Identification of aerodynamic coefficients based on free-flight data

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Introduction – MarcoPolo-R mission

Objective of the mission:

MarcoPolo-R comprise a primary spacecraft with an **E**arth **R**e-entry **C**apsule (ERC)
The spacecraft will fly to a Near-Earth Asteroid, it will obtain a sample of roughly 100 g, which will be returned to Earth with the Earth Re-entry capsule.

→ new depth to our understanding of the early Solar System and of other near-Earth asteroids

Our objective:

ISL testing program in the frame of MarcoPolo-R ERC Dynamic Stability Characterization under ESA/ESTEC (European Space Agency) contract and prime contractor Airbus Safran Launchers

Aeroshape of the Earth Re-entry Capsule designed by Airbus Safran Launchers

- To characterize, from the supersonic to the subsonic regime, the basic aerodynamics of a subscale atmospheric entry space probe with primary focus on the dynamic stability characterization, the dynamic scaling and the influence of the center of gravity position

  → identification of the aerodynamic coefficients based on free flight data

- To complete the aerodynamic data base (AEDB)

Outline

- Experimental framework
- Aerodynamic parameter identification
- Results
- Conclusions

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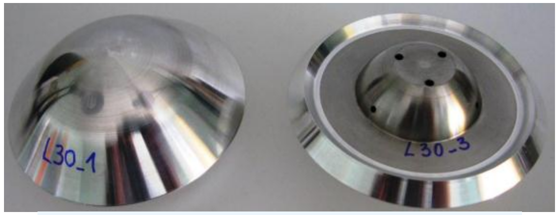
Model design and instrumentation

Subscale models of an Earth Re-entry Capsule (scale of models: 1:11)

Three distinct model architectures: L_25, H_25 and L_30 (Diameter D = 80 mm)

Model L_25
(brass: m=562g)
Xcg/D =25%

Model H_25
(tungsten: m=1150g)
Xcg/D =25%



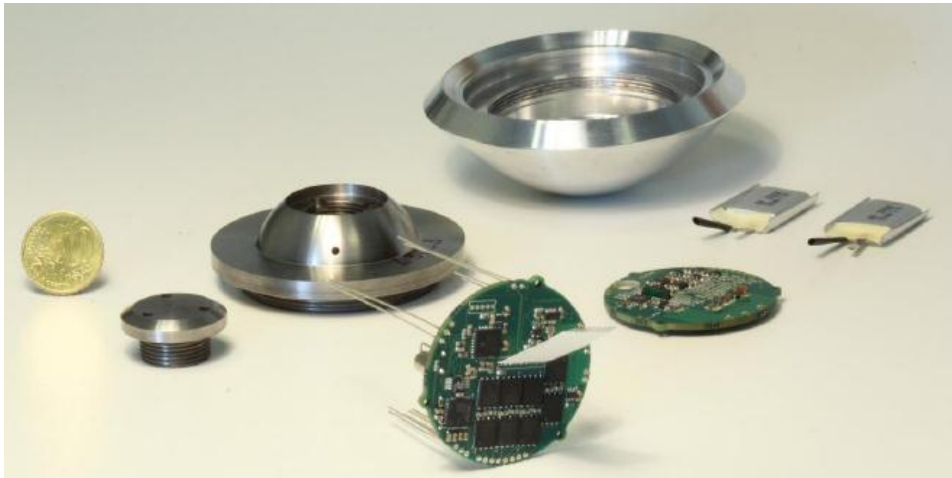
Model L_30
(tungsten/zicral: m=539g)
Xcg/D =30%

Same center of gravity position, distinct masses
→ *for dynamic scaling issues*

Distinct center of gravity positions
→ *for influence of the center of gravity issues*

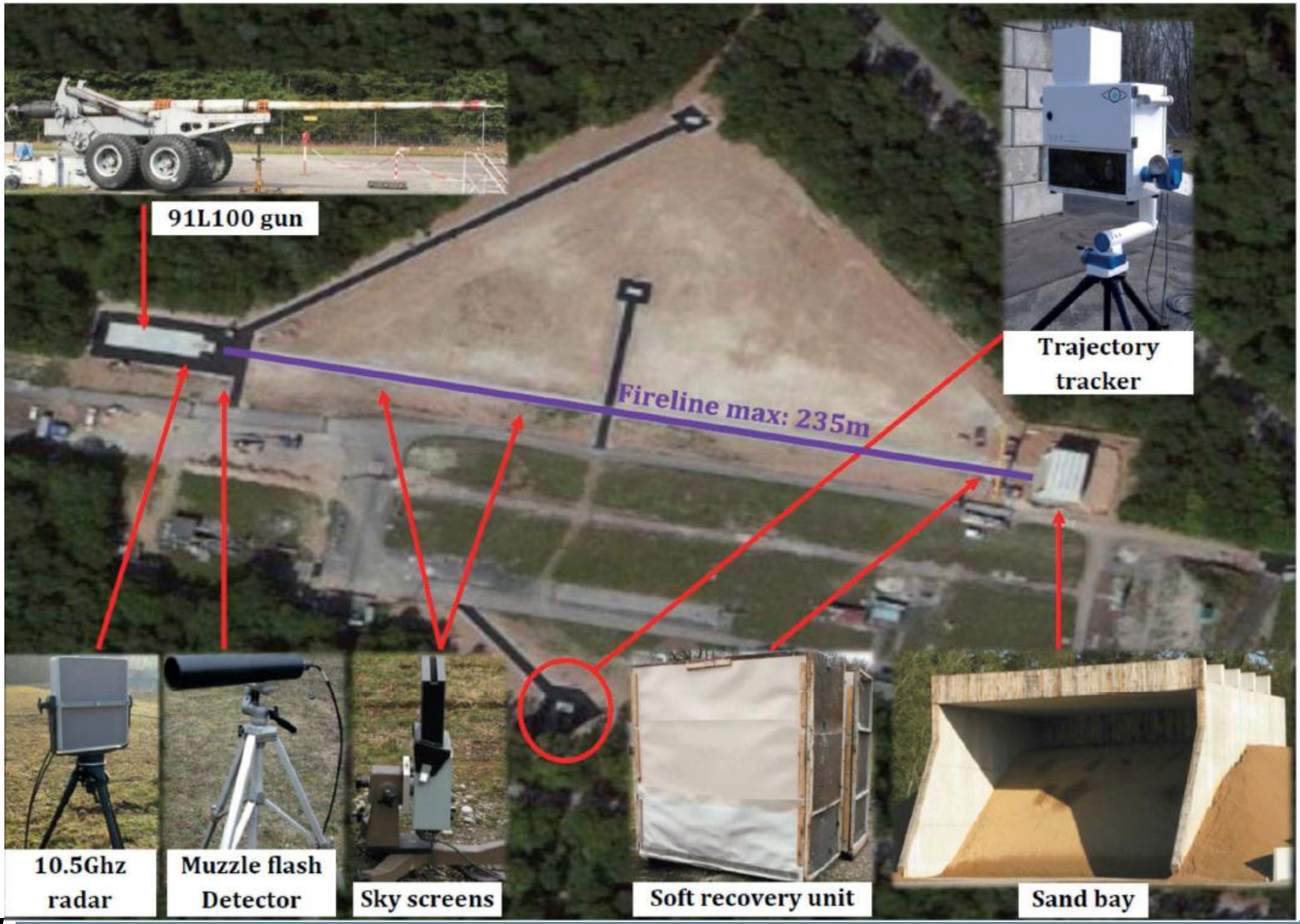
All models equipped with:

- 3 magnetic sensors (1 axial and 2 radials)
- 2 radial accelerometers



Open range test facility and test conditions

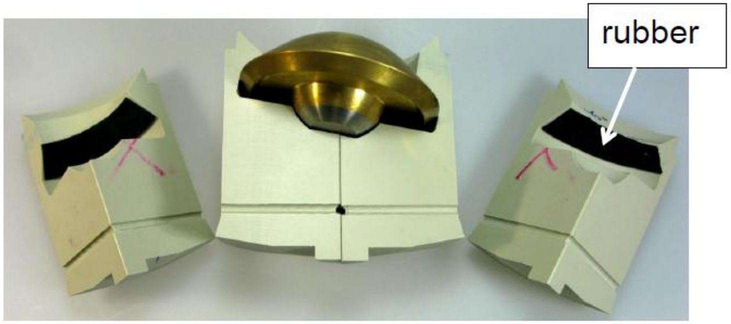
Several free flight tests were performed with the three distinct model architectures (L_25, H_25, L_30) at the ISL Open Range test site



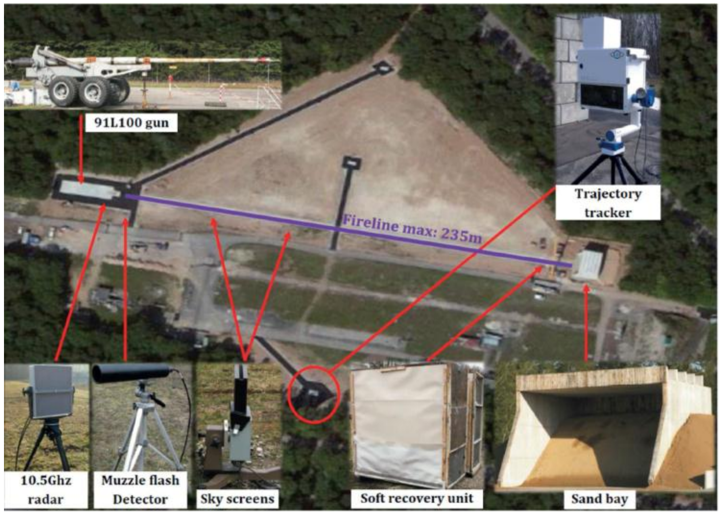
Open range test facility, test conditions and challenges

Experimental conditions and challenges:

- Sabot design for initial angle of attack $\alpha 0$ of 0, 6 and 10°
  - All sabot were made in 4 petals
- Spin rates between 0 and 4.3 Hz
  - Rubber strips glued inside each sabot petal
  - Rifled adapter at the gun muzzle
- Initial Mach number ranging between 0.9 to 3.2, for firing distances of 150 and 225m
- Electronic package potted inside the model in order to prevent damage due to high launch accelerations and impact shocks
- Successful synchronization of distinct measurement techniques



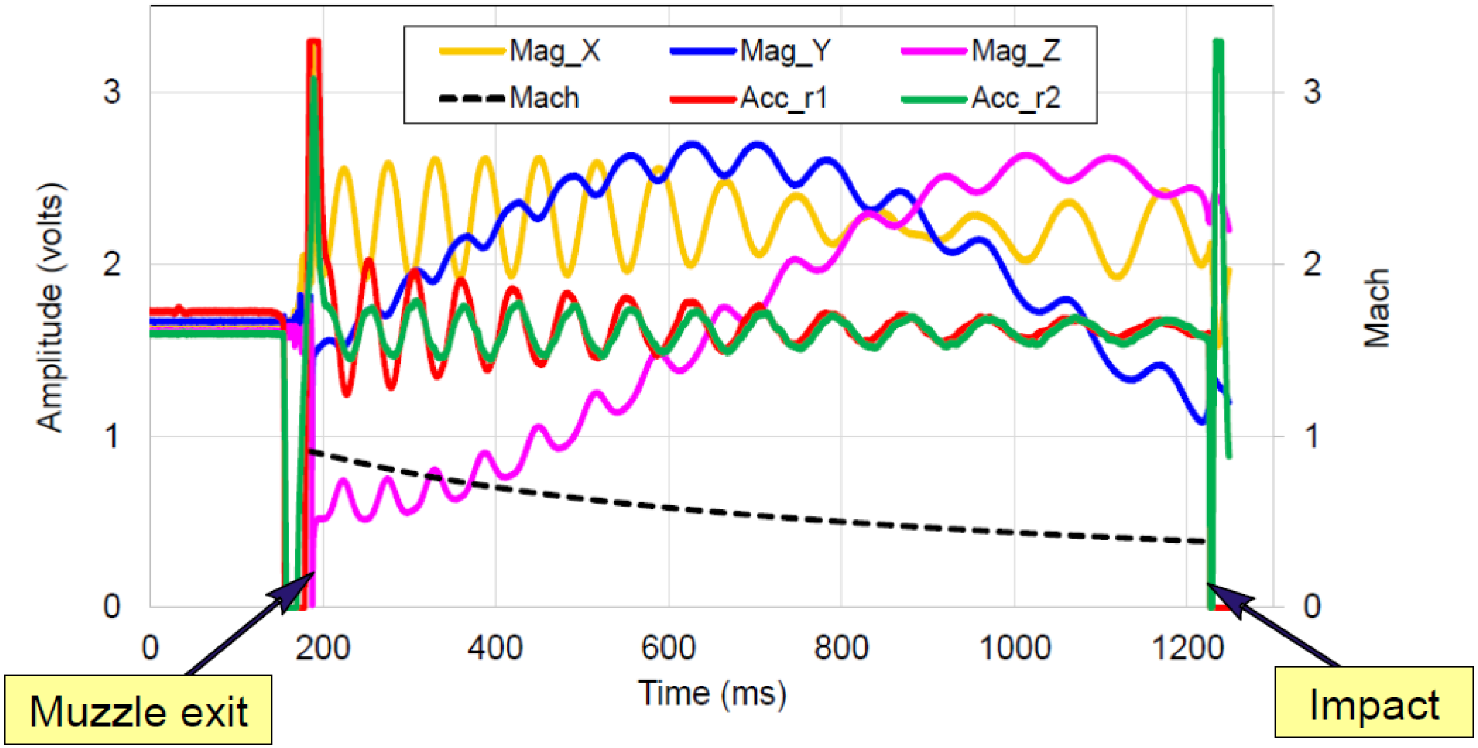
Model/sabot package for $\alpha 0$ = 10°



Measurement techniques

Example of a space vehicle free flight test for M0 = 0.8, $\alpha 0 = 10°$, ω_x=39 rpm

- Raw signals obtained from the embedded sensors



- Video obtained from a high speed video trajectory tracker

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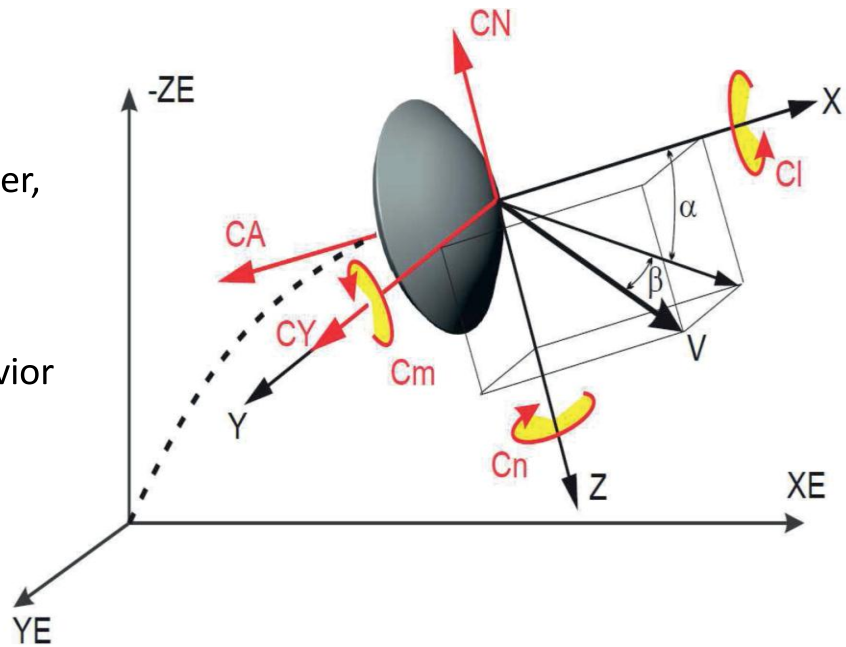
Aerodynamic parameter identification

Let us suppose that we have access to

- Free flight data corresponding to 3D magnetometer, radar and 3D optical system

- Nonlinear state-space model describing the behavior of the vehicle in free flight

$$\begin{cases} \dot{\mathbf{x}}(t) = f\left(x(t), \mathbf{C}(\mathbf{x}(t), \mathbf{p}_a)\right), \quad \mathbf{x}(0) = \mathbf{x}_0 \\ \mathbf{y}(t) = g(\mathbf{x}(t)) \end{cases}$$



where $\mathbf{x} = [V, \alpha, \beta, \omega_x, \omega_y, \omega_z, \phi, \theta, \psi, x_E, y_E, z_E]$ - state variable vector

$\mathbf{y} = [V, H_{x,body}, H_{y,body}, H_{z,body}]$ - output variable vector

$\mathbf{C} = [C_A, C_Y, C_N, C_l, C_m, C_n]$ - global aerodynamic coefficients

$\mathbf{p}_a$ - aerodynamic coefficient parameter vector

▶ Parameter identification of aerodynamic coefficients based on free flight data

Aerodynamic parameter identification

The determination of the aerodynamic coefficients based on free flight data, considering a given mathematical structure of the model flight,

$$\begin{cases} \dot{\mathbf{x}}(t) = f(x(t), \mathbf{C}(\mathbf{x}(t), \mathbf{p}_a)), \quad \mathbf{x}(0) = \mathbf{x}_0 \\ \mathbf{y}(t) = g(\mathbf{x}(t)) \end{cases}$$

corresponds to a parameter identification problem, where the unknown parameters are defined by

- Parameters $\mathbf{p}_i$ describing the aerodynamic coefficients :

$$C_i(M, \alpha_t, \mathbf{p}_i) = h_i(M, \alpha_t, \mathbf{p}_i)$$

$$M = V/a, \quad \alpha_t = \arccos(\cos\alpha \cos\beta)$$

$$i = D, L\alpha, m\alpha, mq$$

- Nine initial state variables:

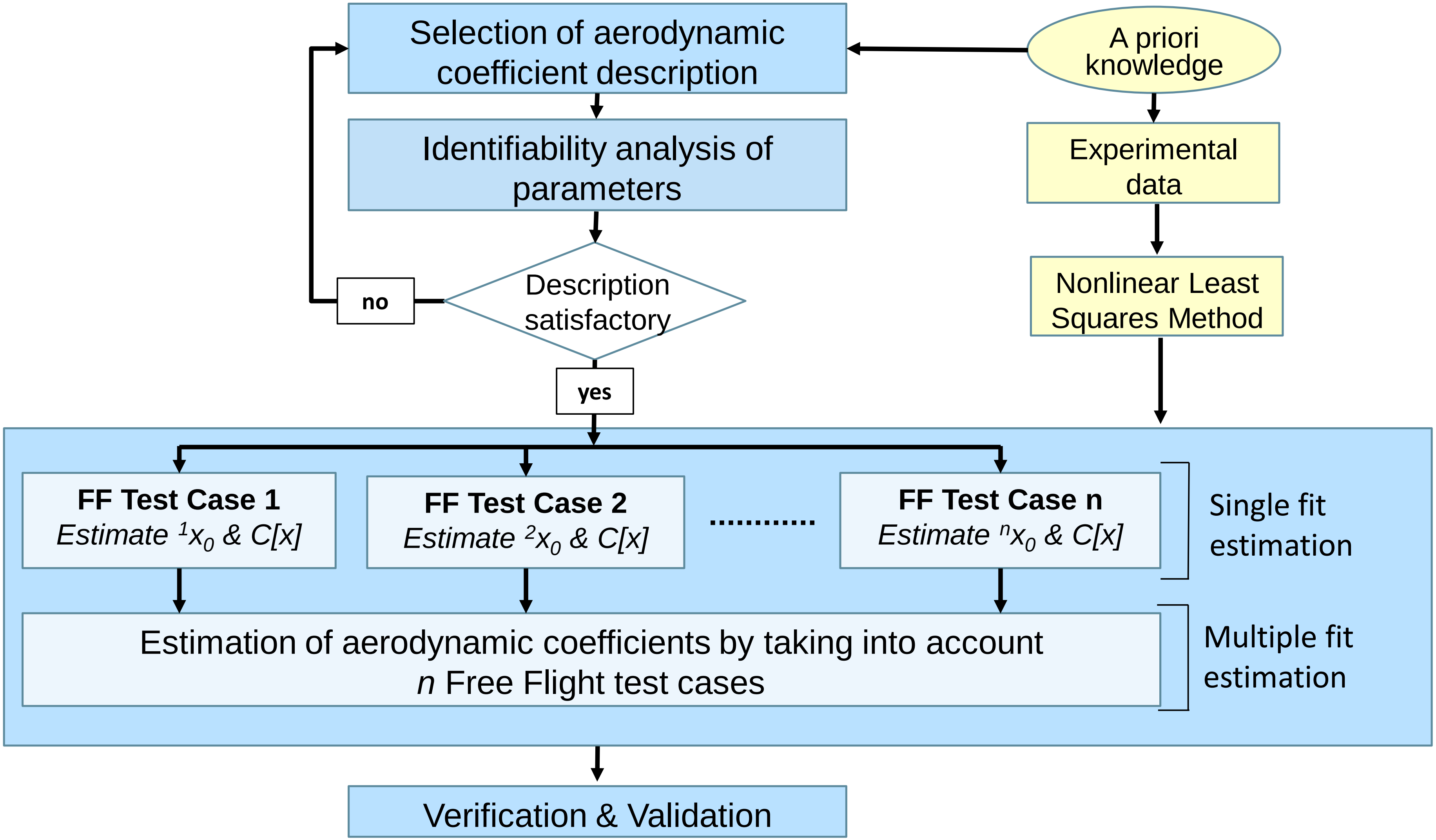
$$[V_0, \alpha_0, \beta_0, \omega_{x0}, \omega_{y0}, \omega_{z0}, \phi_0, \theta_0, \psi_0]$$

The parameter identification problem is challenging mainly due to:

- **The nonlinear structure of the mathematical model**
- **The nonlinear dependency of the aerodynamic coefficients on several state variables**
- **The constraints imposed by the experimental conditions**
- **The absence of an input signal**
- **The additional estimation of the nine initial state variables**

Solution:
Define an adapted identification procedure

Identification procedure



Albisser M., "*Identification of aerodynamic coefficients from free flight data*", PhD Report, 2015. ISL Report R 118/2015

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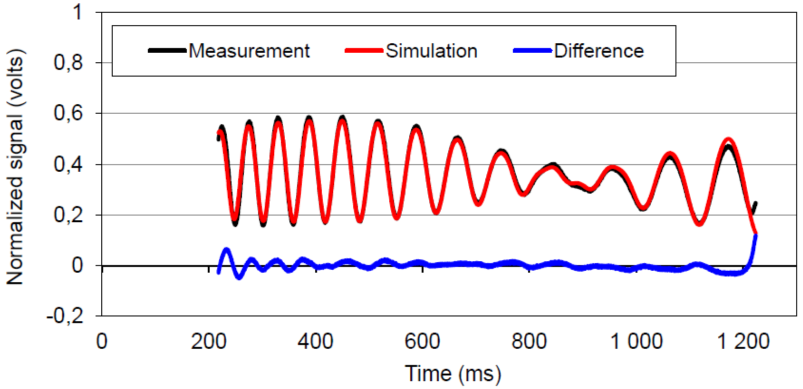
Results

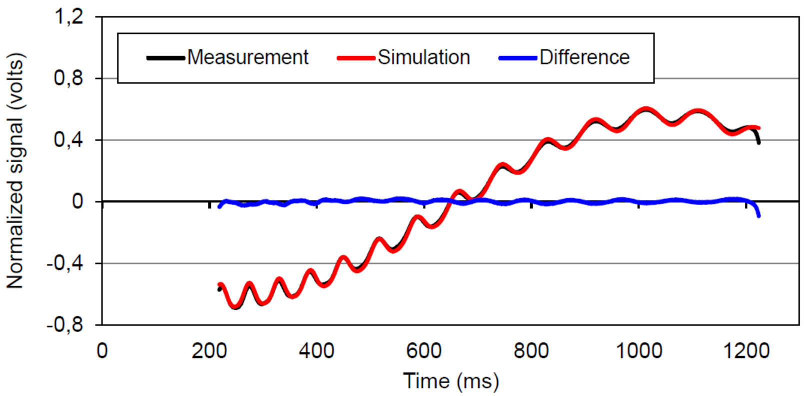
3D magnetometer signals

Run #1452_38, M0=0.8, α0=10°, ω_x=39 rpm

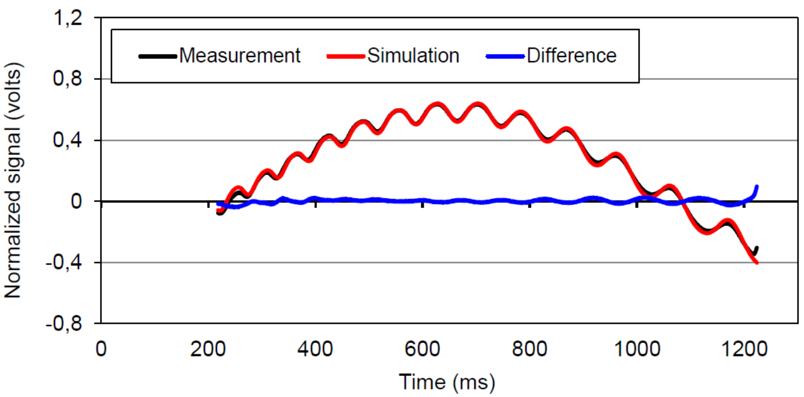


Axial magnetometer

Signals are normalized for values between -1 and 1 corresponding to signal amplitude of 0V to 3.3V



First radial magnetometer

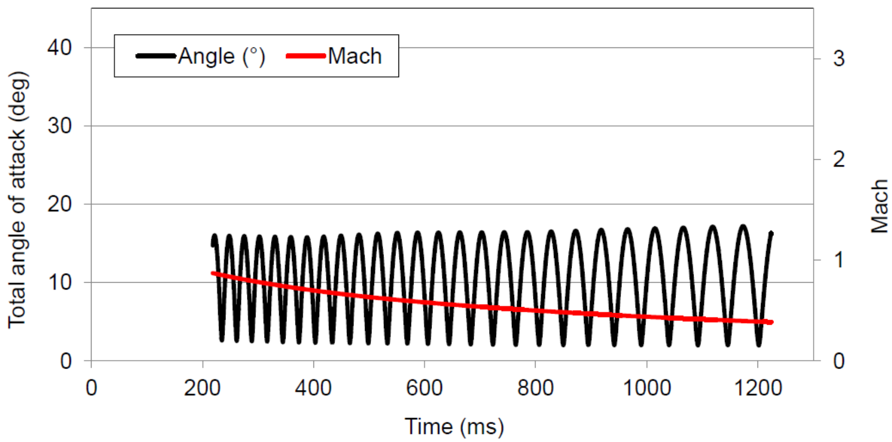


Second radial magnetometer

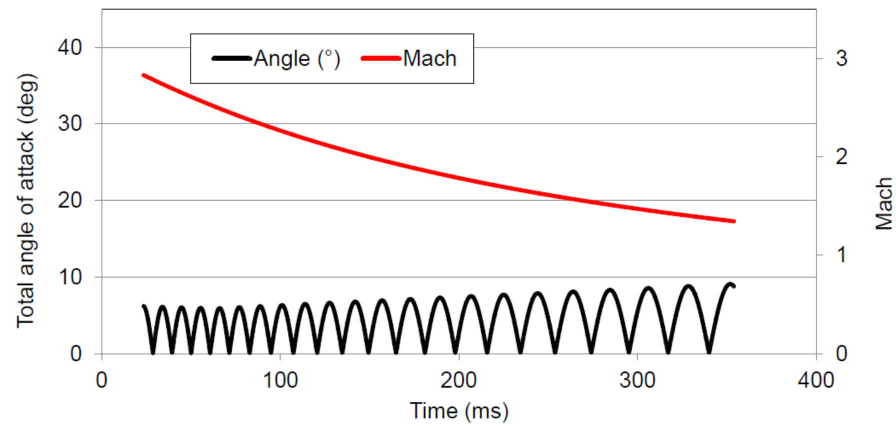
Results

Evolution of the Mach number and total angle of attack α_t

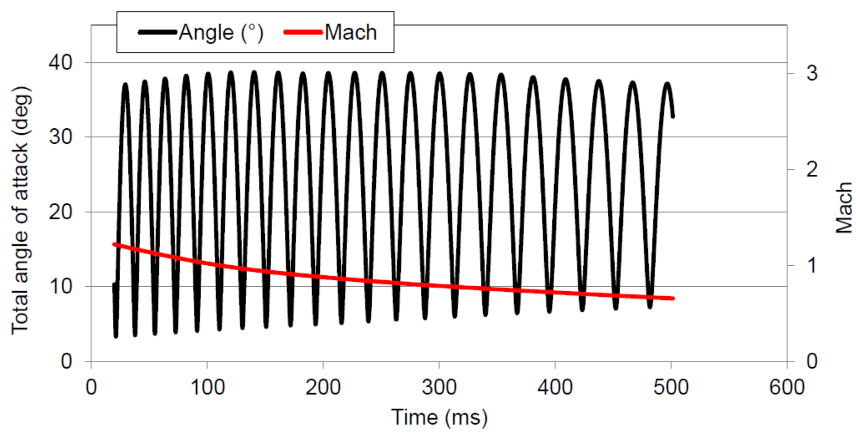
L_25: M0=0.8, α0=10°, ω_x=39 rpm



H_25: M0=3.0, α0=0°, ω_x=37 rpm



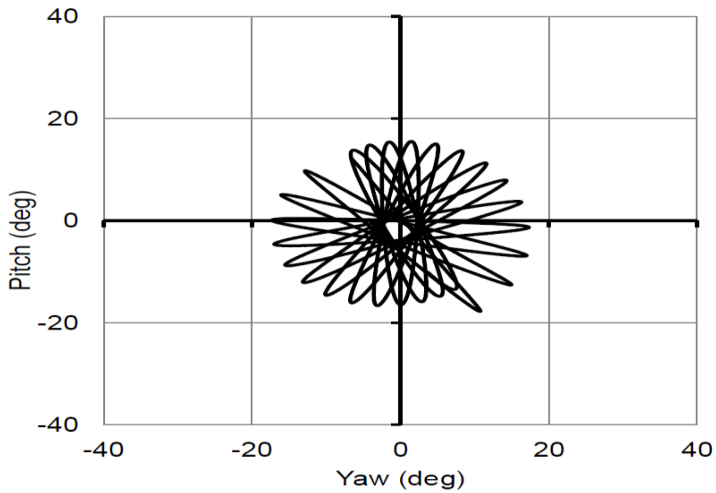
L_30: M0=1.2, α0=6°, ω_x=256 rpm



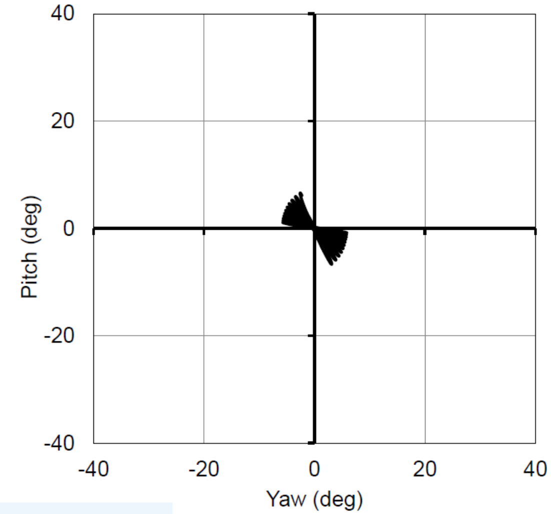
Results

Evolution of the polar motion

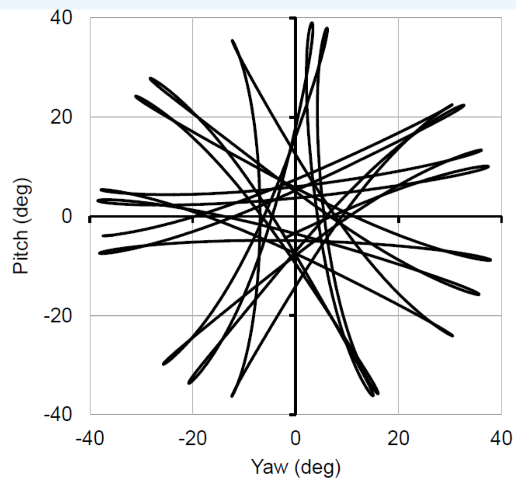
L_25: M0=0.8, α0=10°, ω_x=39 rpm



H_25: M0=3.0, α0=0°, ω_x=37 rpm



L_30: M0=1.2, α0=6°, ω_x=256 rpm

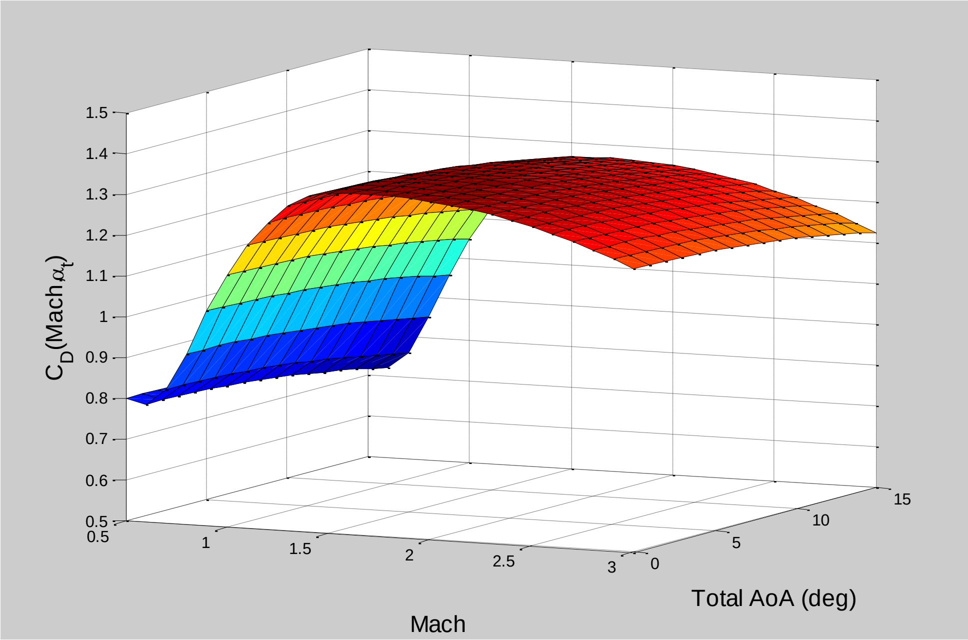


- Qualitative analysis of the polar motion

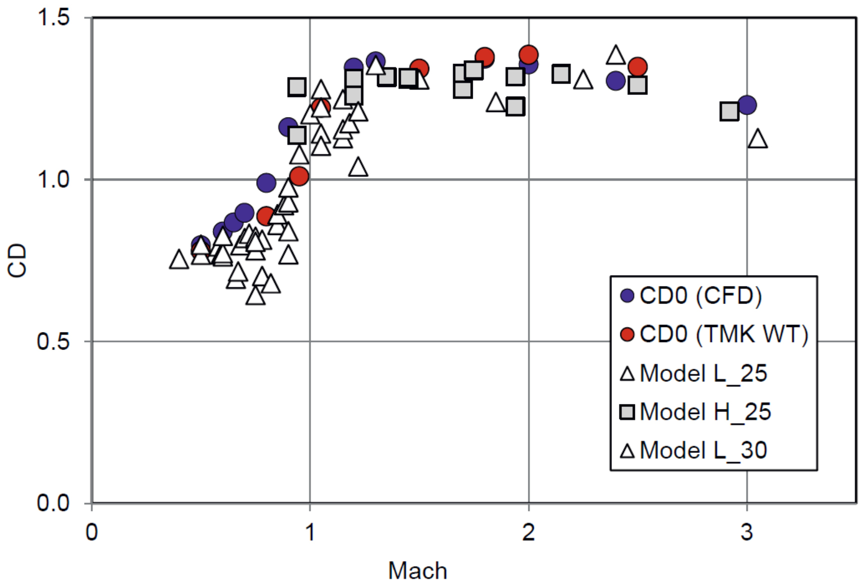
Results

Estimation of the Drag coefficient C_D

Multiple-fit results



Single-fit results



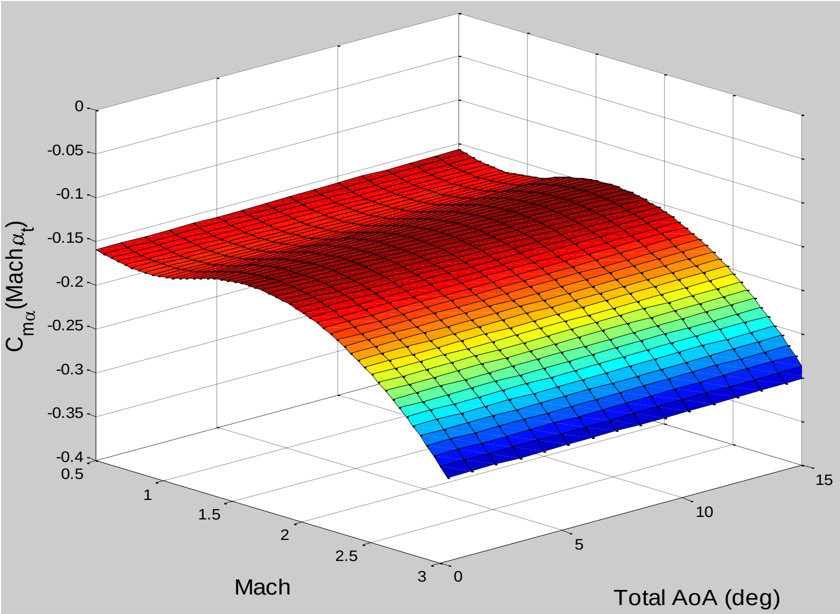
$$CD(M,\alpha) = C_{D,0} + C_{D,\varepsilon 2}.\sin^2\alpha_t + C_{D,m1}.M + C_{D,m2}.M^2 +$$

$$+C_{D,sm1}\cdot\begin{cases}(M-0.8)^2, \text{if } M \geq 0.8 \\ 0, \quad\quad \text{if } M < 0.8\end{cases} + C_{D,sm2}\cdot\begin{cases}(M-1.5)^2, \text{if } M \geq 1.5 \\ 0, \quad\quad \text{if } M < 1.5\end{cases}$$

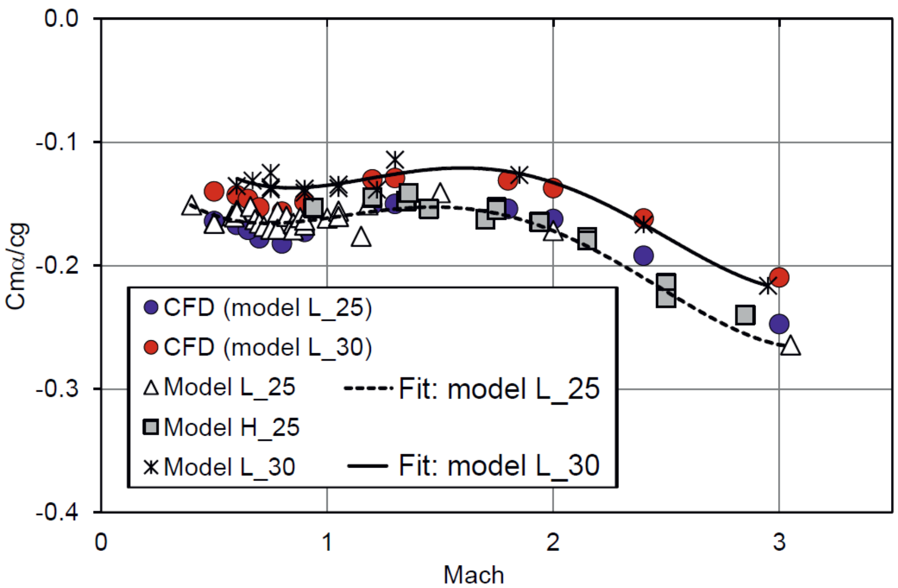
Results

Estimation of the Pitch moment coefficient derivative $C_{m\alpha}$

Multiple-fit results



Single-fit results



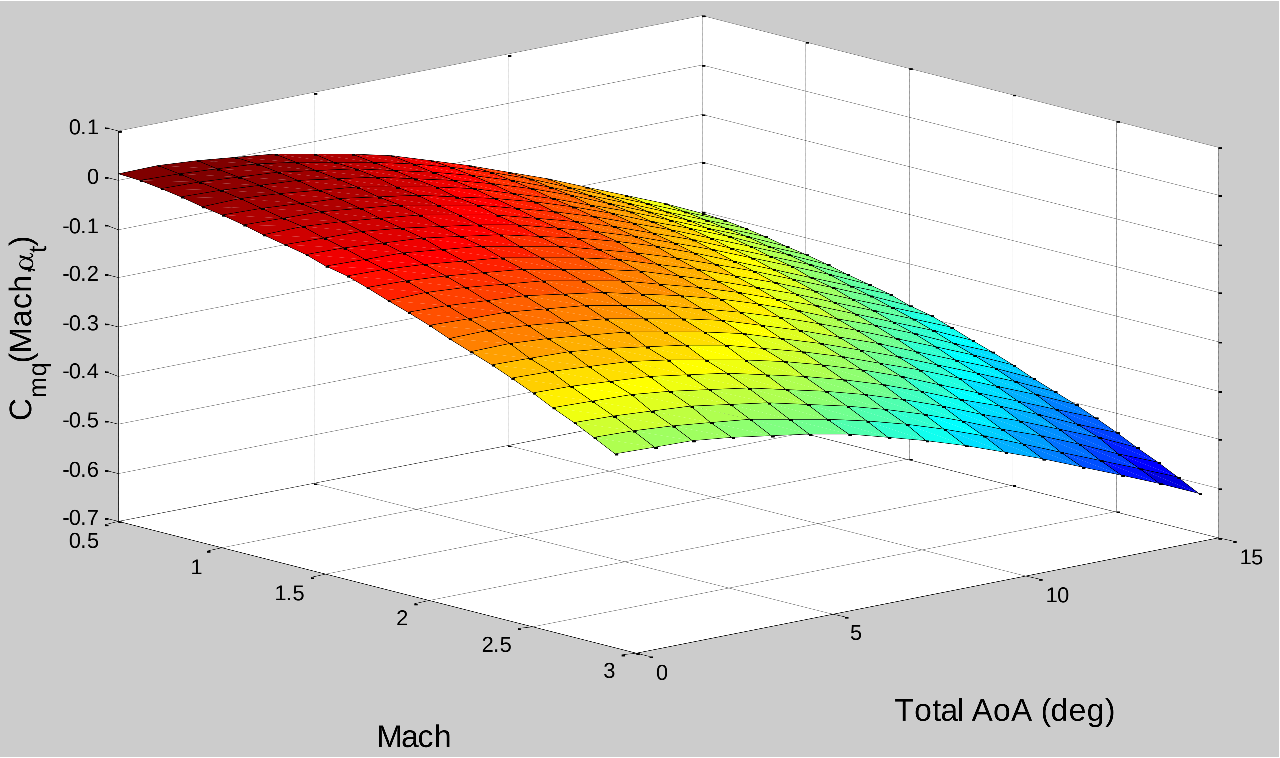
$$C_{m\alpha}(M,\alpha_t) = C_{m\alpha,0} + C_{m\alpha,\varepsilon}.\sin^2\alpha_t + C_{m\alpha,m1}.M + C_{m\alpha,m2}.M^2 +$$

$$+C_{m\alpha,s1}\cdot\begin{cases}(M-1.2)^2, \text{if } M \geq 1.2\\ 0, \quad \text{if } M < 1.2\end{cases} + C_{m\alpha,s2}\cdot\begin{cases}(M-2)^2, \text{if } M \geq 2\\ 0, \quad \text{if } M < 2\end{cases}$$

$$+C_{m\alpha,s3}\cdot\begin{cases}(\alpha_t-\bar{\alpha}_{t,1})^2, \text{if } \alpha_t \geq \bar{\alpha}_{t,1}\\ 0, \quad \text{if } \alpha_t < \bar{\alpha}_{t,1}\end{cases}; \qquad \bar{\alpha}_{t,1} = 10°$$

Results

Estimation of the Pitch damping coefficient C_{mq}



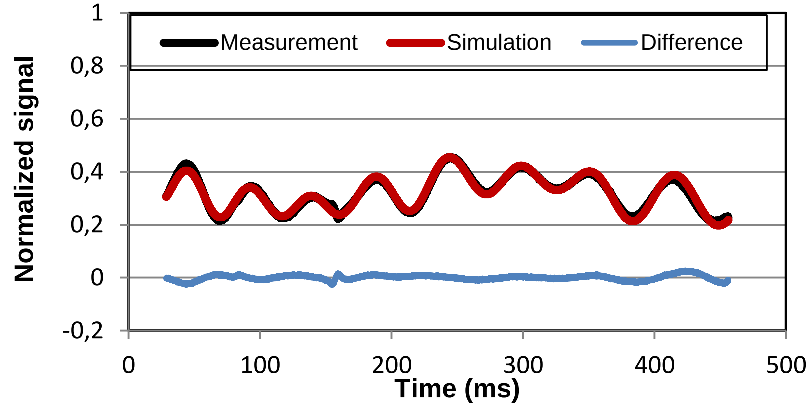
$$C_{mq}(M,\alpha,\beta) = C_{mq,0} + C_{mq,\varepsilon 2} \cdot \sin^2 \alpha_t + C_{mq,m1} \cdot M + C_{mq,m2} \cdot M^2 +$$

$$+ D_{\alpha 1} \cdot \begin{cases} (\alpha_t - \bar{\alpha}_{t,1})^2, \text{if } \alpha_t \geq \bar{\alpha}_{t,1} \\ 0, \qquad\qquad \text{if } \alpha_t < \bar{\alpha}_{t,1} \end{cases}; \qquad \bar{\alpha}_{t,1} = 10°$$

Results

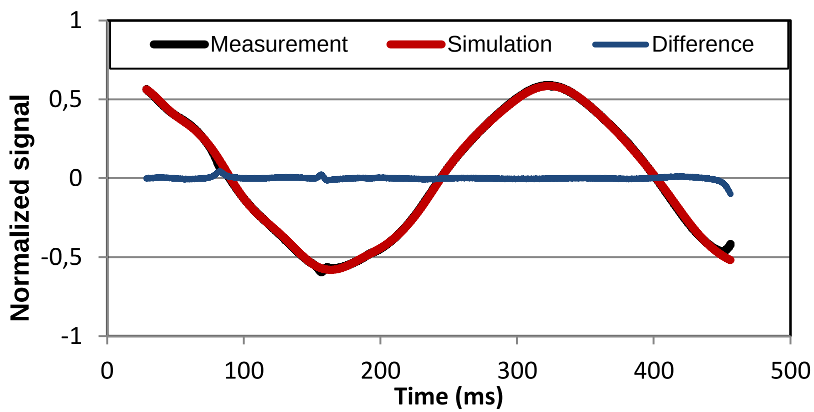
Validation step (3D magnetometer signals)

Run #1452_45, M0=0.8, α0=0

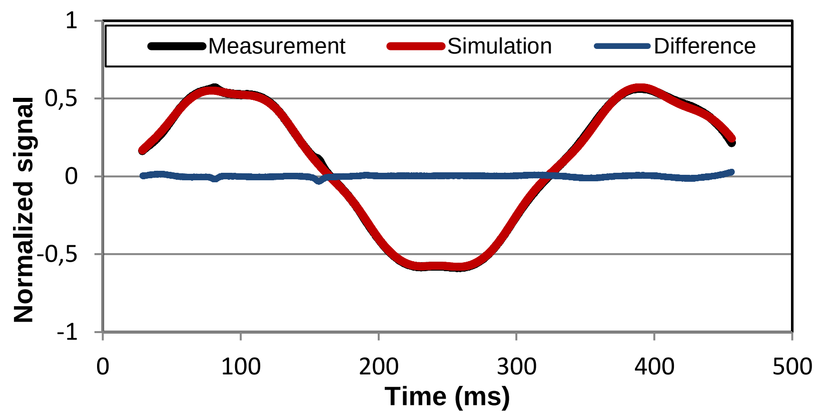


Axial magnetometer

Signals are normalized for values between -1 and 1 corresponding to signal amplitude of 0V to 3.3V



First radial magnetometer



Second radial magnetometer

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Conclusions

- Three types of instrumented models were launched at initial Mach numbers equal to 0.8, 1.2, 1.8 and 3.0, for initial angles of 0, 6 and 10° and spin rates between 0 and 250 rpm

- Data reduction:
  - a multiple fit strategy was applied in order to determine the evolution of the aerodynamic coefficients as a function of the Mach number and total angle of attack α_t
  - was very arduous especially for an accurate determination of the initial conditions of the state variables

- Obtained results showed that:
  - with the exception of the normal force coefficient, coefficients C_D, $C_{m\alpha}$ and C_{mq} were determined as a function of Mach and angle of attack
  - in all cases a combination of pitching and yawing that induces in some cases a strong conical or wobbling motion associated to small or large spin rates
  - the dynamic stability derivatives are a complex function of angle of attack and Mach number

- The ISL results allowed the population of the MarcoPolo-R aerodynamic data base (AEDB)

Conclusions
Challenges

- **Model design:** *from a mechanical and electronical point of view*

- **Instrumentation:** *design and manufacturing of the electronic equipment, calibration of the sensors*

- **Sabot design:** *to ensure the desired behavior in flight*

- **Free flight test:** *challenges in terms of synchronization between measurement techniques, spin system, recovery*

- **Data reduction : *identification of aerodynamic coefficients***

Acknowledgments
- the free flight team (ABX) for the design of the models and sabots, conducting the tests
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- the ISL main workshop for manufacturing the models and sabots

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