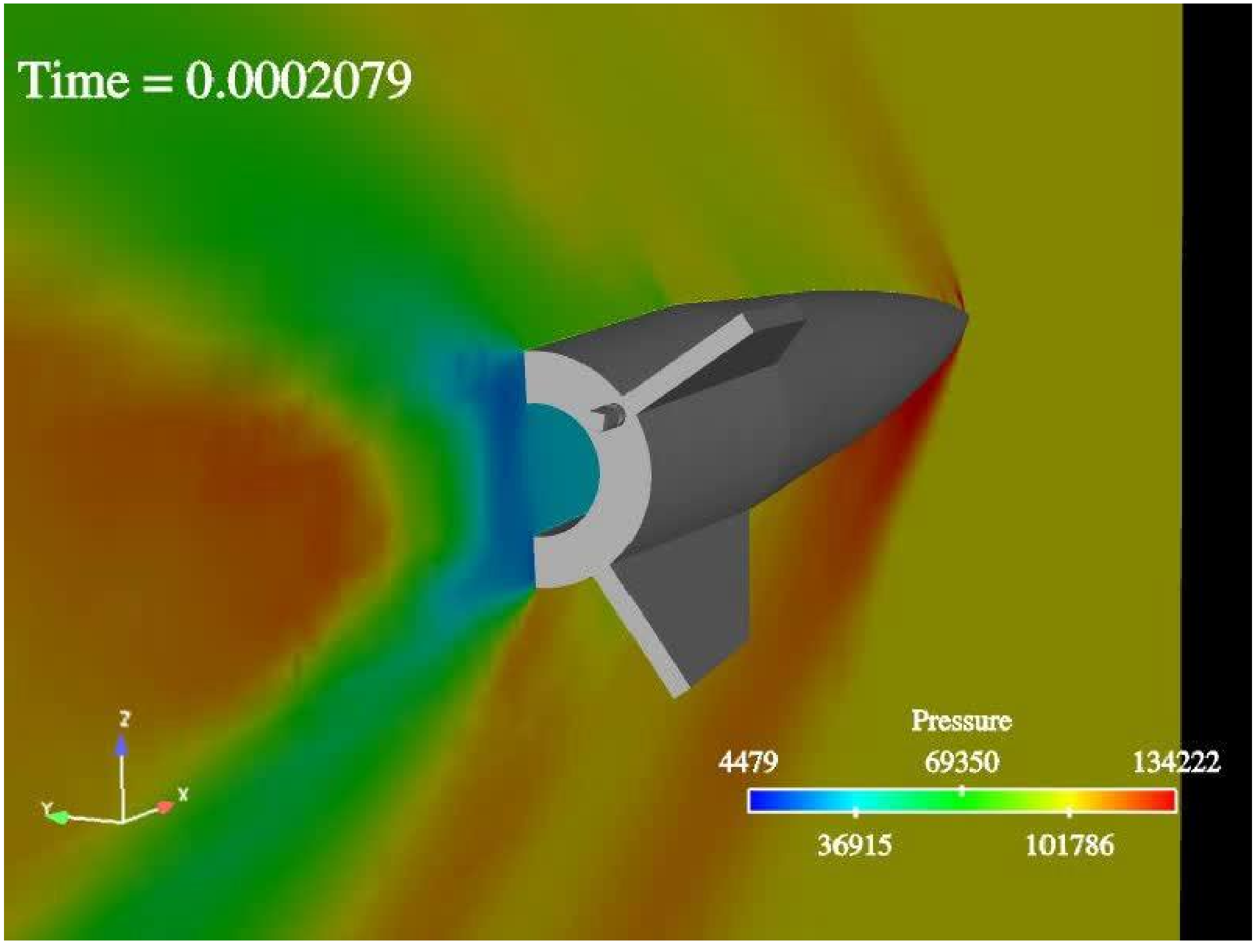
Extraction of Aerodynamic Coefficients from Virtual Fly-Out Simulations



Finned Projectile

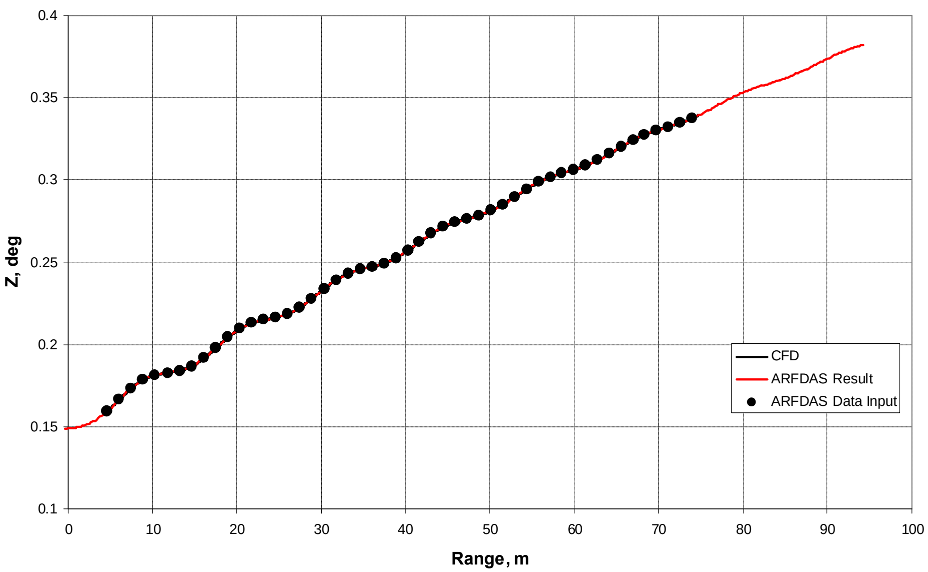
...al Fly-out of a Finned Projectile

...al Velocity, Mach = 3 (Supersonic)

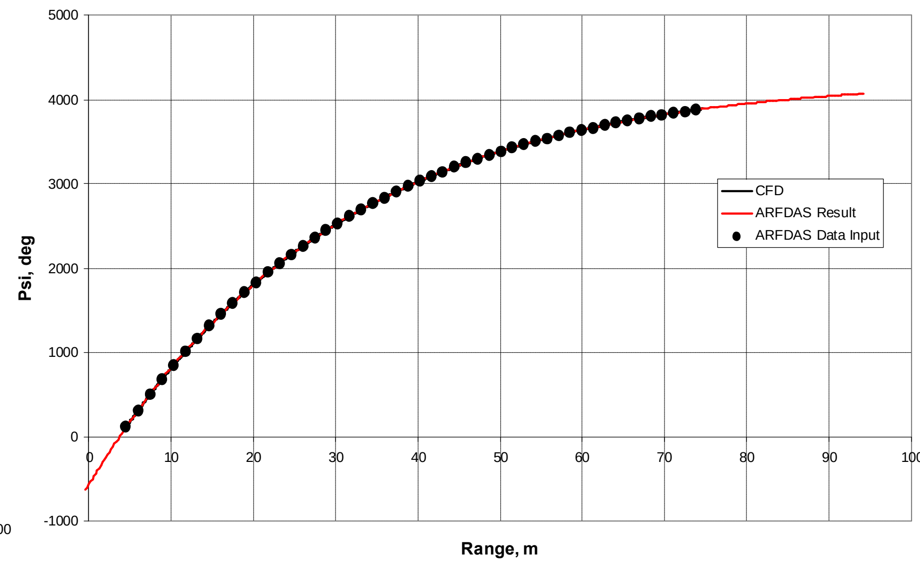


RFDAS Fit of CFD Generated data Initial M = 3.0

1. Aerodynamic coefficients extracted from CFD using range reduction software, ARFDAS using the virtual fly-out solutions
2. Position (x,y,z) and the orientation (three Euler angles) of the projectile, obtained from the virtual fly-out simulations, were provided as input to ARFDAS. ***Same procedure is used for actual flight measured data.***



Z-distance



Euler roll angle

Extracted Aerodynamic Coefficients from Virtual Fly-Out Simulation

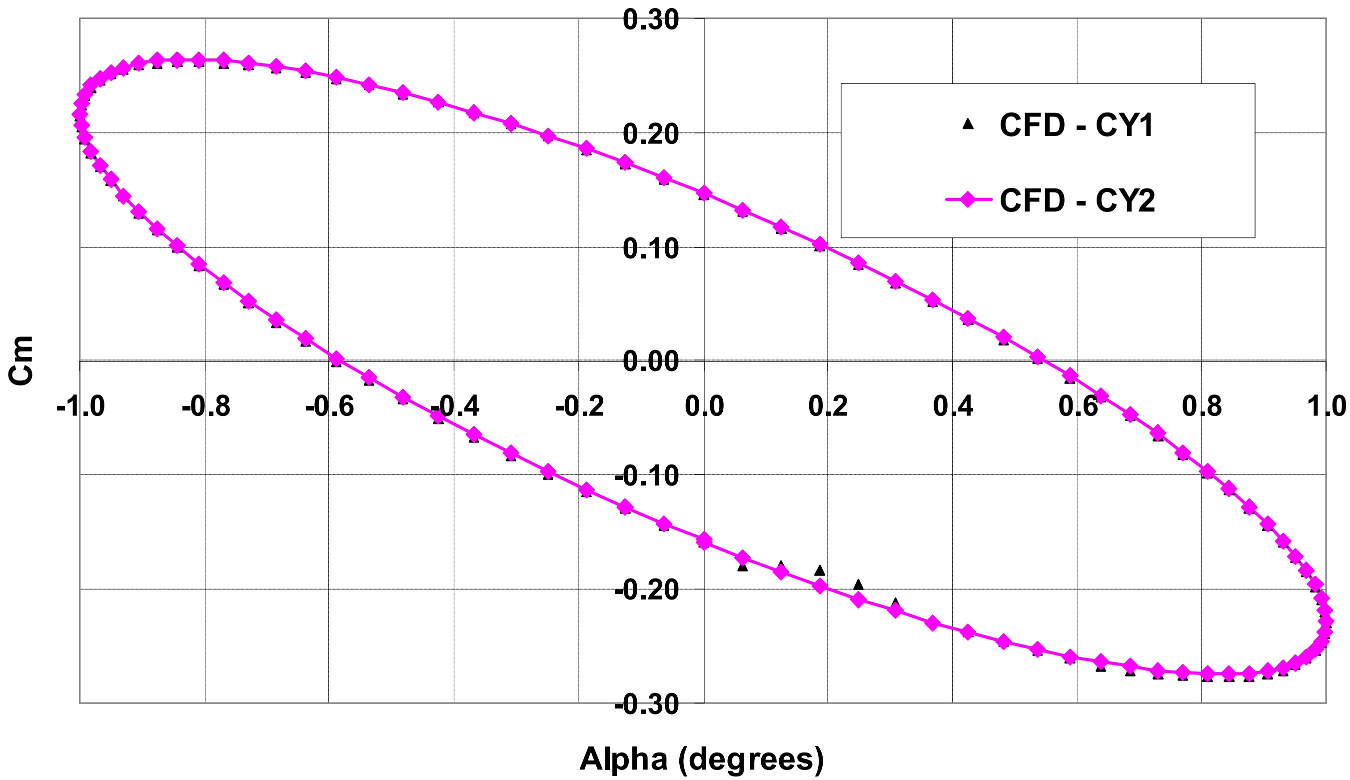
Data Source	Mach No.	CXo	CNa	Cma	Cmq	Clp
Spark Range	3.0	0.221	5.83	-12.60	-196	-2.71
CFD	3.0	0.253	5.88	-12.46	-172	-3.24

Pitch-Damping Moment Coefficient

...e-history of the Pitching Moment with Angle of Attack

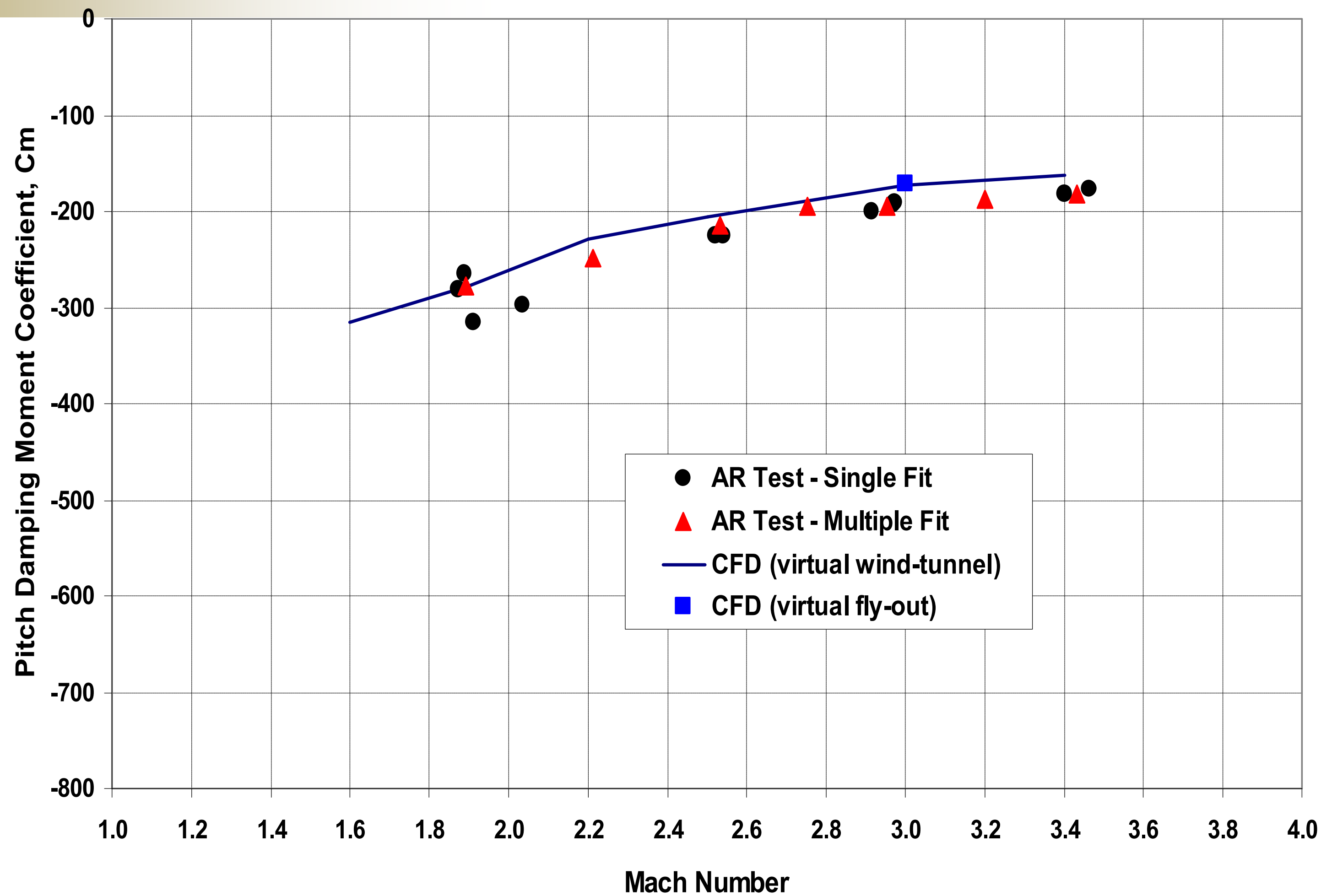
Mach = 3.0

Virtual Wind Tunnel Method



Pitch damping moment is obtained directly from the time-history plot of the pitching moment coefficient resulting from the imposed pitching motion.

omputed Pitch-Damping Moment icient as a function of Mach number



- Computed pitch-damping moment coefficients match fairly well with the data obtained from free flight tests.
- Almost identical prediction by both virtual fly-out and virtual wind-tunnel techniques.

Concluding Remarks

- Multidisciplinary CFD/Rigid Body Dynamics Coupling for Virtual Fly-Outs
  - Integrated unsteady aerodynamics and flight dynamics
  - All aerodynamic coefficients (static and dynamic) can be easily extracted from the same virtual fly-out solution
  - Technique easily reduces to the virtual wind tunnel approach for computation of dynamic pitch damping derivatives
- Aerodynamic coefficients extracted (both static and dynamic) match fairly well with the data obtained from free flight tests
- Both virtual fly-out and virtual wind-tunnel methods essentially predict the same dynamic pitch damping moment coefficients