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Free-Flight Motion Analysis Based on Shock-Tunnel Experiments

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Outline of the Study

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Objective

To prove the relevance of aerodynamic coefficients extraction based on ultra-short trajectories (10 to 20 cm) observed in shock-tunnels.

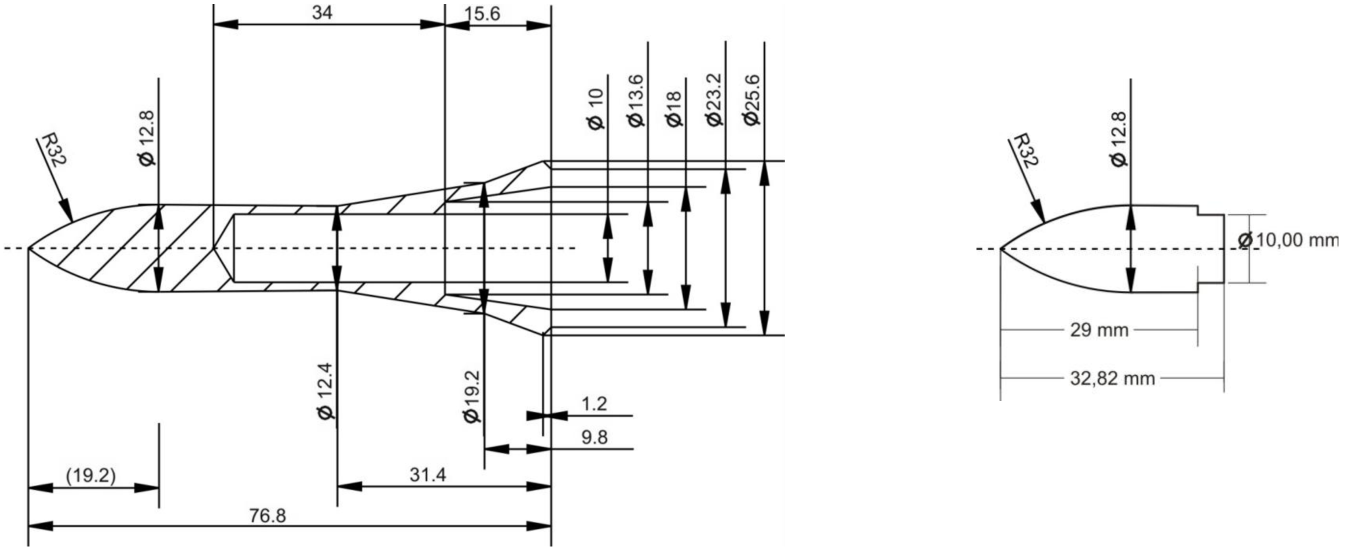
Means and Techniques

- Reference model (EFP)
- Shock-tunnel facility (supersonic regime)
- Flow measurement (velocity, pressure)
- Optical set-up (motion visualization and recording)
- Image processing (trajectory tracking)
- Data extraction (model-based fit process)

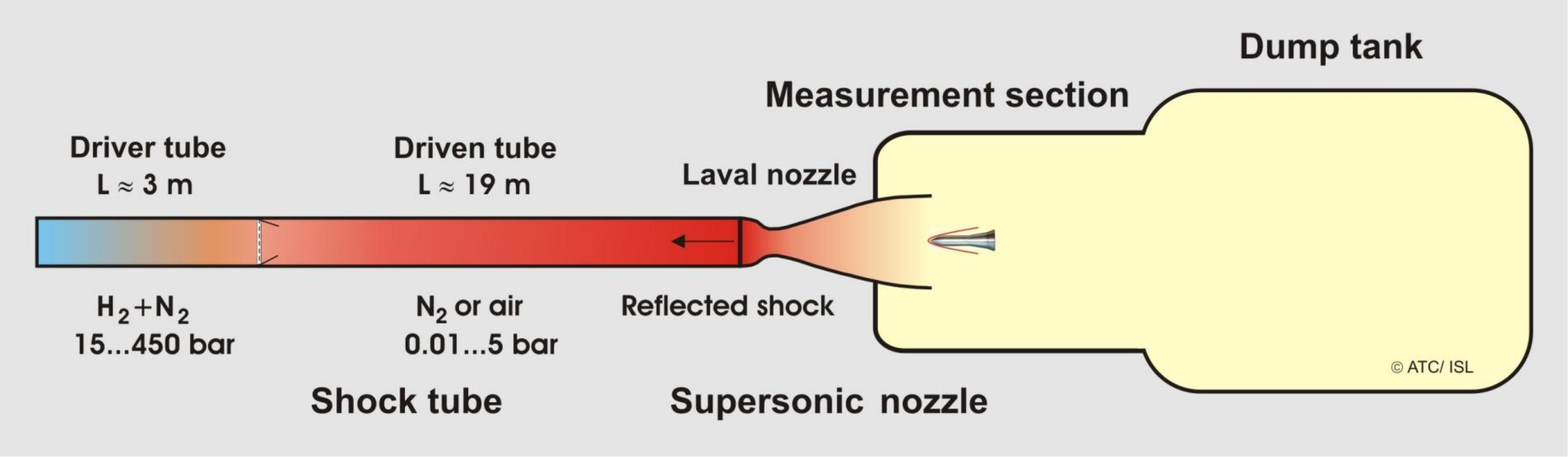
} **Free-flight Force Measuring (FFM) Technique**

Reference Model

- 12.8 mm caliber Explosively Formed Projectile (EFP)
- Stable in supersonic regime, small size of full scale model, simplicity of manufacturing
- Full aerodynamic data from Mach 3.2 to Mach 5.5 defined using free-flight analyses, wind-tunnel measurements and CFD results (references: ARL 1998, ISL 1999)
- Three models: 1- steel, 2- steel body + tungsten nose, 3- Dural



ISL Shock-Tunnel Facility

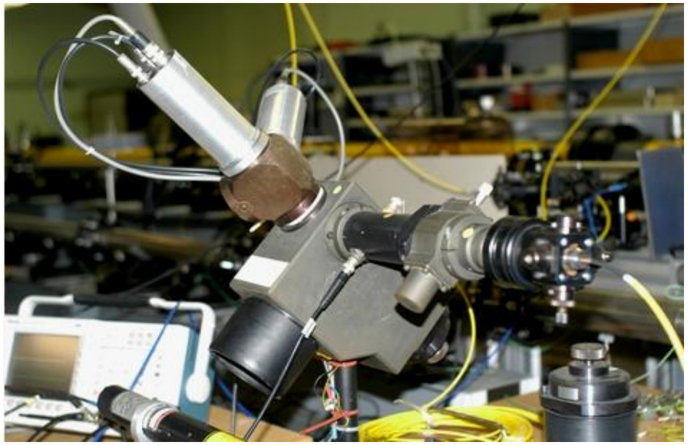


- STA and STB shock tunnels
- Nozzle Mach numbers: 3 to 14
- Nozzle exit diameters: 130 to 400 mm
- Stationary flow conditions: 2 to 4 ms
- Constant Mach number: 15 ms

Measuring the Flow Conditions

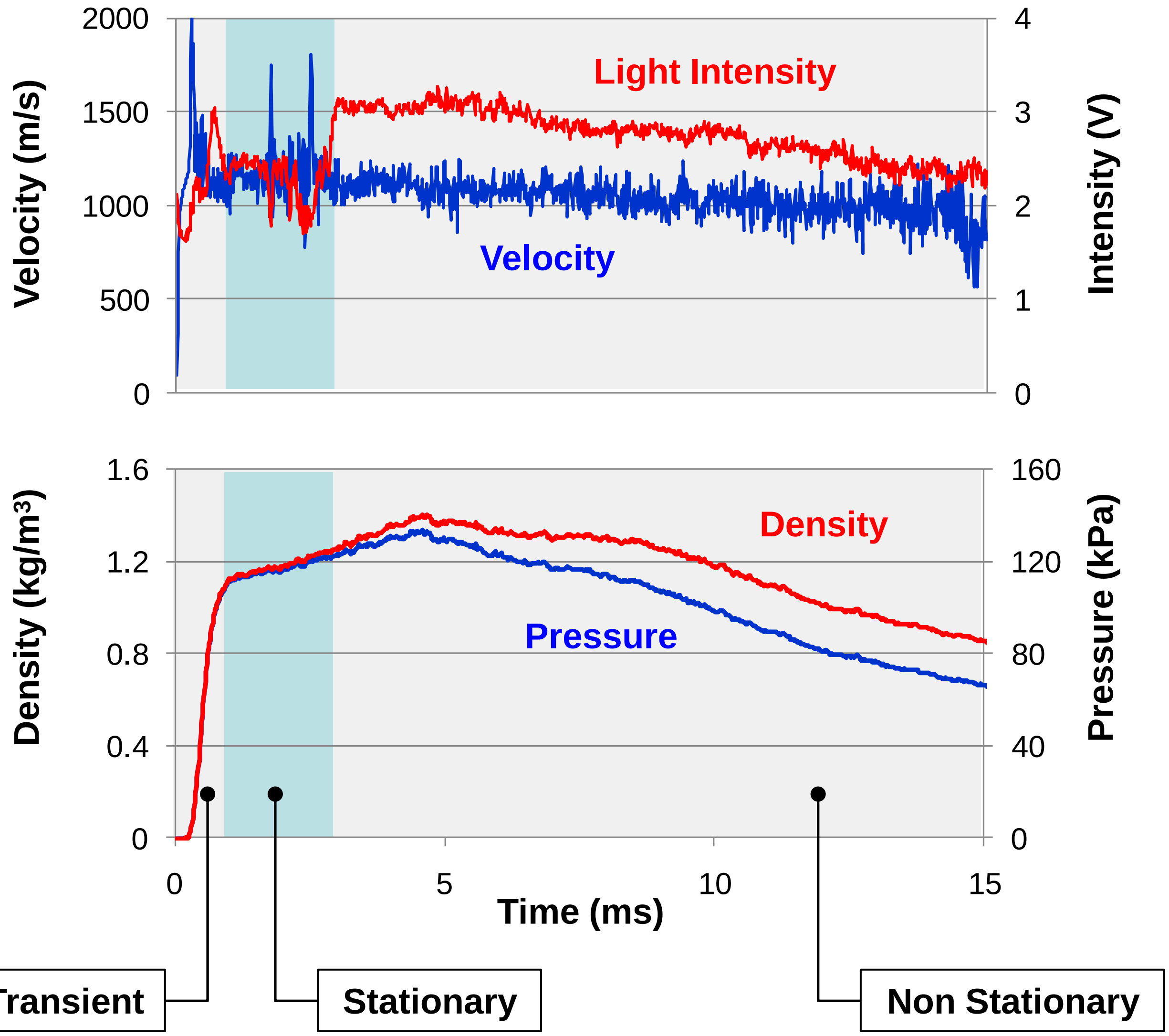
- The flow Mach number is constant during 15 ms until the gas driver arrives to nozzle
  - → the aerodynamic coefficients are fixed during the testing time
- The flow velocity and pressure are to be recorded because the flow conditions are not stationary
  - → time history of the dynamic pressure: $\frac{1}{2}\rho(t)\,u^2(t)$

<u>ISL Laser Doppler Velocimeter</u>



<u>Wall pressure gauge</u>

Flow Measurements at Mach 3



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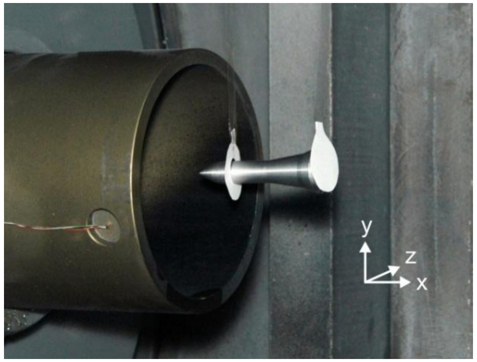
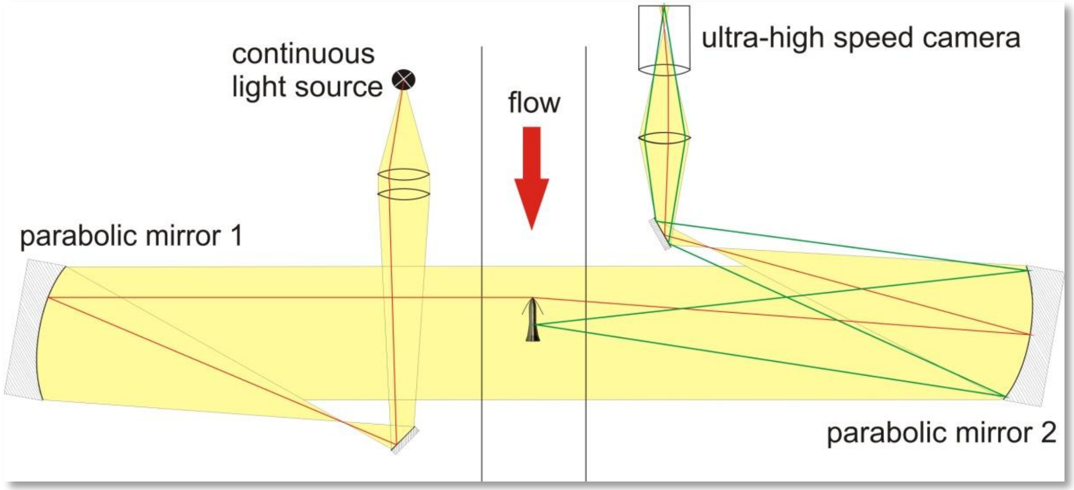
Optical Set-up



Two cameras are used to visualize the motion of the model in the horizontal and vertical planes.



Compared to a standard shadowgraph set-up, the image of the object is sharply focused onto the camera using parabolic mirrors to improve the motion visualization.

Observation Sequences

Videos and pictures are taken with two ultra-high speed Photron cameras to observe the model displacements in the vertical and horizontal planes.

- 12500 frames per second: time interval 80 µs
- Time exposure: 1 µs (no motion blur)

EFP Model #1 at Mach 3, Vertical plane, AOA = 0°

Duration = 10. 72 ms, Displacement = 13.60 cm

Testing Section Limit

The testing section is limited by the Mach cone generated by the Laval nozzle. The section size increases with the nozzle exit size and the Mach number.

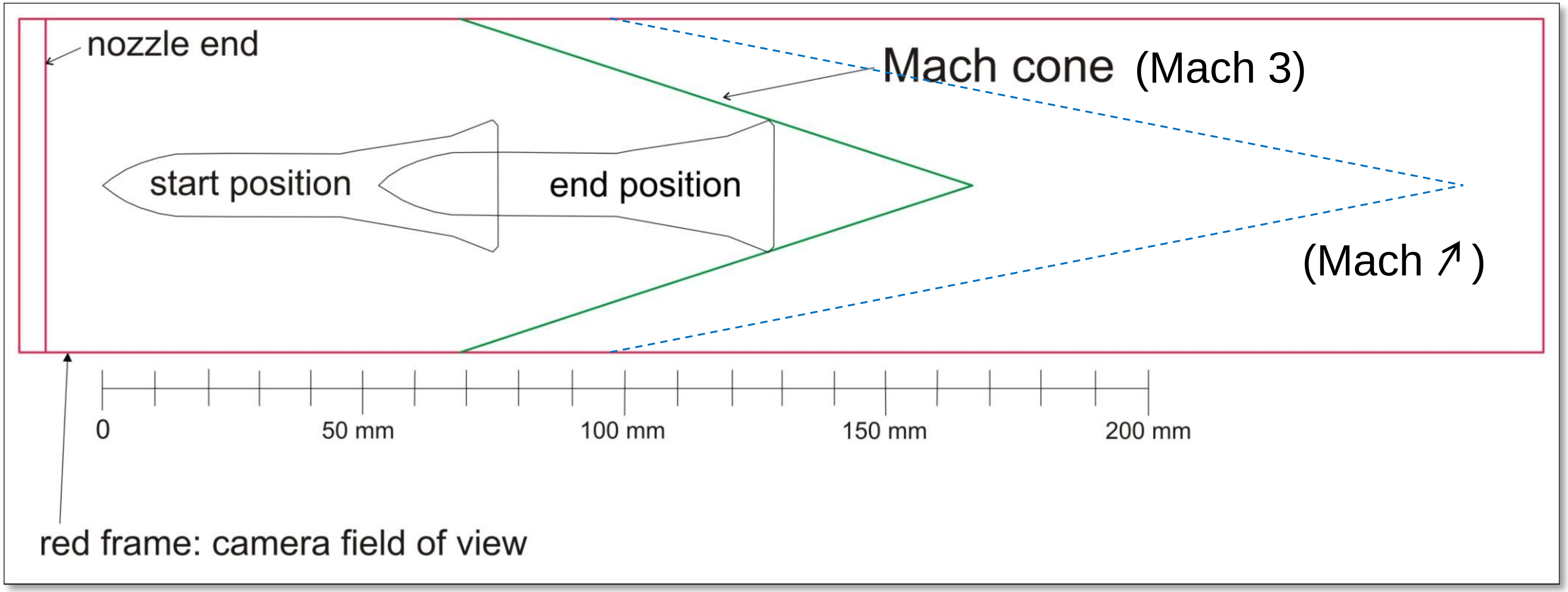
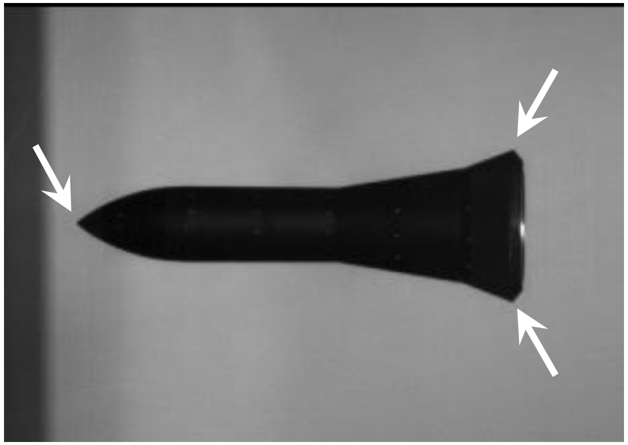


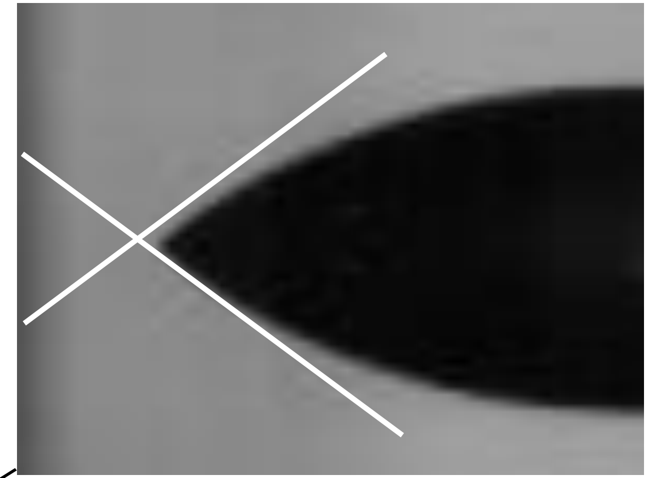
Image Processing

Tracking of three reference points:

→ Trajectory of centre of mass

→ Angular motion



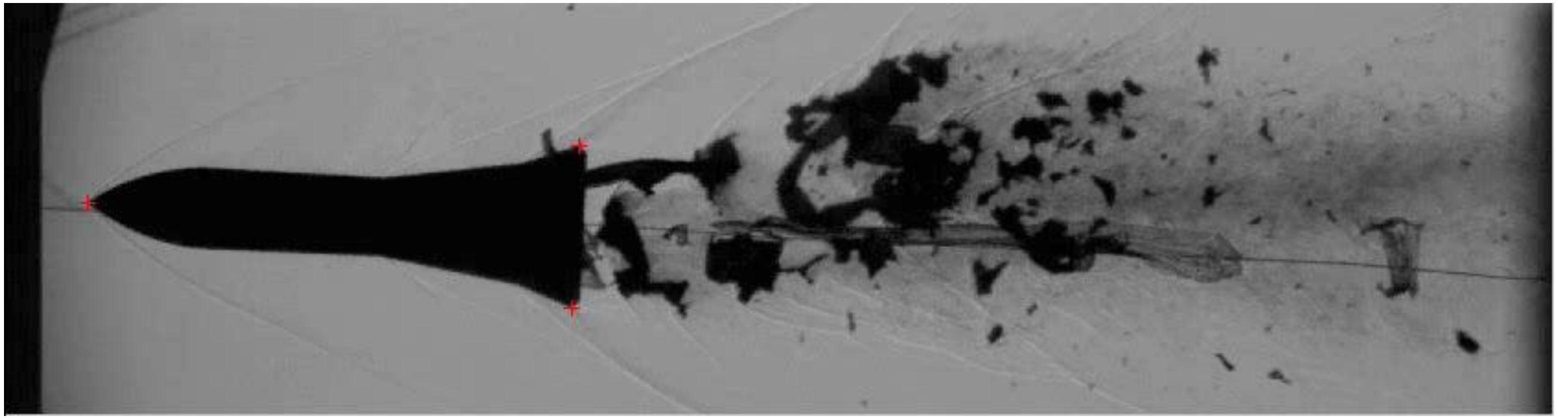


Harris method based on local contrast detection:

→ Specific pattern detection with proper directions (Eigen value analysis)

→ Path of analysis windows is predicted to prevent loss of reference point

Motion Tracking Example



EFP Model #1 at Mach 3, Horizontal plane, AOS = 3°

Duration = 10. 72 ms, Displacement = 13.60 cm

Data Extraction Methodology (1/2)

Basic methodology

The theoretical motion of the model is computed by means of a simple 2nd order Runge-Kutta integration using the time varying flow conditions.

Aerodynamics coefficients are estimated by comparing theoretical and observed motions using a least-square fit process.

Drag force coefficient

Theoretical x-axis acceleration ($C_D = 1$): $\dot{v} = \frac{1}{2} \rho u^2 \frac{S}{m}$

Initial conditions: $v_0 = 0,\ x_0 = 0$

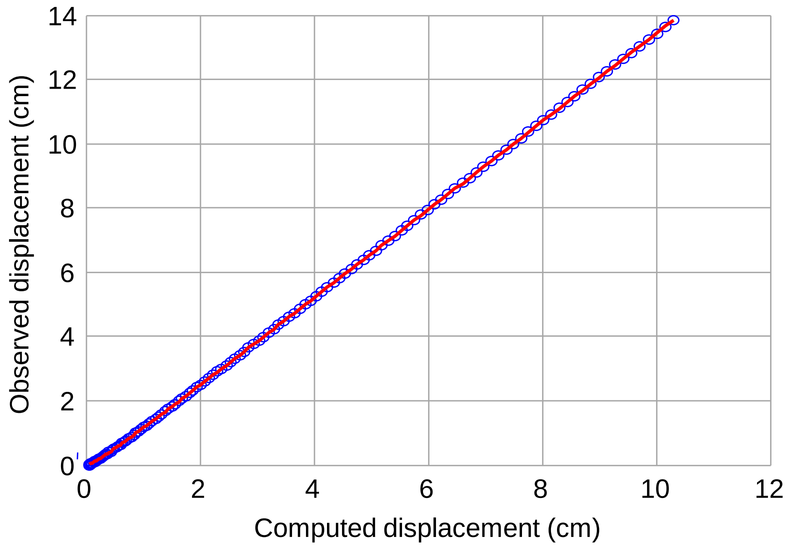
Quasi-linear fit between the observed and computed x values:

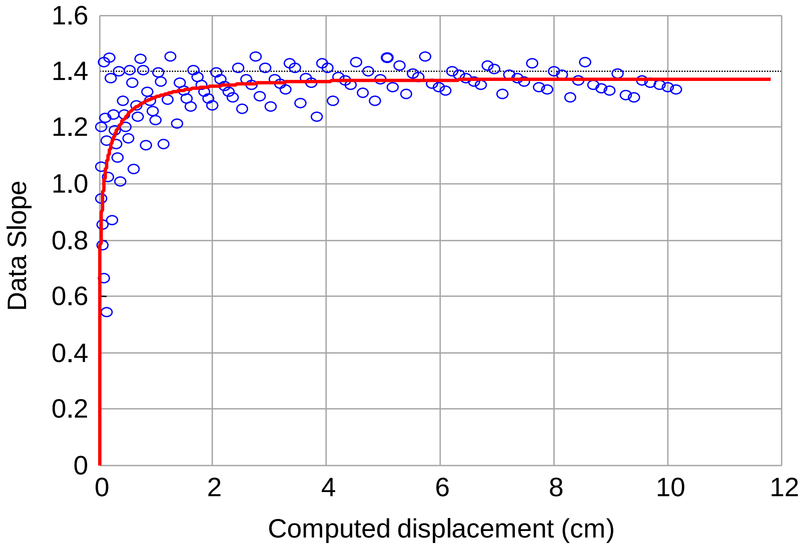
$$x_{obs} = C_D (1 - e^{-bx^c}) x + d$$

→ Origin shift

→ Non-linear fit at the beginning of the trajectory due to transient flow phase and support removal

Drag Coefficient (1/2)

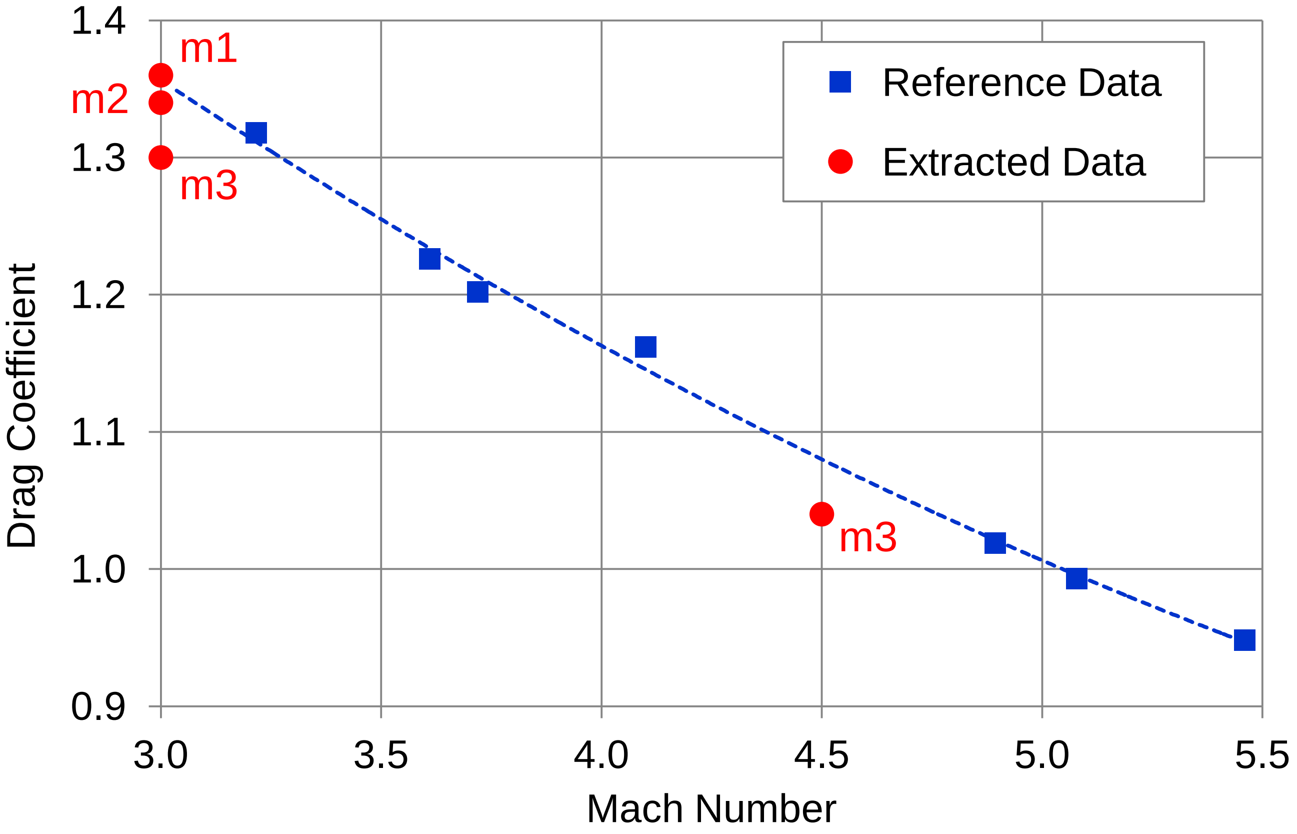




<u>EFP Model #1 at Mach 3</u>

Observation time	10. 88 ms
Observed displacement	13.83 cm
Extracted drag	1.36
Reference drag	1.35

Drag Coefficient (2/2)



"Heavy" models 1 & 2 compares extremely well with the reference data

Data Extraction Methodology (2/2)

Pitching moment and pitch damping coefficients

Theoretical angular acceleration: $\dot{\omega} = \frac{1}{2}\rho u^2 \frac{S\,d}{I_t}(C_{M\alpha}\sin\alpha + \frac{\omega d}{u} C_{Mq})\,\delta(t_0)$

Initial conditions: $\omega_0 = 0,\ \alpha_0$

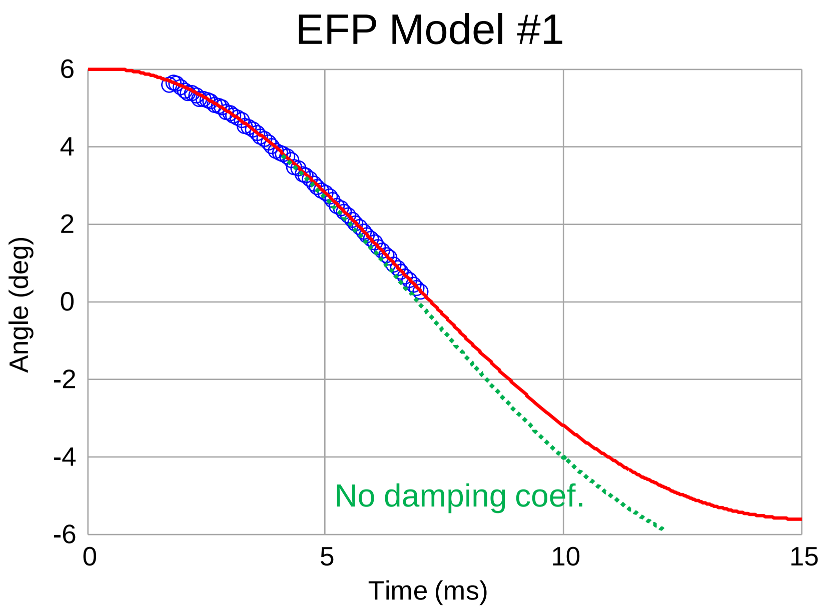
The time-shift $\delta(t_0)$ at the beginning of the trajectory takes into account the transient flow phase and the influence of the support removal.

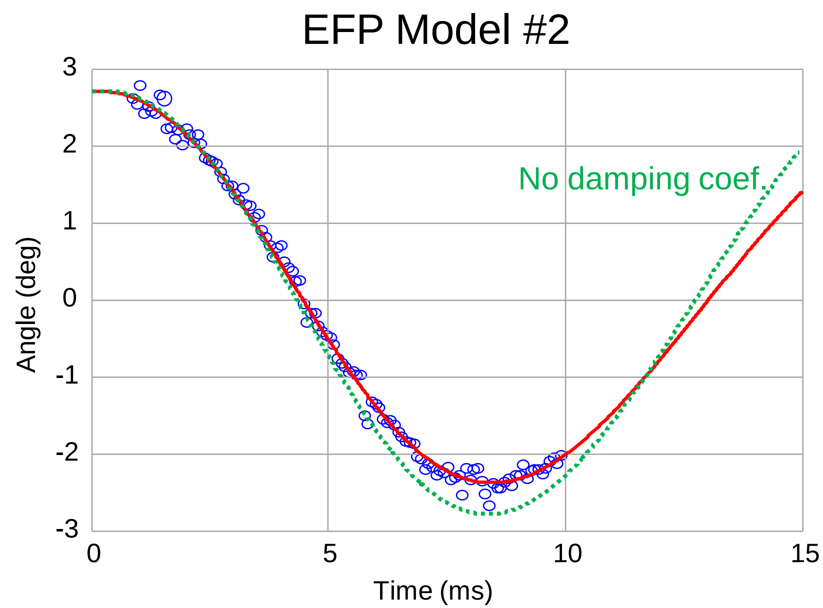
Cycle through the fit parameters to minimize the sum of square errors.

Static margin and normal force coefficient

These coefficients can be analytically computed using the pitch moment coefficients that are extracted from two models with different center-of-mass positions.

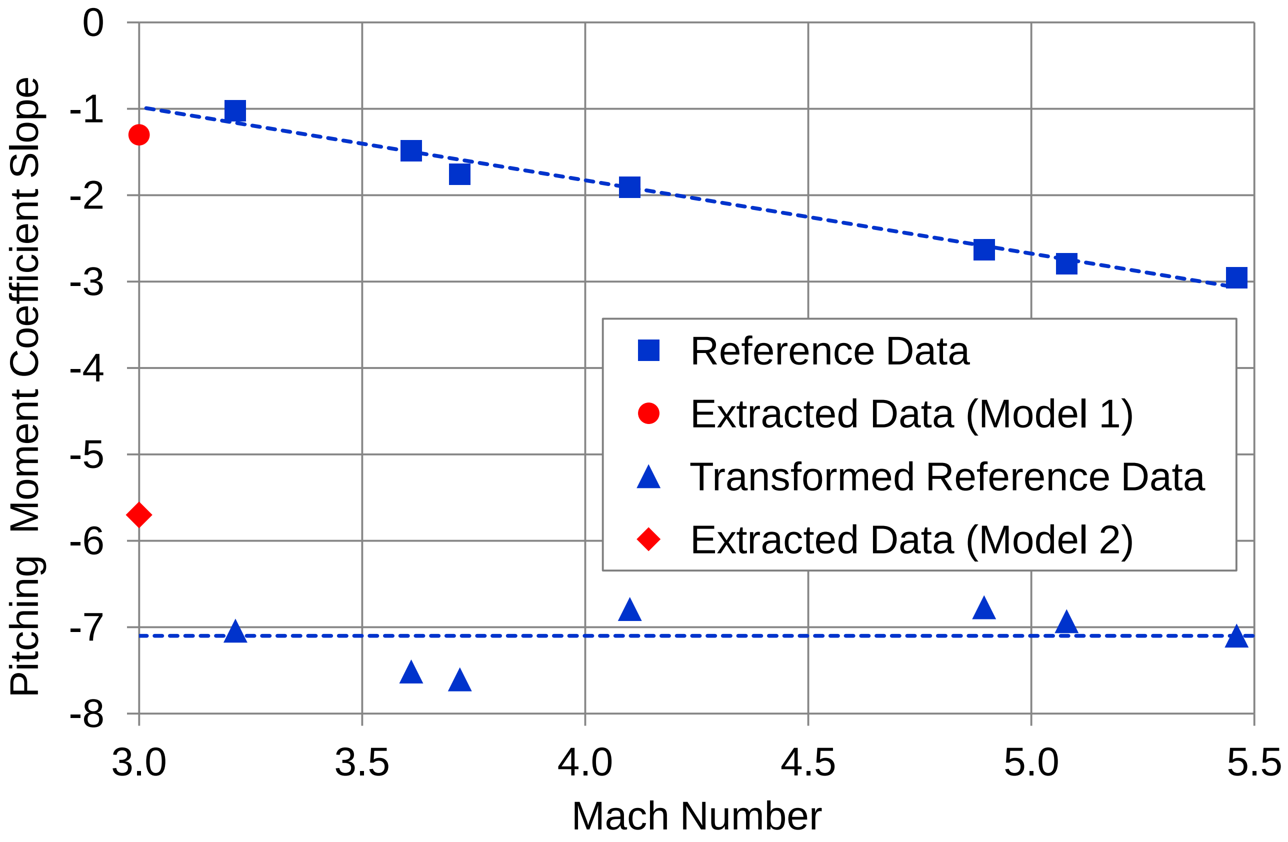
Pitching Motion Coefficients





Model	t_0 (ms)	α_0 (deg)	$C_{M\alpha}$	Ref. $C_{M\alpha}$	C_{Mq}	Ref. C_{Mq}
1	0.4	6.0	-1.4	-1.0	-80	-100
2	0.4	2.7	-5.7	-7.1	-90	-100

Pitching Moment Coefficient Slope



Experiments to be conducted at Mach 4.5 to increase model stability

Summary and Outlook

- The innovative Free-flight Force Measuring (FFM) technique covers a wide range of skills: shock-tunnel facility, flow condition measurement, high-speed video observation, image processing and aerodynamic data reduction.
- The FFM technique was successfully tested against three reference EFP models at Mach 3.
- The extracted drag coefficients compare extremely well with the reference data. The pitching moment and pitch damping coefficients compares fairly well.
- Further experiments will be conducted at Mach 4.5 very shortly.
- The mid-term goal is to provide a low cost facility to extract the aerodynamic coefficients of projectiles or air vehicles operated in the supersonic and hypersonic regimes.