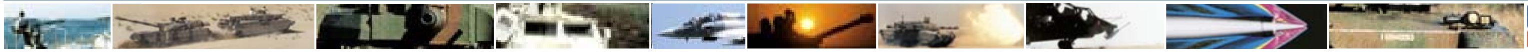


Recent Computations and Validations

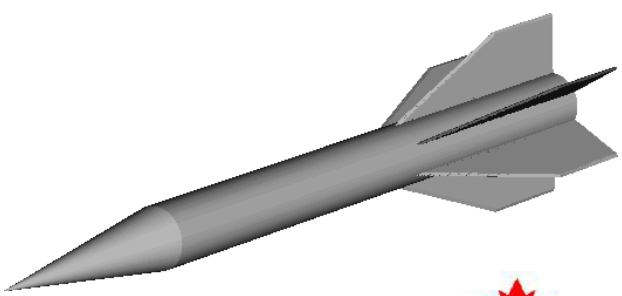
of

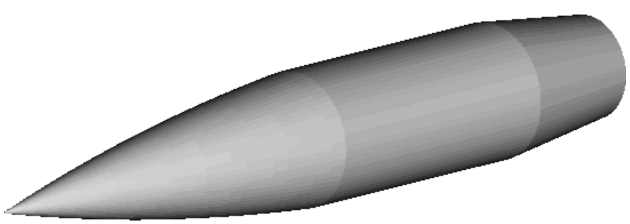
Projectile Unsteady Aerodynamics

R.Cayzac, E.Carette, R.Thépot and P.Champigny

GIAT industries

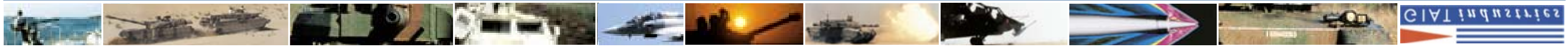
ONERA





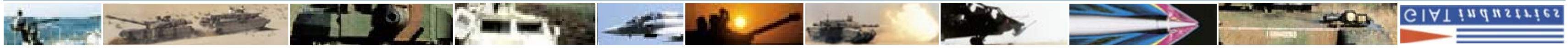
- OBJECTIVES
- THEORETICAL AND NUMERICAL APPROACHES
- WIND TUNNEL TESTS
- VALIDATION RESULTS
  - > YAWING AND SPINNING PROJECTILES
  - > KINETIC PROJECTILES
- CONCLUSIONS

Main Aerodynamic Coefficients Concerned



- **FORCE COEFFICIENTS**
  - > $CA = CA(\alpha=0) + \Delta CA\ (M, \alpha, \beta)$
  - > $CN = CN\alpha(M)\alpha + CNq(M).qD/V + \Delta CN\ (M, \alpha, \phi)$
  - > $CY = Cyp\alpha(M).p.\alpha.D/V + \Delta CY\ (M, \alpha, \phi)$
- **MOMENT COEFFICIENTS**
  - > $Cm = Cm\alpha(M).\alpha + \Delta Cm\ (M, \alpha, \phi) + Cmq(M).qD/V$
  - > $Cn = Cnp\alpha(M).p.\alpha.D/V + \Delta Cn\ (M, \alpha, \phi) + Cnr(M).rD/V$
  - > $Cl = Clo(M) + \Delta Cl\ (M, \alpha, \phi) + Clp(M).pD/V$
- **DYNAMIC COEFFICIENTS→ DAMPINGS, MAGNUS AND PSEUDO-MAGNUS EFFECT**

Computational Fluid Dynamics

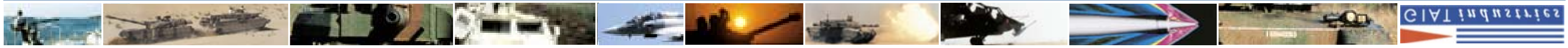


- **Theoretical and Numerical Approaches (FLU3M and elsA)**
  - **3D Navier-Stokes equations, RANS and URANS**
  - **Baldwin-Lomax, Spalart-Allmaras, k-ω,.., turbulence models**
  - **Finite volume method**
  - **Cell-centered discretization in an absolute frame**
  - **Fully implicit Gear scheme (1st and 2nd order)**
  - **(Pulliam under-iteration technique (URANS), grid movement)**

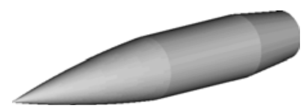
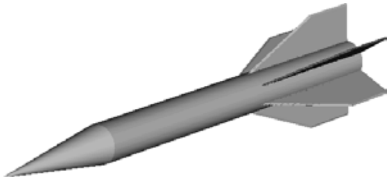
- **Grid : multiblocks structured with hexahedral cells**
  - **Wall cell ≈ 1 μm**
  - **30 to 50 cells in the boundary layer**
  - **Stretching factor < 1.2**
  - **$Y^+ \approx 1$ (a posteriori criterion)**
  - **Up to 5,000,000 cells**

- **Computational Performances**
  - **≈ 1 μs/cell/iteration NEC SX-6**
  - **≈ 45 μs/cell/iteration SGI Octane RISC 12000**
  - **≈ 20 μs/cell/iteration Cluster of Xeon (2.2 GHz)**

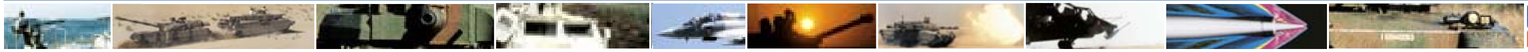
Main Aerodynamic Coefficients Concerned and CFD Generalities

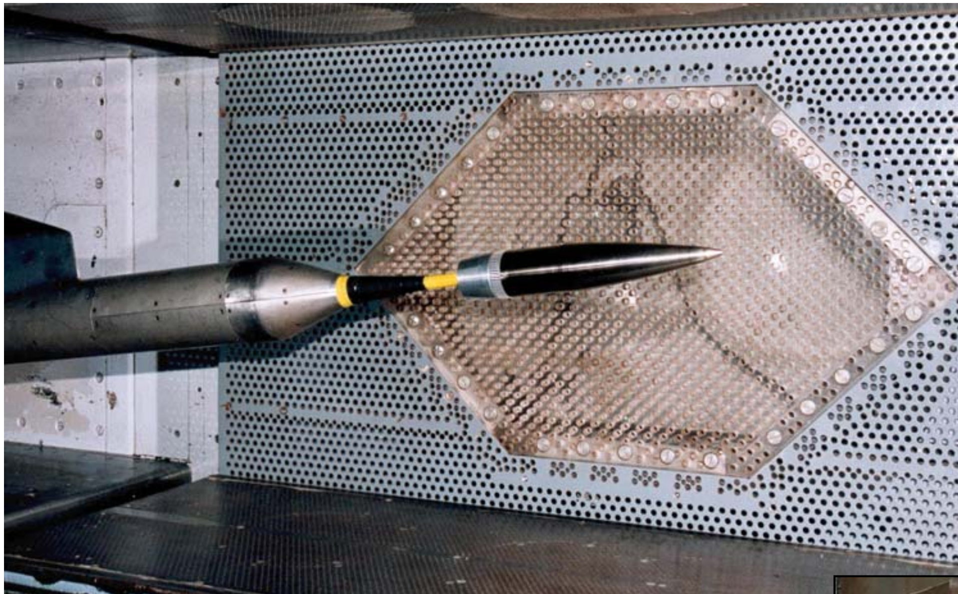


- Cell-centered discretization of RANS equations expressed in an absolute framework R, grid partition in blocks of rigid hexahedral cell

		
• Magnus • Clp • Cmq	• “Steady algorithm” • “Steady algo.” • “Pseudo unsteady”	• “Unsteady algorithm” • “Unsteady algo.” • “Pseudo unsteady”
• Grid	• Not moving	• Spinning at Ω for unsteady algo

Validation: Wind Tunnel Tests

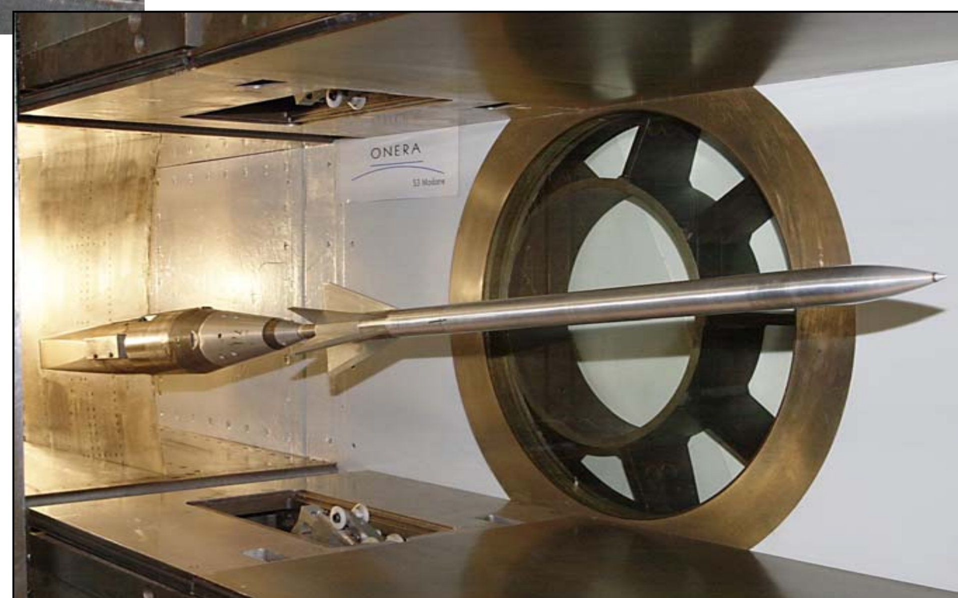




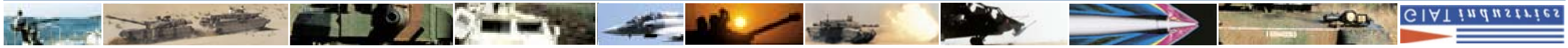
ONERA: S3MA

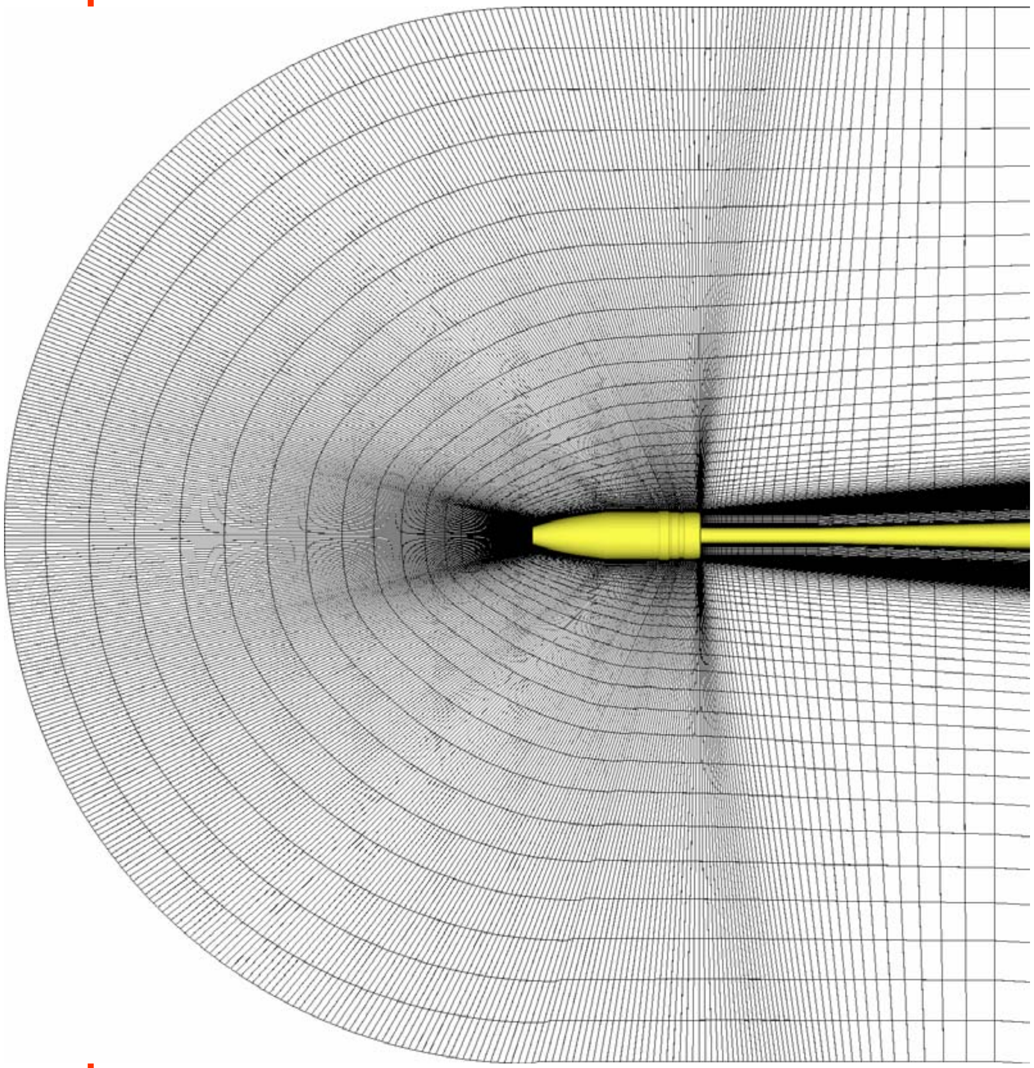
- Static coefficients
  - CA, CN, Cy, Cl, Cm, Cn
- Dynamic coefficients
  - Cy ($Cyp\alpha$), Cn ($Cnp\alpha$)
  - $CNq+CN\alpha$, $Cmq+Cm\alpha$
  - Clp

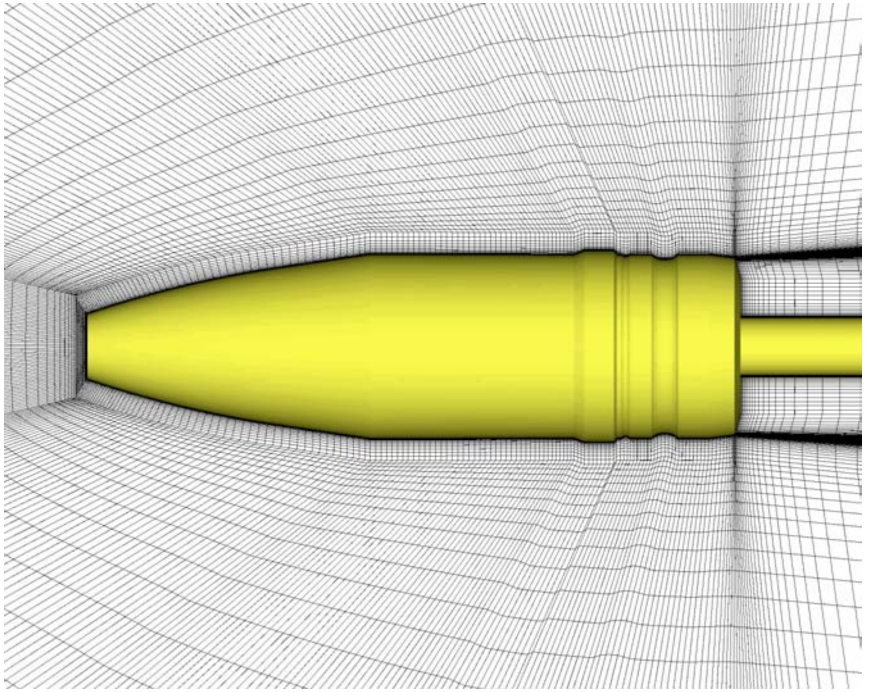
- Mach number
- Reynolds number
- Roll rate p ($P^*=p.D/v_\infty$)
- Pitch rate q
- Damping frequency
- Angle of attack
- Roll position ϕ



Example of Yawing and Spinning Projectile Grid





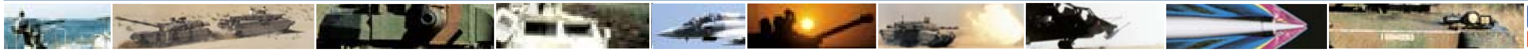


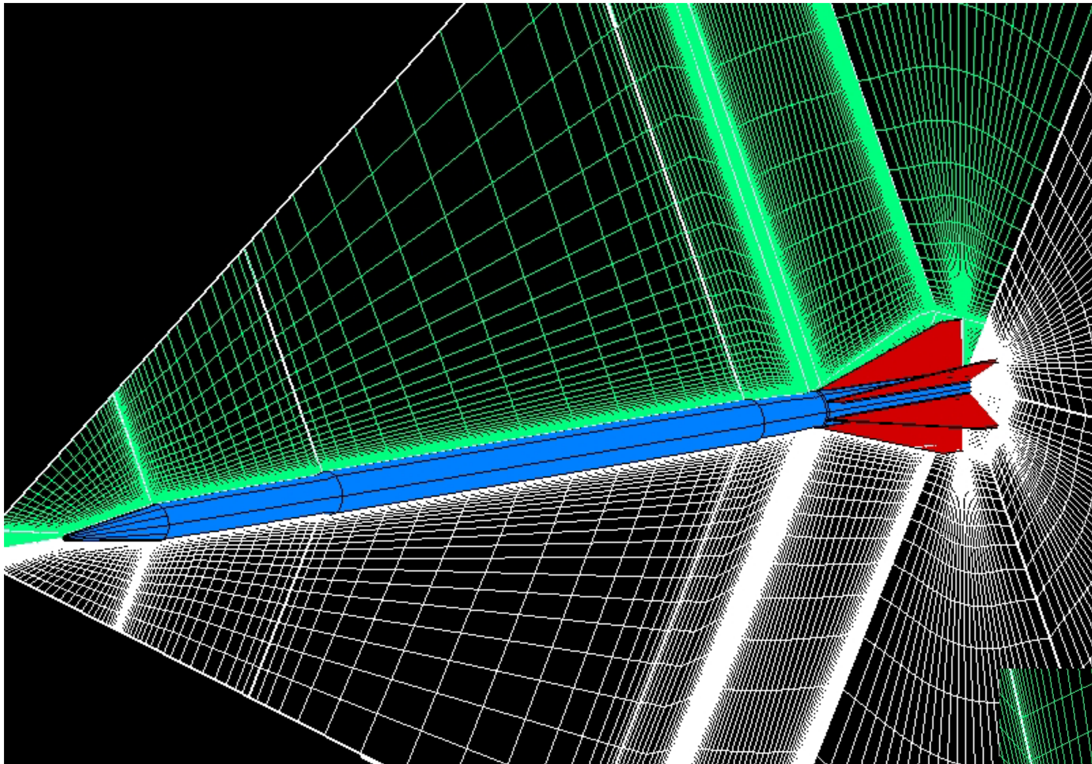
2,074,896 cells

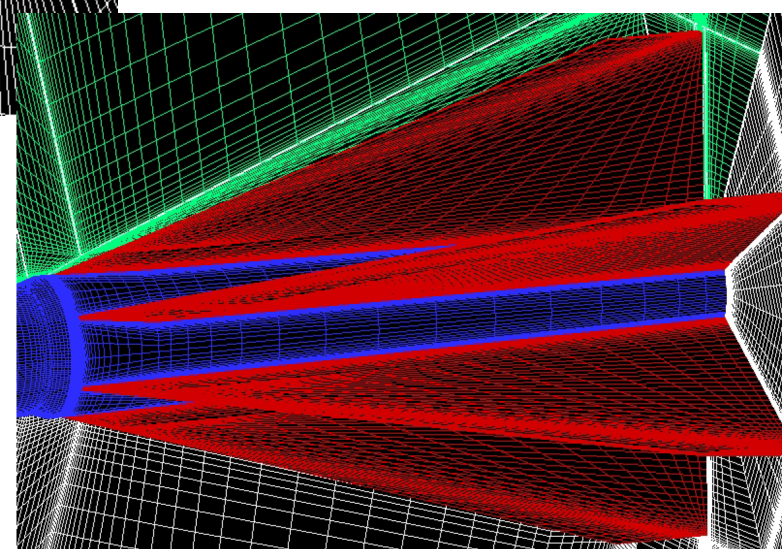
$Y^+ \approx 1$

40 cells in the boundary layer

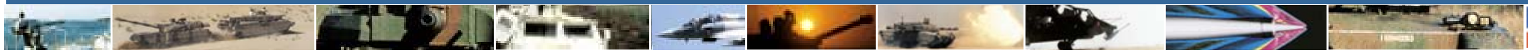
Example of Kinetic Projectile Grid



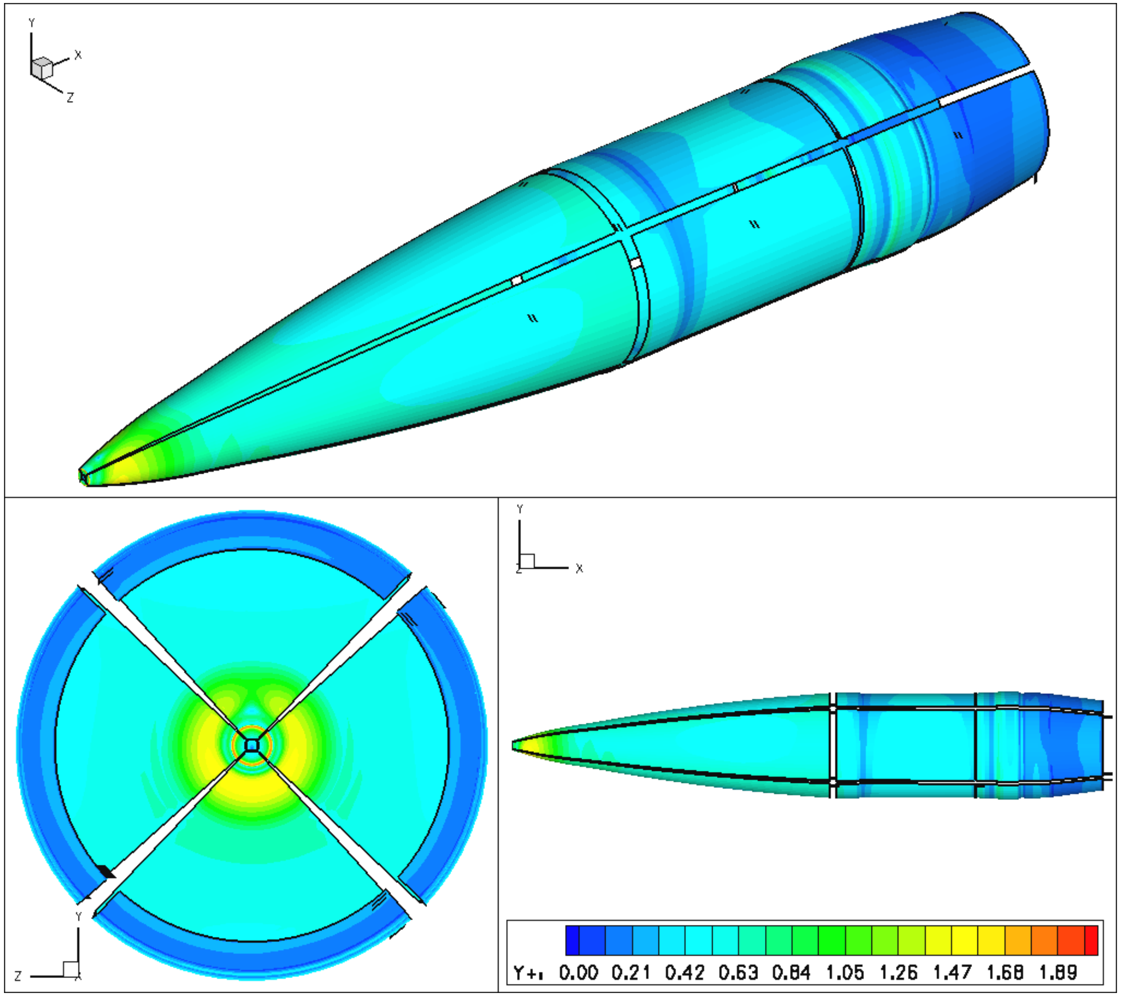




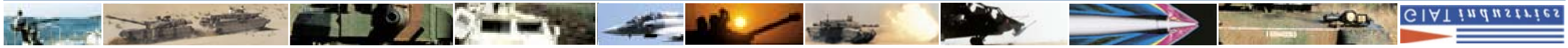
90 Blocks
≈2,700,000 cells
$Y^+ \approx 1$
40 cells in the boundary layer



- **y^+ distribution**
  (Mach = 0.90, α = 3°, Pi = 1.20E+05 Pa, Ti = 300.0 K)



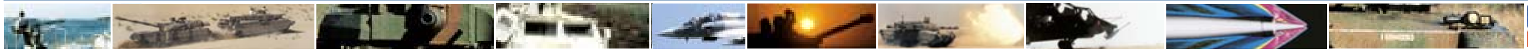
Yawing and Spinning Projectiles: Magnus Validation Results



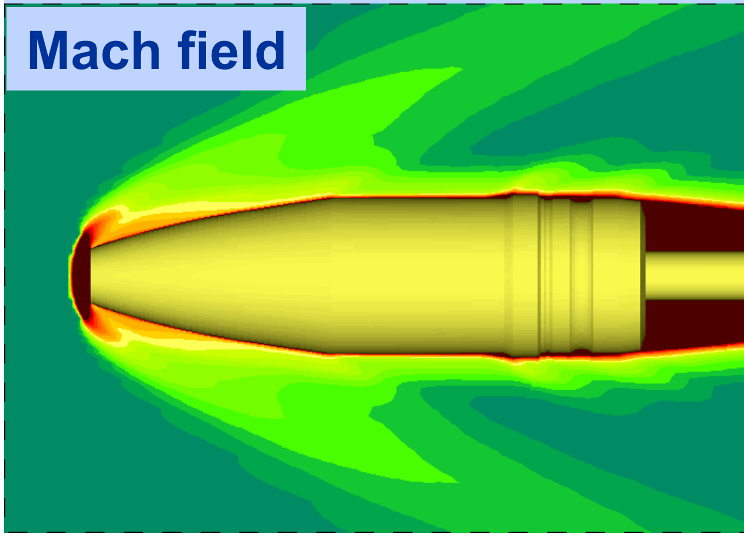
- [1]"Navier-Stokes Computations and Validations of a Yawed Spinning Projectile", 18th International Symposium on Ballistics, 15-19 November, San Antonio, Texas, USA, 1999.
- [2]"Recent Developments on Aeroballistics of Yawing and Spinning Projectiles: Part I, Wind Tunnel Tests ", 20th International Symposium on Ballistics, 7-11 October, Orlando, USA, 2002.
- [3]"Recent Developments on Aeroballistics of Yawing and Spinning Projectiles: Part II, Free Flight Tests ", 20th International Symposium on Ballistics, 7-11 October, Orlando, USA, 2002.
- [4]"Recent Developments on Aeroballistics of Yawing and Spinning Projectiles: Part III, Validation Results", 20th International Symposium on Ballistics, 7-11 October, Orlando, USA, 2002.
- [5]"Analysis of Static and Dynamic Stability of Spinning Projectiles", 21st International Symposium on Ballistics, Adelaide, Autralia, 19-23 April , 2004.

- **Agreement between computations and experiments is satisfactory at moderate angles of attack on the Magnus dynamic coefficients**
- **Strong difficulties at high incidence (up to 10°) and in the transonic regime**
- **RANS → MILES, DES, etc., simulations (ARL, De Spirito, etc.)**

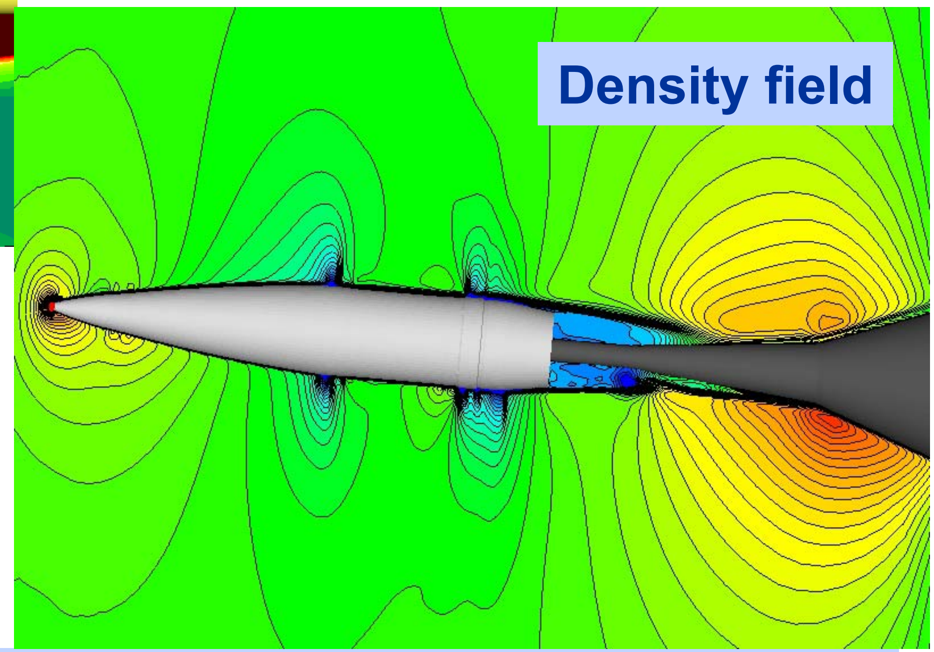
Example of Validation Results: Cmq, Pseudo-URANS



Supersonic Conditions: Wind Tunnel C4/ FLU3M Baldwin-Lomax
(M_∞= 2.89, α = 0° (1° for static), Pi = 3.224 bar, Ti = 299 K, $\theta \pm$ 1°, f = 9 to 13 Hz)



FLU3M	TEST	CFD	Error(%)
$C_{N\alpha}$	2,52	2,36	6,3
$C_{m\alpha}$	-3,55	-3,38	4,8
X_F/D	1,41	1,43	-1,4
C_{mq}	-5,1	-5,4	-5,8

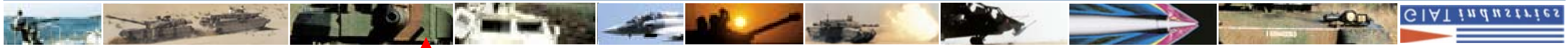


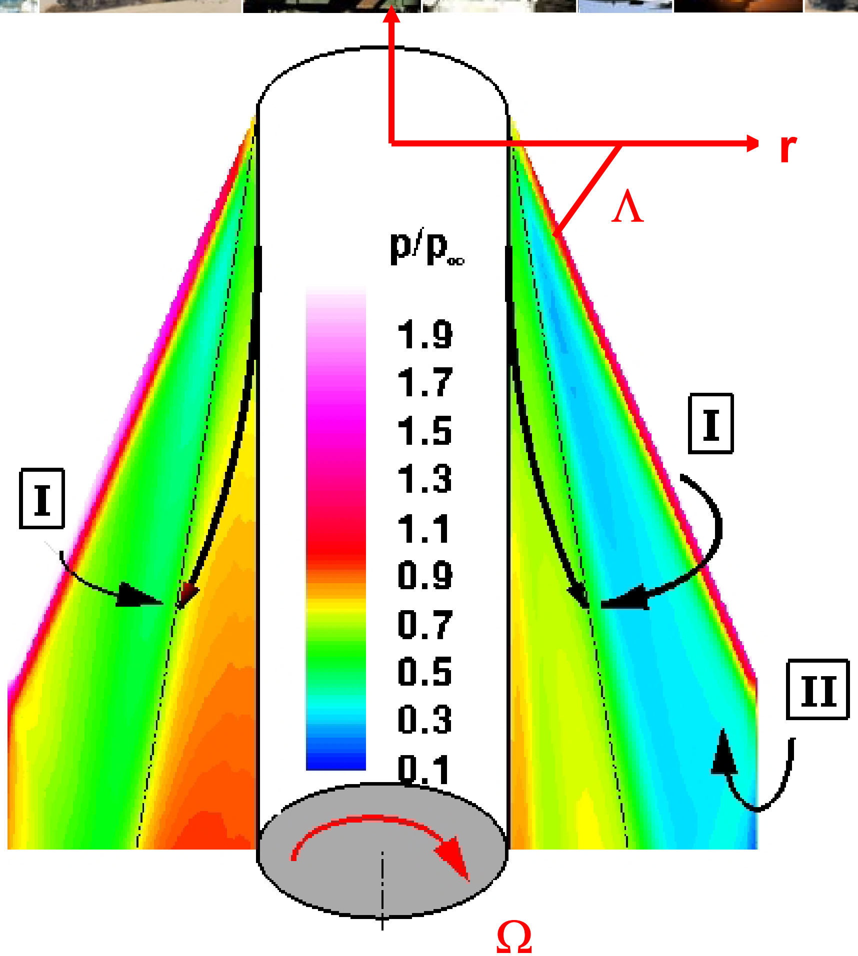
Elsa	CFD	TEST	Error(%)
C_{mq}	-6,3	-7,1	11%

Transonic Conditions: Wind Tunnel S3Ma/ elsA k-ω
(M_∞= 0.9, α = 3°, Pi = 1.2 bar, Ti = 300 K, $\theta \pm$ 1°, f = 6 à 10 Hz)

ONERA

Example of Validation Results: Magnus of Kinetic Projectiles



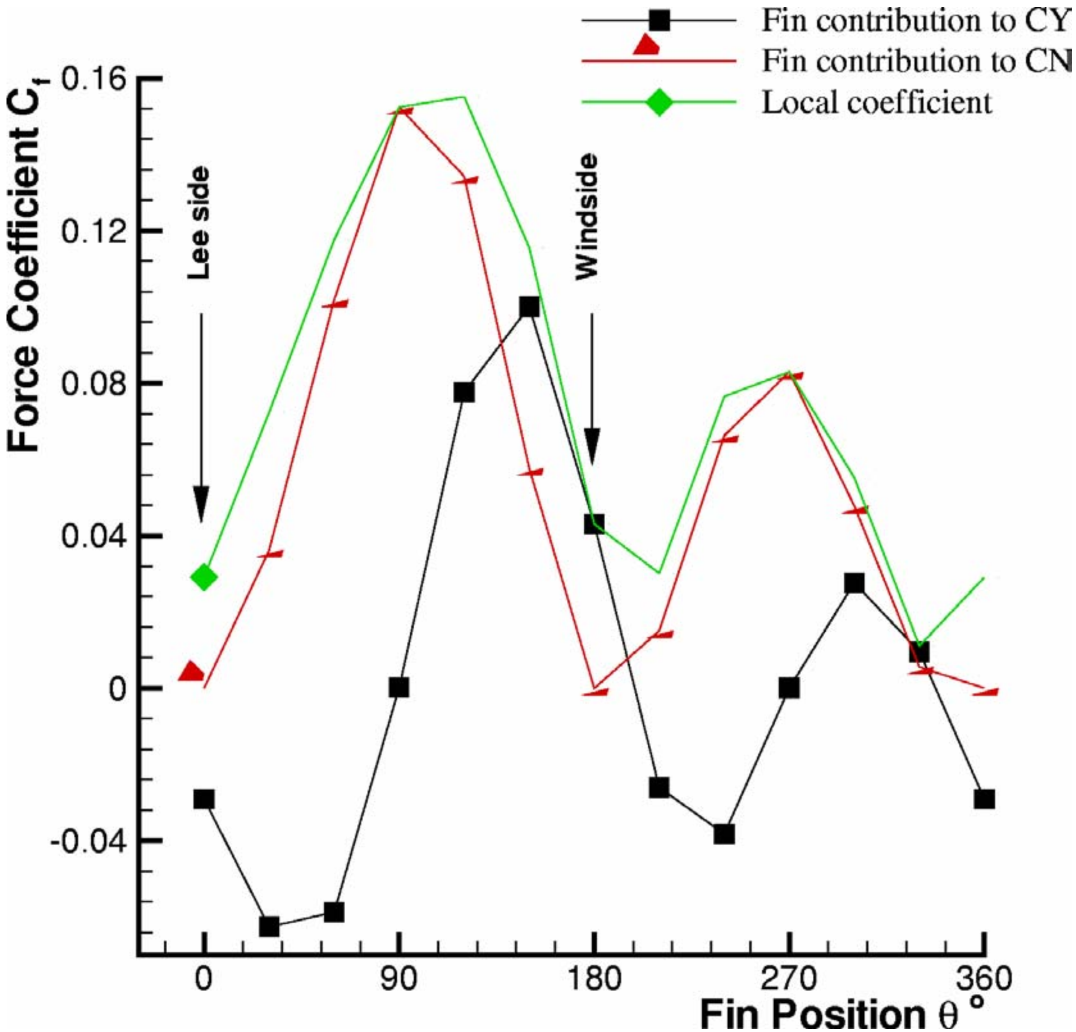


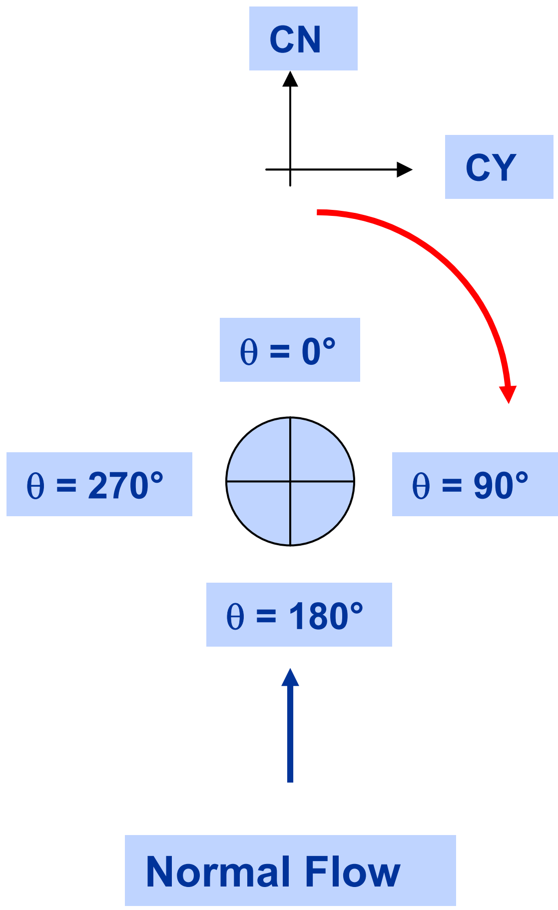
- **Magnus effect origin on fins**
  - **Interaction with asymmetric fuselage wake**
  - **Modifications of the local incidences induced by spin (apex shock & tip vortex)**
- **Flow description**
  - **I Apex shocks**
  - **II Tip vortex**

- → $\alpha_{local} = f(\alpha,\delta,r,\Omega)$ $\alpha_{local} = \alpha \pm \delta \pm r.\ \Omega/V_\infty$
- → $\alpha_N = \tan^{-1}(\tan \alpha_{local}/\cos \Lambda)$
- → $Mach_N = Mach_\infty \sqrt{(1-\cos^2 \alpha_{local} . \sin^2 \Lambda)}$

- **URANS, Baldwin-Lomax, Mach 4.3, p^*= 0.041, Pi = 7.7 Bar, Ti = 295 K, α = 4.22°, L/D = 12.5.**

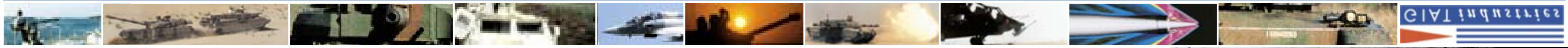
Example of Validation Results: Magnus of Kinetic Projectile

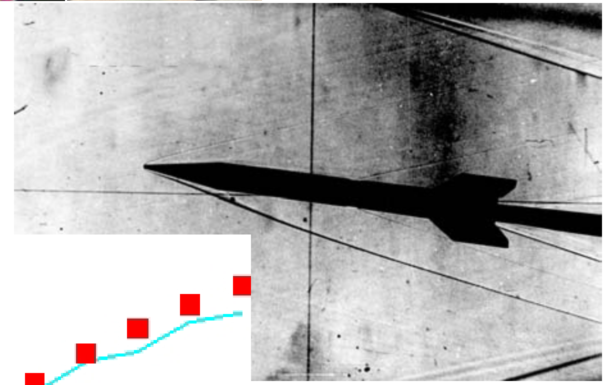


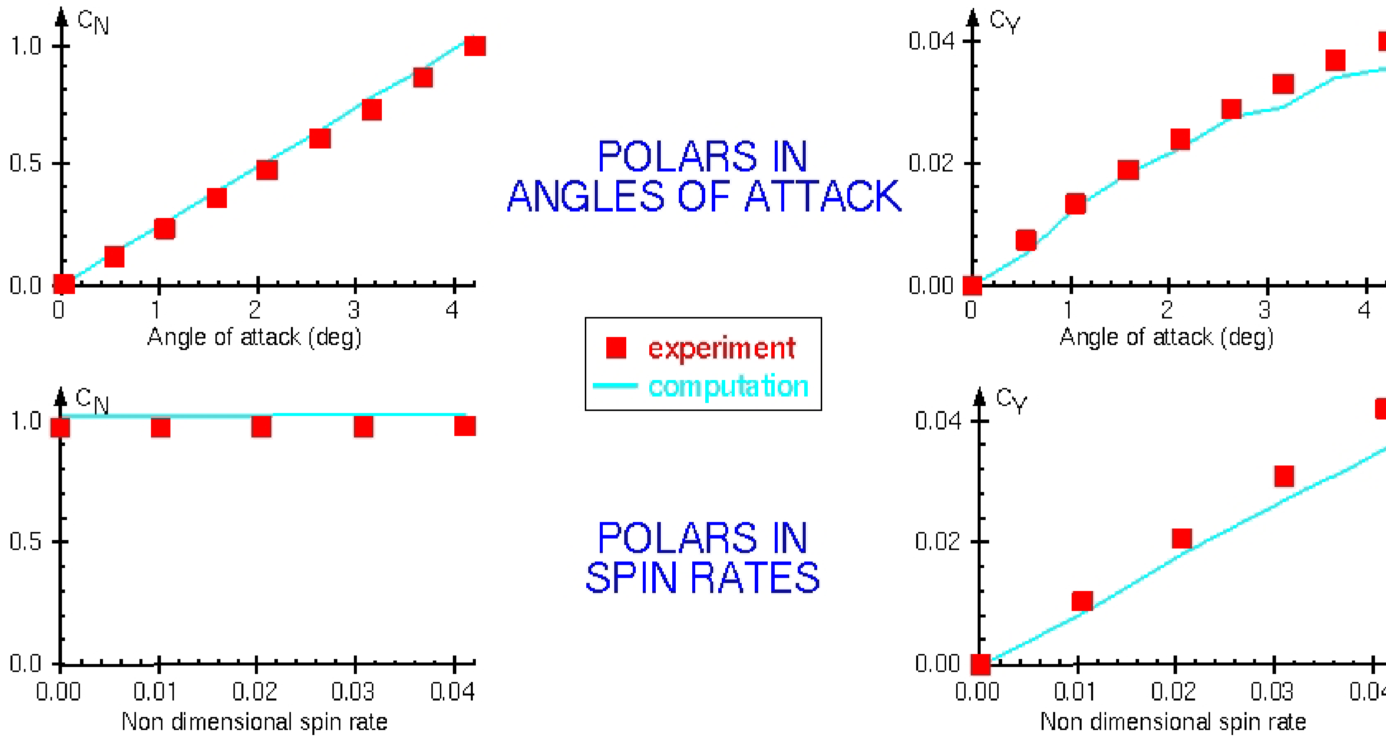


Fin azimuthal position influence (variations of the local incidence) on force coefficients
URANS, Baldwin-Lomax, Mach 4.3, p^*= 0.041, Pi = 7.7 Bar, Ti = 295 K, α = 4.22°, L/D = 12.5.

Example of Validation Results: Magnus of Kinetic Projectile

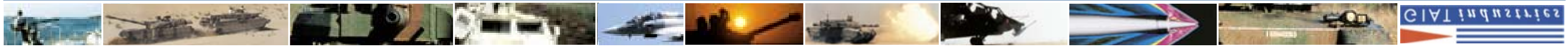




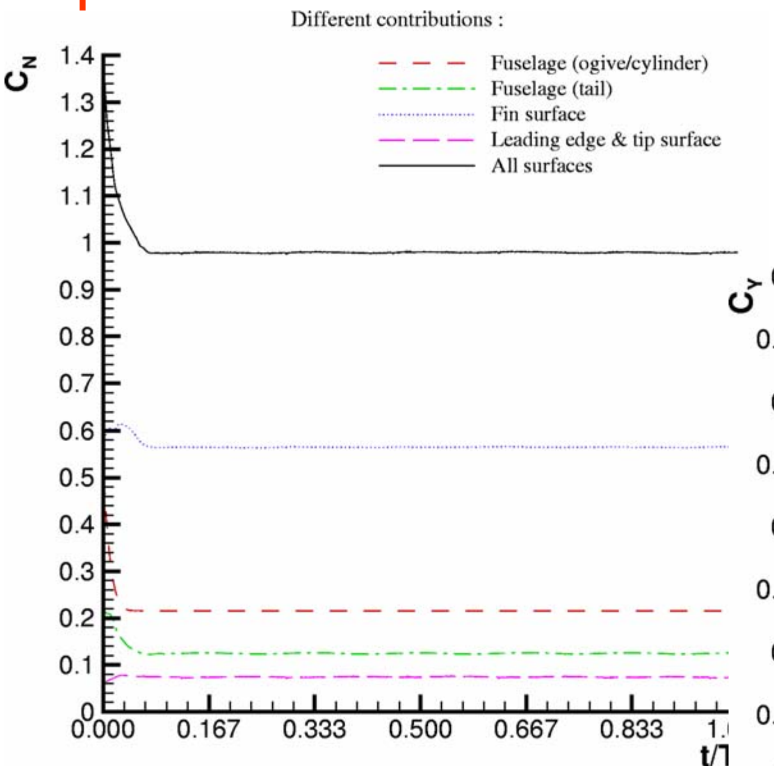


- **URANS FLU3M Baldwin-Lomax**
  - > **Mach 4.3, p^*= 0 → <u>0.041</u>, Pi = 7.7 Bar, Ti = 295 K, α = 0°→ <u>4.22</u>°, L/D = 12.5.**

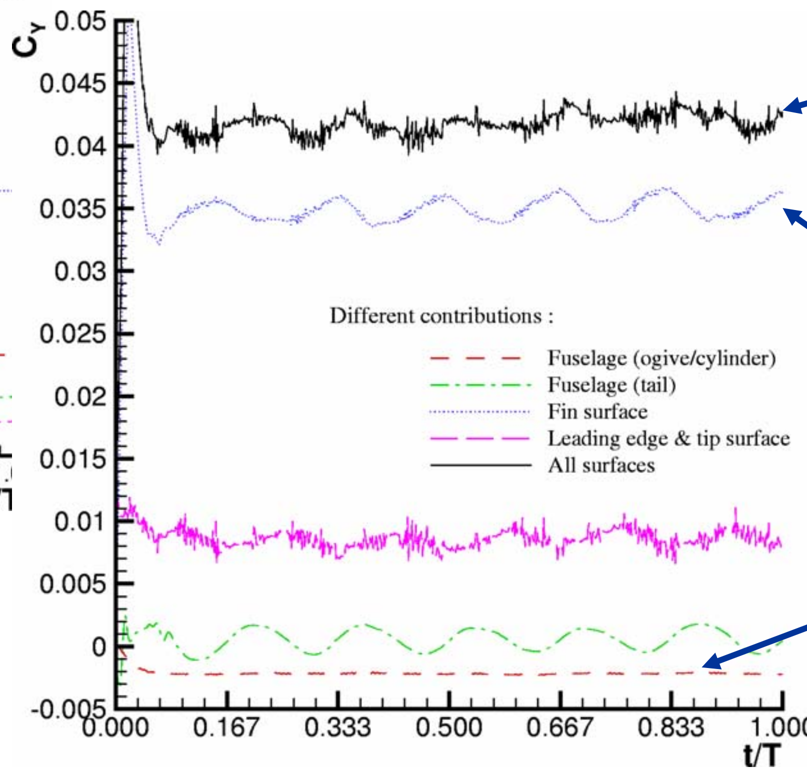
Example of Validation Results: Normal force and Magnus Coefficients of Kinetic Projectile



- **Global normal force is independent of the rotation**
- **Mach 4.3, p^*= 0.041 (100 rounds/s), Pi = 7.7 Bar, Ti = 295 K, α = 4.22°, L/D = 12.5.**



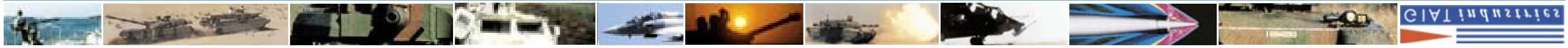
Numerical convergence
- **7200 iterations/round**
- **6 under-iterations/iteration**



- **Global Magnus force**
- **Fin surface contribution**
- **Inverse contribution of the fuselage**

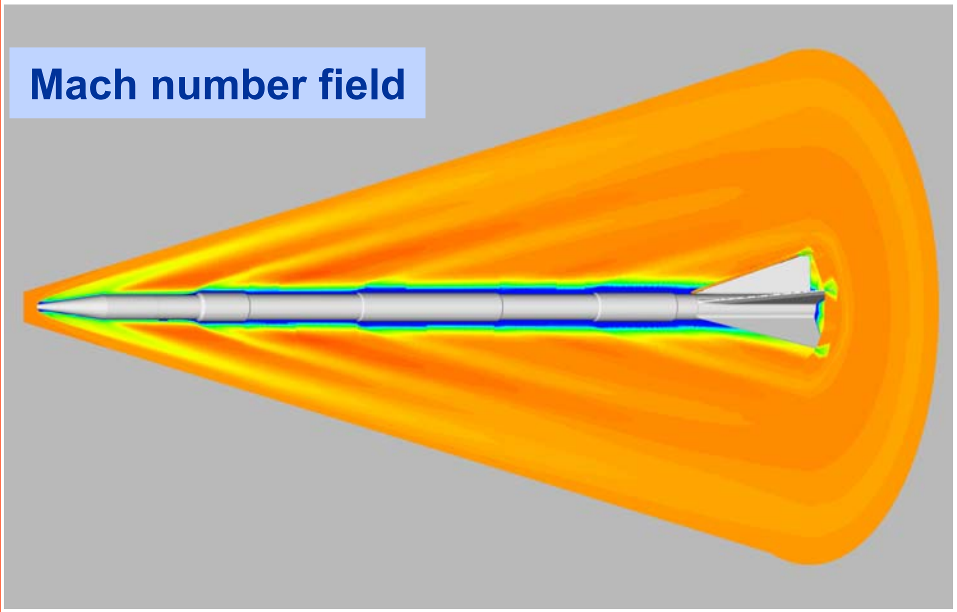
Wind Tunnel S3Ma
Model's scale: 1.6, L/D = 30

Example of Validation Results: Cmq, Clp and Magnus of Kinetic Projectiles

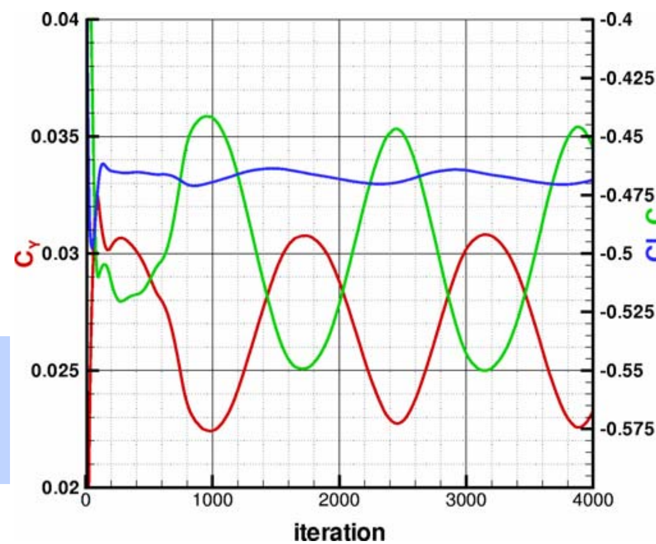


CFD (URANS FLU3M+Balwin-Lomax and Elsa+k-ω) / Wind Tunnel S3Ma (L/D = 30)

Cmq: M_∞= 4.5, α = 0°→ 5°, Pi = 6 bar, Ti = 299 K, θ ± 1.5°, f = 2.2 → 4.2 Hz (FLU3M)
Clp: M_∞= 4.5, α = 0°→ 5°, Pi = 6 bar, Ti = 299 K, p = 1.5 → 55 Rd/s (elsA)
Magnus: M_∞= 4.5, α = -1°→ 5.5°, 3°, Pi = 6 bar, Ti = 356 K, p = 10→ 90 Rd/s (65) (FLU3M)



	TESTS	CFD	Errors (%)
Clp	–15	-15.35	**2.3**
Cmq	-2800	-2619	**6.5**
Cy	0.045	0.0474	**-5.3**
Cn	-1.071	-1.112	**-4**



- **Periodic behaviour of the Magnus and roll moment coefficients during unsteady computation**
- **Mach 4.4, p^*= 0.02, Pi = 6 Bar, Ti = 360 K, α = 2°, L/D = 30.**

CONCLUSIONS

- **Extensive wind tunnel database for validation, need free flight results**

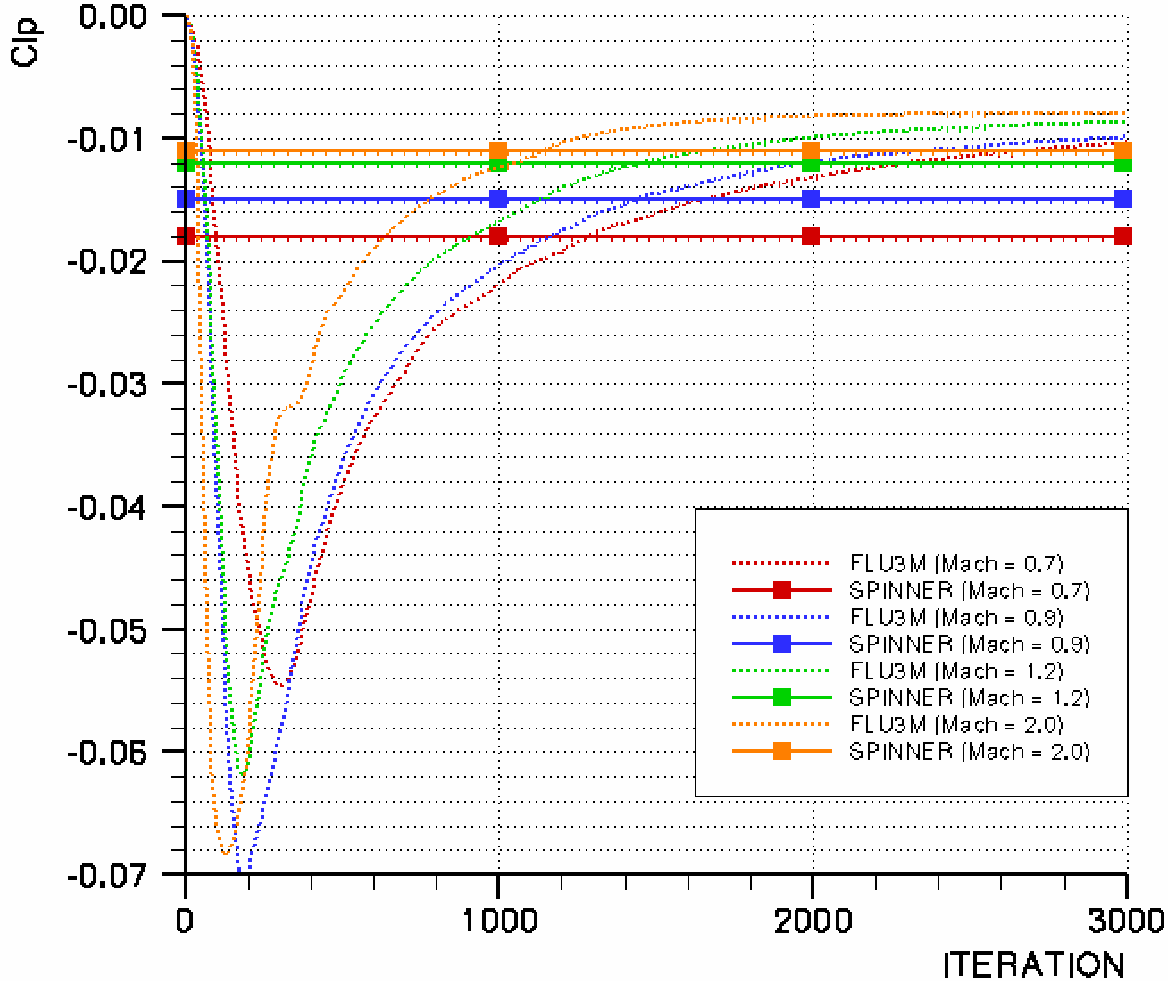
- **Progress in CFD allows us to predict projectile unsteady aerodynamics. With respect to spinning and kinetic projectiles, a demonstration of the capability of the numerical approach was carried out**

- **Satisfactory agreement between computations and experiments on the pitch and roll dampings and on the Magnus effect**

Example of Validation Results: Clp of Spinning Projectile

- $Cl_p = (Cl_{(p)})/(p.L_{réf}/V_{\infty})$

CFD (RANS, Baldwin-Lomax), p* ≈ 0.2, α = 0°)



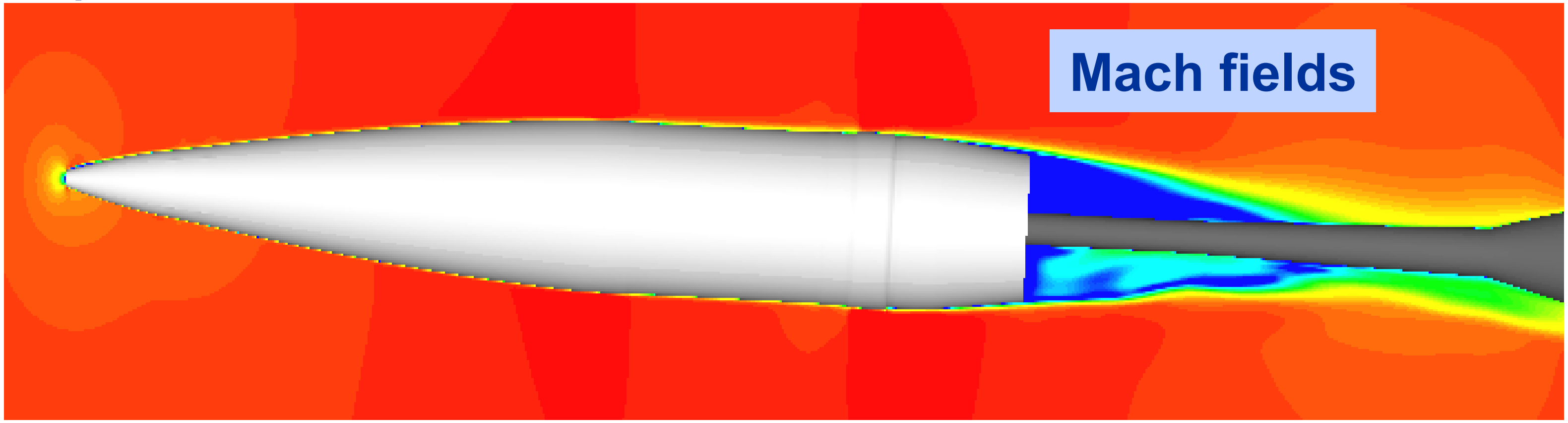
Mach Number	Clp	
	FLU3M	SPINNER
0.70	-0.010	-0.018
0.90	-0.010	-0.015
1.20	-0.009	-0.012
2.00	-0.008	-0.011

CFD Prediction of the Pitch Damping Coefficient: Pseudo-URANS

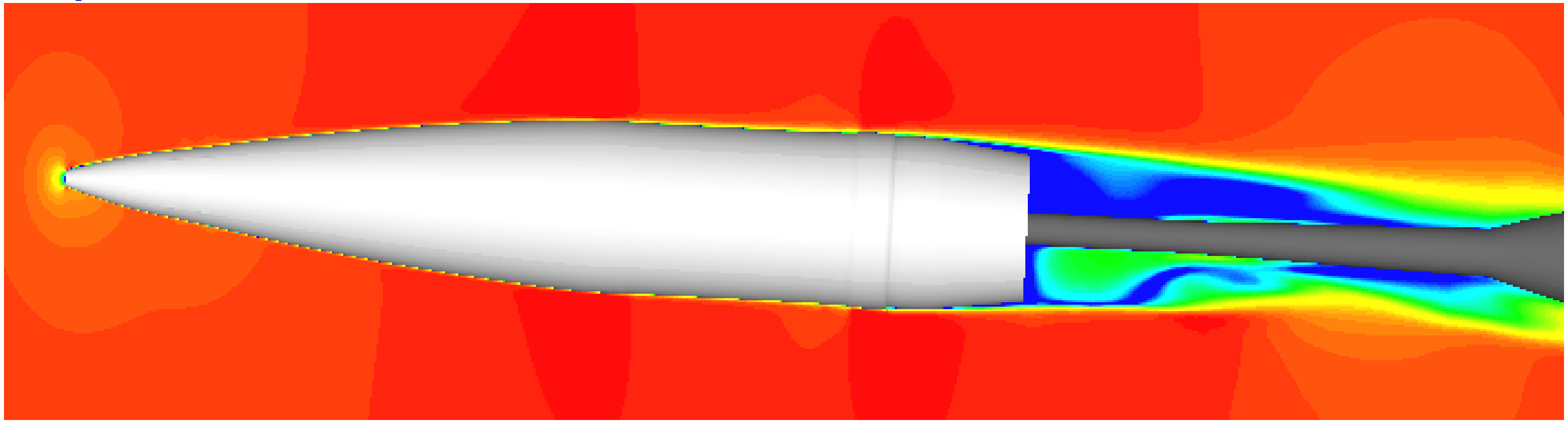
- $Cm_q = (Cm_{(q)} - Cm_{(q=0)})/(q.L_{réf}/V_{\infty})$

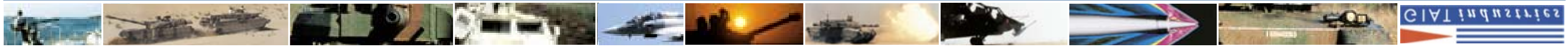
  (Mach = 0.90, α = 3°, Pi = 1.20 Bar, Ti = 300 K)

> q = 0 rad/s

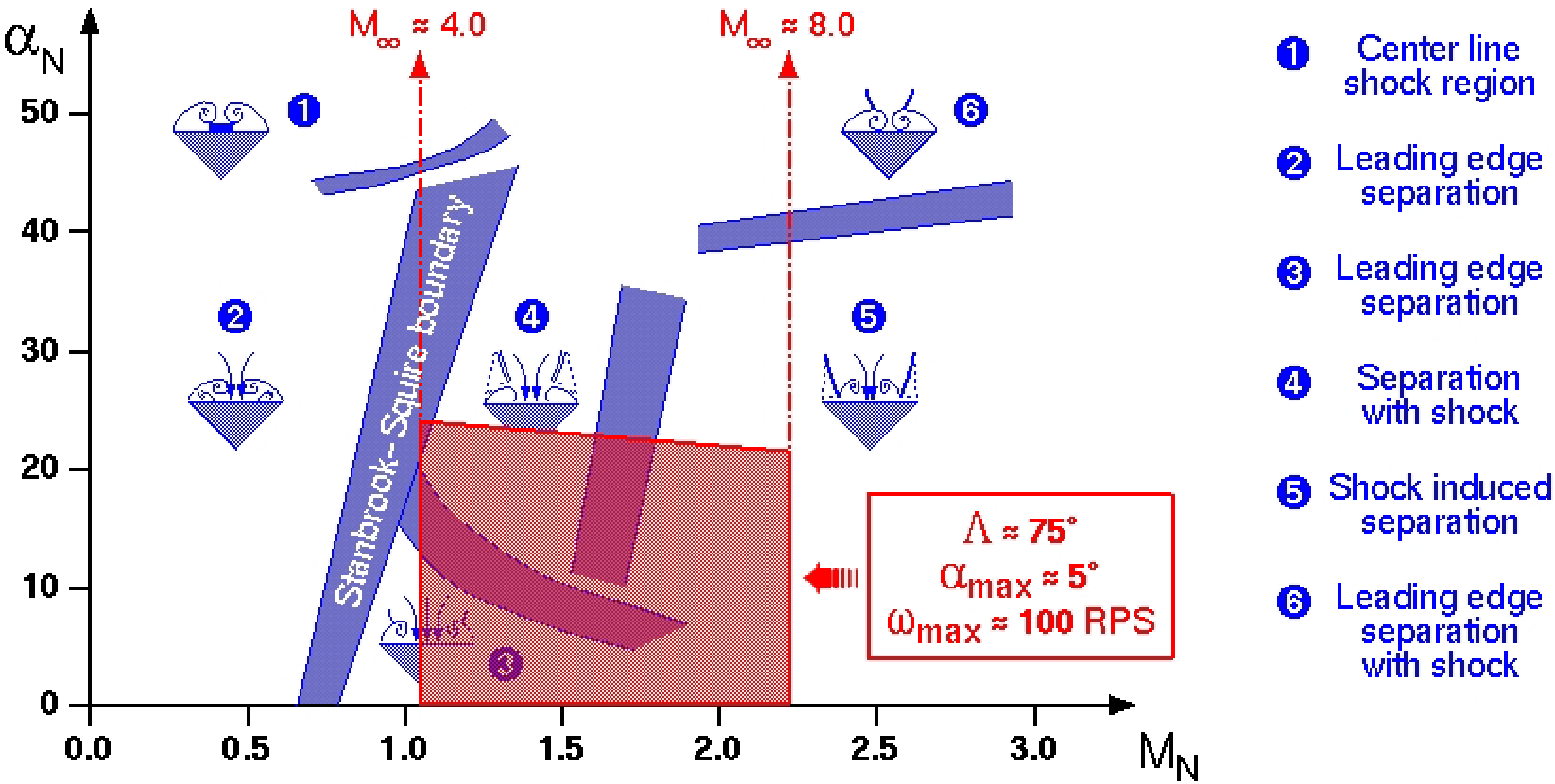


> q = 10 rad/s



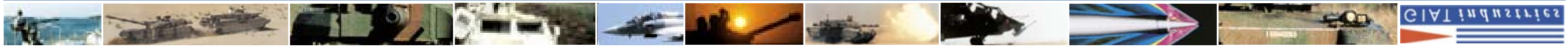


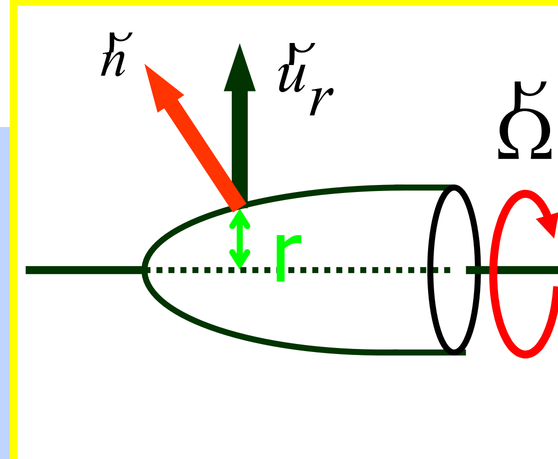
CLASSIFICATION OF LEESIDE FLOWFIELDS FOR THICK DELTA WINGS WITH SHARP LEADING EDGES



$\Lambda = 70°$, Mach 4.3, $p^* = 0.041$, Pi = 7.7 Bar, Ti = 295 K, $\alpha = 4.22° \rightarrow M_N = 1.52$ et $\alpha_N = 0.27$

Boundary Conditions





- **Fuselage state**
  - > no slip condition $\vec{V}_w = r\vec{\Omega}$
  - > adiabatic wall $\left.\frac{\partial T}{\partial n}\right|_w = 0$
  - > normal pressure gradient $\left.\frac{\partial P}{\partial n}\right|_w = \rho r \Omega^2 \left(\vec{u}_r \cdot \vec{n}\right)$
- **Fin state**
  - > slip or no slip conditions $\vec{V}_w \cdot \vec{n} = 0$ $\vec{V}_w = r\vec{\Omega}$
- **Outer boundary condition is obtained from the Theory of Characteristics**

22nd International Symposium on Ballistics
14-18 November 2005, Vancouver, BC, Canada.