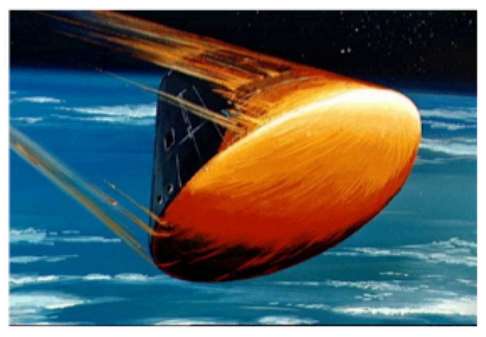
Experimental Determination of the Dynamic Derivatives of a Reentry Capsule in Transonic Supersonic Regime

Sébastien Paris[1], Özgür Karatekin[2]

[1] Von Karman Institute for Fluid Dynamic, Chaussee de Waterloo, 72 B-1640 Rhode Saint Genes, BELGIUM
[2] Royal Observatory of Belgium, 3 av. Circulaire, 1180 Brussels, BELGIUM
e-mail:paris@vki.ac.be

Introduction




- **Objective:**
  - Improve the dynamic characterization of reentry vehicle in order to ensure safe **parachute deployment** and delay the **parachute opening**
  - To determine the aerodynamic damping for the re-entry vehicle in **subsonic and supersonic** flow regimes
  - Assessment of the **support effect and associated error**
  - Lessons for future activities

The free oscillation technique

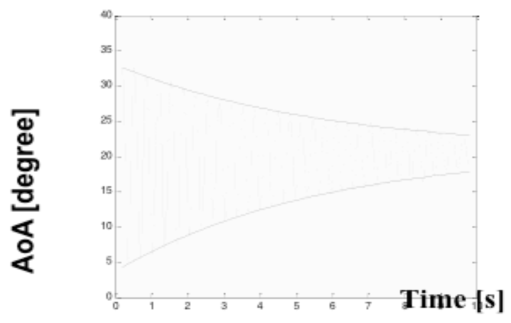
- The method consists in releasing the model free to tumble
- Envelope Method was selected

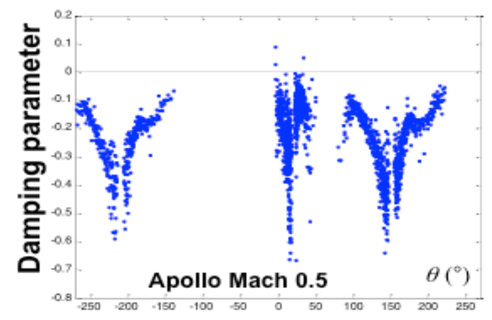
$$a = \frac{2}{nT}\ln\left(\frac{x_2}{x_1}\right)$$

T is the period of the signal
x1 and x2 are two extreme values separated by n periods

Processing was performed with n=7

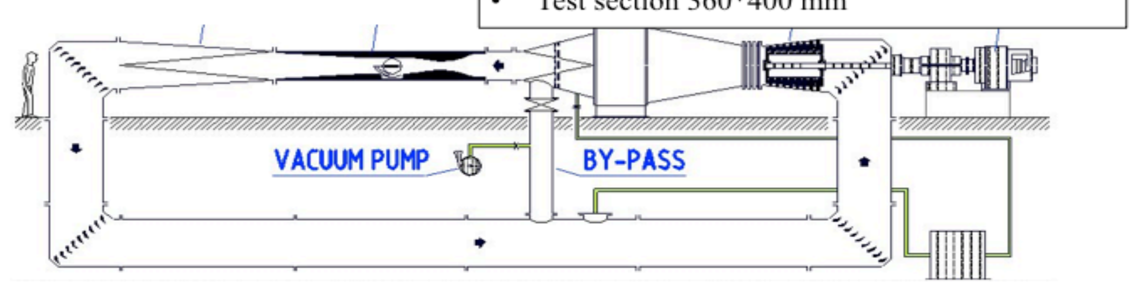
$$C_{mq} + C_{m\dot\alpha} = -\frac{I\,a}{q_\infty S D \frac{D}{2U_\infty}}$$





Facility : S1 Wind Tunnel

- Mach number capability: 0.2 – 1.05, 2.0
- Typical Reynolds number: 4 X10^6 [/m]
- Test section 360*400 mm



Mach	*P (Pa)*	*T (K)*	U_∞ *(m/s)*	q_∞ *(m/s)*	*Re* (m^{-1})
0.5	23598	286.2	168.63	4129,6	$2.57.10^6$
0.69	21744	279.0	232.28	7246,8	$3.22.10^6$
0.87	20261	274.8	287.62	10734,9	$3.60.10^6$
2.08	5319	161.6	529.53	16107,0	$1,50.10^6$

Theory

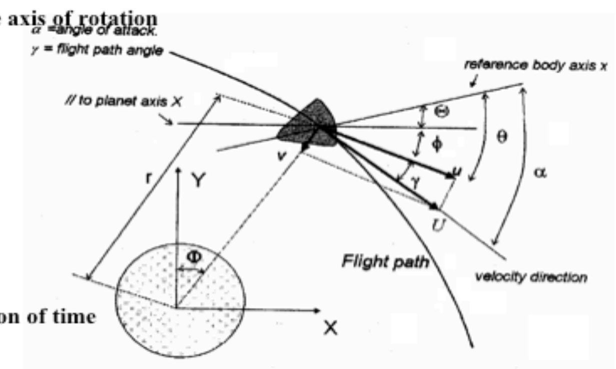
The governing equation for a 1 DoF in rotation

$$I\ddot\theta - \left(C_{m_q} + C_{m_{\dot\alpha}}\right)\frac{q_\infty S D^2}{2U_\infty}\dot\theta - q_\infty S D\frac{\partial C_m}{\partial\theta}\theta = M(t)$$

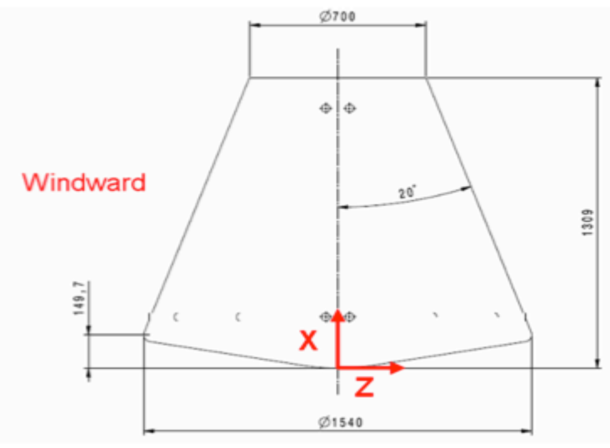
term of inertia — Damping component — Stiffness — External moment

$$C_{m_\alpha} = \frac{\partial C_m}{\partial\left(\frac{\dot\alpha D}{U_\infty}\right)} \qquad C_{m_q} = \frac{\partial C_m}{\partial\left(\frac{q D}{U_\infty}\right)}$$

- I is the vehicle moment of inertia about the axis of rotation
- θ is the of pitch attitude angle
- α is the angle of attack
- C_m is the pitch moment coefficient
- q_∞ is the free stream dynamic pressure
- S is the vehicle reference area
- D is the vehicle characteristic length
- U_∞ is the total free stream velocity
- $M(t)$ is an external forcing moment as a function of time



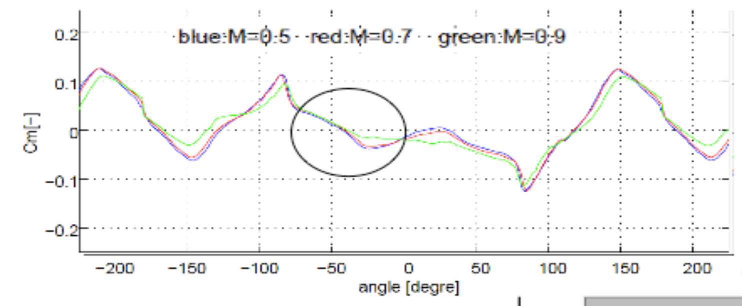
Reference geometry



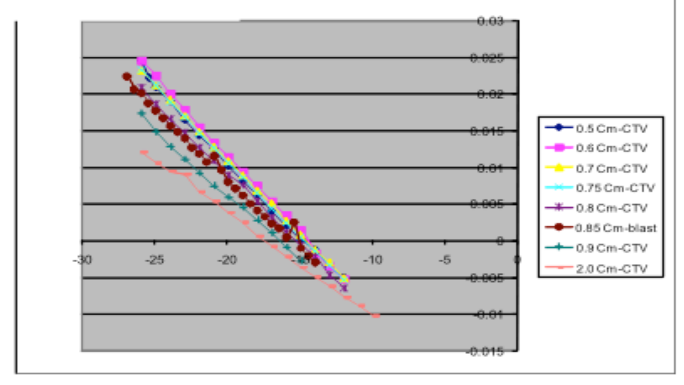
Wind tunnel Model
Reference Length: 77mm diameter
Material: Ureole for static measurement
Light Resin for dynamic testing

	CTV B1	CTV B2
Lref [mm]	4400	7466
Mass [kg]	TBD	TBD
X_{COG} [%]	34	34
Z_{COG} [%]	-2.18	-2.18
Y_{COG} [%]	0	0
Ixx [kg.m²]	TBD	17500
Iyy[kg.m²]	12300	16800
Izz [kg.m²]	12300	16800

Pitching moment coefficients for CTV 1996/2010



CTV-1996
$A_{trim} \approx -42; -43$
Mach=[0,5-0,9]



CTV-2010
$A_{trim} \approx -14; -17$
Mach=[0,5-0,9 ; 2]

Parameter to be matched for the similitude: Strouhal Number

- In order to reproduce the dynamic behaviour of the vehicle, we have to match the flight and experimental "Strouhal number"

$$St = \frac{fD}{U_\infty}$$

- Strouhal (flight)= Strouhal (wind tunnel)
- In flight, the natural frequency is deduced from the resolution of the second order differential equation

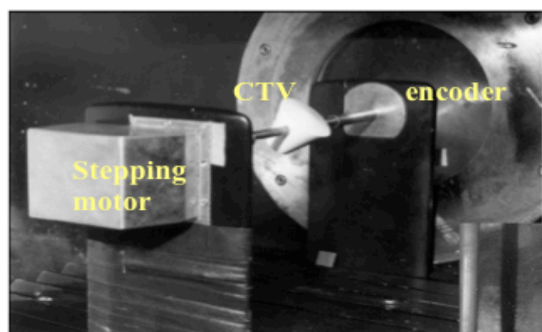
$$(\omega_n)_n = \left(\sqrt{\frac{q_\infty S D\left(\frac{\partial C_m}{\partial\theta}\right)}{I} - \left(\frac{q_\infty S D\left(C_{m_q} + C_{m_{\dot\alpha}}\right)}{2I}\right)^2}\right)_n$$

Second term negligible

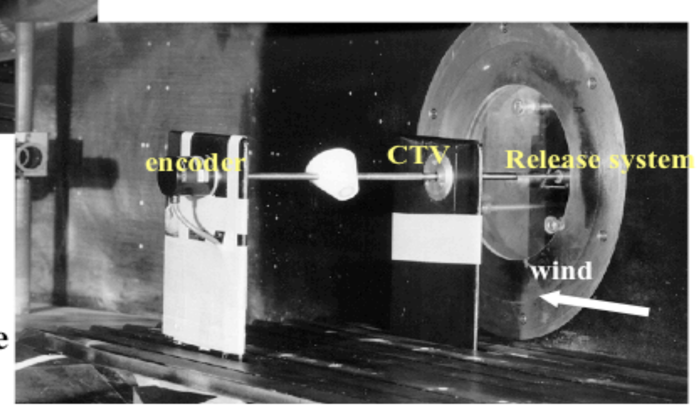
Flight Strouhal number become:

$$(St)_n = \left(\frac{\omega_n D}{2\pi U_\infty}\right)_n = \left(\sqrt{\frac{\rho_\infty S D^3\left(\frac{\partial C_m}{\partial\theta}\right)}{8\pi^2 I}}\right)_n$$

1996 Old set-up for static and dynamic experiment

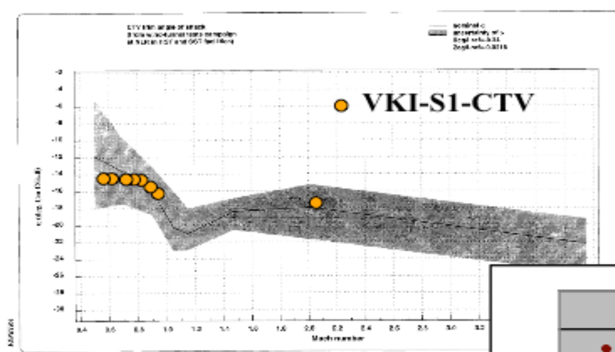


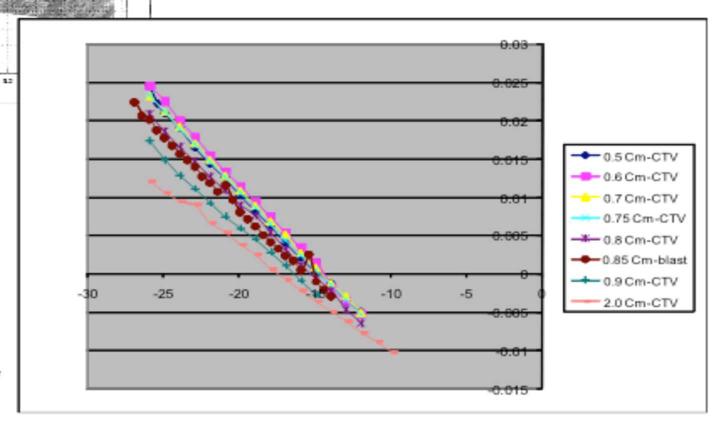
Set-up for static force measurement



Set-up for free to tumble experiment

Comparison with existing literature data





CTV-2010
$A_{trim} \approx -14; -17$

Parameter to be matched: Strouhal Number

- For free oscillation

$$I_{experiment} = \left(\frac{I}{\rho_\infty D^5}\right)_{flight} * \left(\rho_\infty D^5\right)_{experiment} \rightarrow \textbf{Inertia}$$

Mass of the model
Need of light material

- For forced oscillation

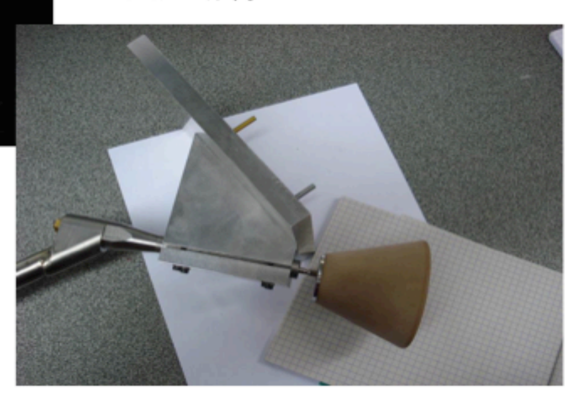
$$f_{oscillations} = \frac{1}{2\pi}\left(\sqrt{\frac{\rho S D^3\left(-\frac{\partial C_m}{\partial\alpha}\right)}{2I}}\right)_{flight}\left(\frac{U}{D}\right)_{experiment} \rightarrow \textbf{Frequency}$$

Powerful driving mechanism
Need of light material

2010 Wind tunnel Models for static measurement

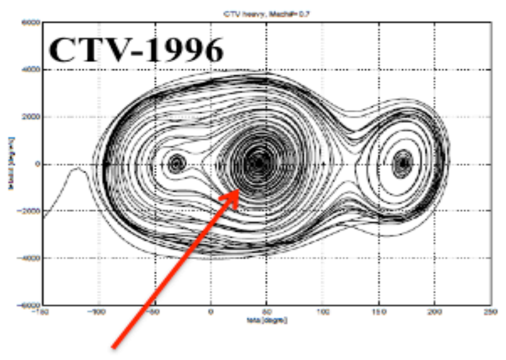
Model installed in the wind tunnel

This balance was designed and build to fit into the model
Calibration matrix was defined and uncertainty analysis gives error less than 1.5%

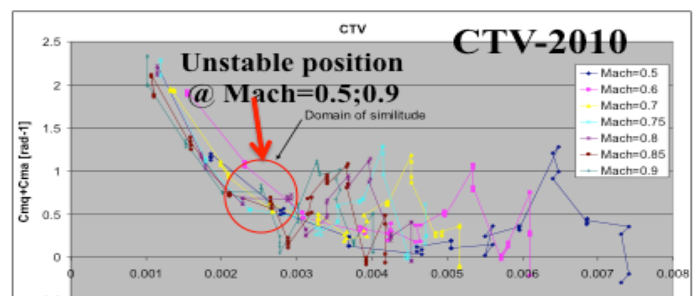


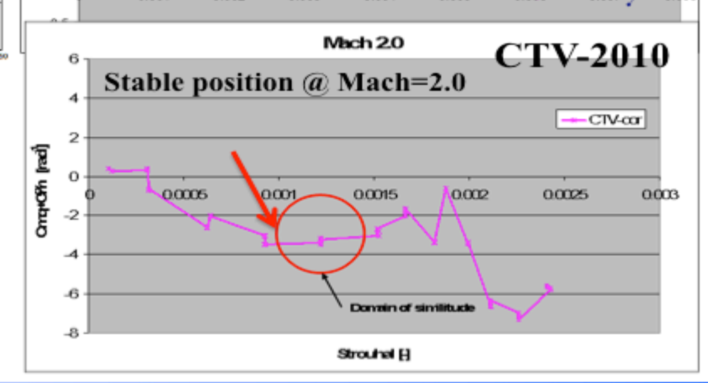
Model equipped with the support of electronic level (+/- 10')

Results for the dynamic tests



Stable position @ Mach=0,7





As the flight Strouhal number vary with Mach number and inertia, the frequency of oscillation was varied from very low to high frequency.

Parameter to be matched: Strouhal Number

- For free oscillation

$$I_{experiment} = \left(\frac{I}{\rho_\infty D^5}\right)_{flight} * \left(\rho_\infty D^5\right)_{experiment} \rightarrow \textbf{Inertia}$$

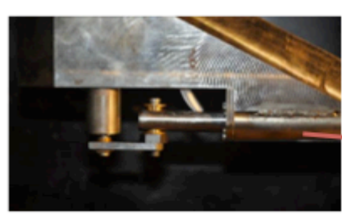
Mass of the model
Need of light material

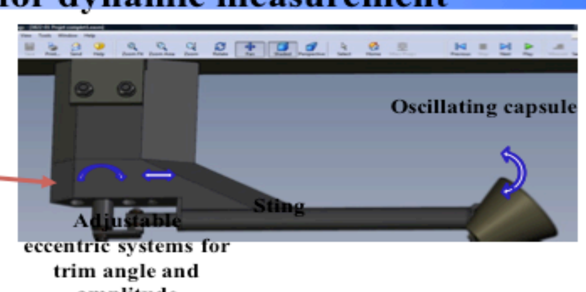
- For forced oscillation

$$f_{oscillations} = \frac{1}{2\pi}\left(\sqrt{\frac{\rho S D^3\left(-\frac{\partial C_m}{\partial\alpha}\right)}{2I}}\right)_{flight}\left(\frac{U}{D}\right)_{experiment} \rightarrow \textbf{Frequency}$$

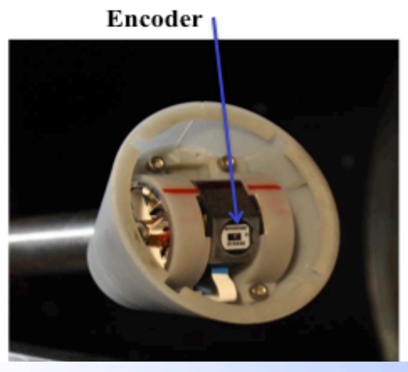
Powerful driving mechanism
Need of light material

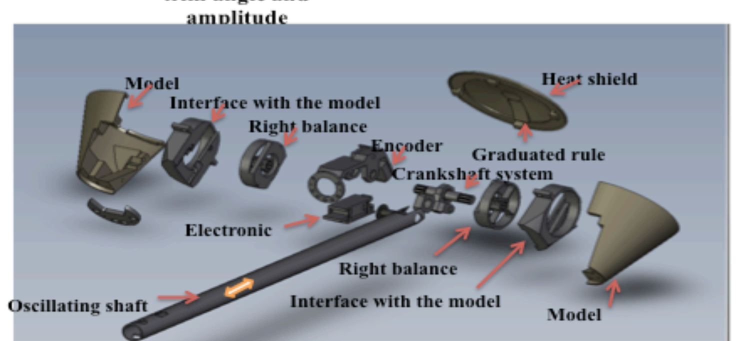
2010: Experimental set up for dynamic measurement





Encoder





Preliminary analyze

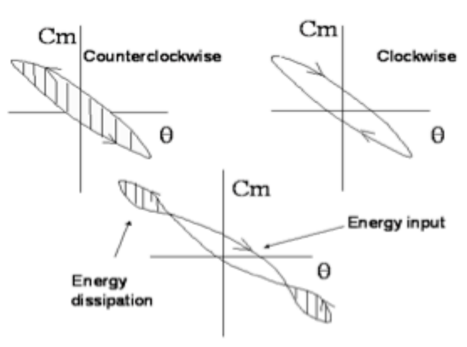
- New static results (with the sting) are in agreement with existing literature data
- New static data disagree with previous data obtain at VKI (probably due to the transversal support). Trim angle shift by 25° !!
- Old data from Free to tumble experiment show stable behavior for subsonic condition while recent data from forced oscillation give unstable capsule in the same condition
- Good repeatability of the dynamic
- Inertia doesn't play a significant role
- First successful forced oscillation testing with a sting configuration
- Many improvement have been done to improve the quality of the measurement like:
  - Acquisition card 16bit 8 channels
  - Sting, new encoder, balance …

The forced oscillation technique

- the technique consists in forcing the model in oscillation +/-5° and measuring the pitching moment
- The energy method was selected as the best one
- The aerodynamic energy exchanged by the oscillatory system over one oscillation is:

$$W = q_\infty S D \oint C_m d\theta$$

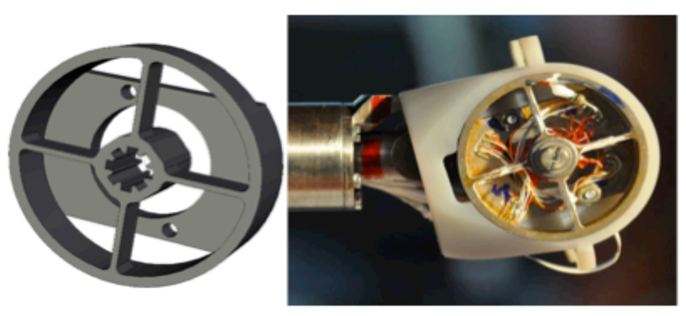
The assumption that is made when using this method is that $C_{m\dot\alpha} + C_{mq}$ should not be a function of the pitch angle θ

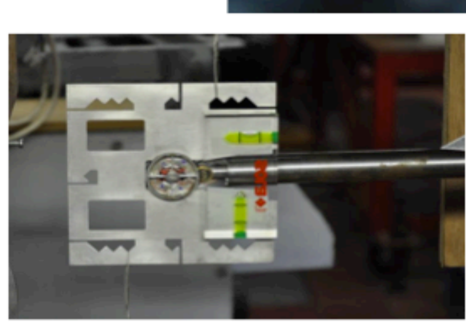


The pitch aerodynamic damping is defined as

$$C_{m\dot\alpha} + C_{mq} = \frac{\oint C_m d\theta}{\int_T \dot\theta^2 dt}\frac{2U}{D}$$

Balance for the dynamic measurement





2 Balances were designed and build for the dynamic testing.
3 components balance

Calibration matrix was defined and uncertainty analysis gives error less than 2.5%

Balance is inserted inside the model.
The CG should be exactly at the center of reduction of the balance

Special interface is build for the calibration

Lessons learnt

- Effect of the support: seems to be very important – it should be more deeply investigated for every new model
- Measurements of the angles are much better thanks to the new DAS
- Adjustment of gap between pieces must be very precise
- Stiffness of all the oscillating mechanism should be as high as possible
- The method should be validated carefully
- What is the role of amplitude???
- Is there a coupling between the wake and the model
- Intermediate Mach number (between 1 and 2) is necessary to complete the database
- Other derivatives should be investigated