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On the validation of experimental results for the dynamic stability of re-entry capsules

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ABSTRACT

The following document presents a trustworthy method for validating dynamic stability results obtained from wind-tunnel test campaigns. The first phase comprises the *calibration* of the electromagnetic test setup, in order to obtain a relation between the supplied current and the generated magnetic damping. In the *validation* phase this setup is attached to the dynamic stability forced oscillations test structure, outside of the wind tunnel. Several runs are performed with different oscillating speeds and a wide range of known values of magnetic damping for configurations with and without a spring element resembling the aerodynamic stiffness experienced by the model in the wind-tunnel. The Energy Method is then used to process the momentum and angular position recorded during the test and compute the damping acting on the system. The magnetically applied damping and the computed damping are then compared, in order to access the magnitude of the error. For the system without spring applied, results show that low values of error and uncertainty are obtained for most part of the considered curve. The magnitude of the error usually diminishes for an increase in the oscillating speed, but increases for lower values of damping.

1. Introduction

For low supersonic, transonic and subsonic regimes, re-entry capsules usually employ sets of drogue parachutes, not only as a way to decelerate the descending motion, but also as a strong stability device. In fact, for this type of flow regimes, blunt bodies are prone to present static and dynamic instability [1–3]. This instability phenomenon is driven by unsteady pressure forces acting on the afterbody of the capsule [4].

Though they are a quite standard technology, parachute aerodynamics and behaviour are difficult to access and control, namely if the opening must correct a non-stable position of the capsule.

Accordingly, the future should pass by a delay in the parachute opening, reducing its required size, provided that the capsule can maintain a static and dynamic state of stability, during transonic/subsonic flight. Following that objective, this project is developed in the framework of the dynamic stability characterization of the ARV capsule, as part of a research contract established with ESA and Astrium. Its final aim is to develop and apply a *validation technique*, that is able to access the uncertainties present in the dynamic pitch parameter obtained from wind-tunnel testing.

2. Stability theoretical and experimental approach

2.1. Re-entry governing equations

The deduction of the equations of motion of a general re-entry body are available in literature. In fact, Julian Allen already presents them in his paper [5], though the formulation presented here is the one found in more recent studies, such as [6,7]. A good starting point to determine the motion of a re-entry body is to consider that it occurs in a planar, inertial system, and that it is composed by a sum of rotation and translation movements, which allows to compute an Eulerian system of equations. This derived equations: (1) assume that the aerodynamic derivatives are independent of the Mach number and vary linearly with angle of attack; (2) neglect rotational and gravitational effects; (3) are only valid for low L/D vehicles, flying at small angles of attack ($\alpha < 30^\circ$), which is the case of most blunt re-entry capsules.

Considering the coordinate system of Fig. 1, it is possible to enounce three equations, concerning, respectively, the forces acting on the body in the direction of motion, the change in flight path angle due to forces normal to the direction of motion and the sum of moments acting on the vehicle.

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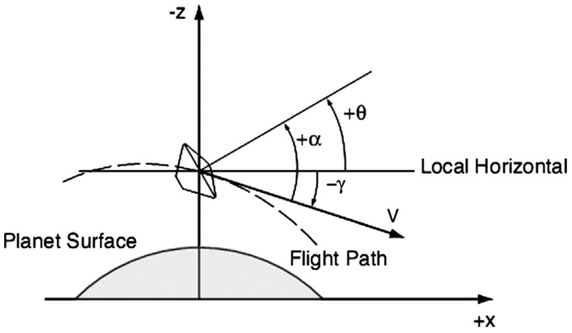

Fig. 1. Coordinate system for re-entry capsule [7].

$$\dot{V} = -\frac{\rho V^2 S C_D}{2m} - g \sin\gamma_0 \tag{1}$$

$$\dot{\gamma} = \frac{\rho V S C_L}{2m} - \left(\frac{g}{V} - \frac{V}{r}\right) \cos\gamma_0 \tag{2}$$

$$\ddot{\theta} = \frac{\rho V^2 S D}{2I} \left(Cm_q \frac{\dot{\theta} D}{2V} + C_{m_{\dot{\alpha}}} \frac{\dot{\alpha} D}{2V} + Cm_\alpha \alpha \right), \tag{3}$$

being the static and dynamic derivatives

$$C_{m_q} = \frac{\partial C_m}{\partial \left(\frac{qD}{2V}\right)} \qquad C_{m_{\dot{\alpha}}} = \frac{\partial C_m}{\partial \left(\frac{\dot{\alpha} d}{2V}\right)}. \tag{4}$$

These are the coupled, analytically unsolvable, equations for the re-entry of a rigid body. By applying the assumptions formulated before, one can consider the mean flight path angle to be a constant over a trajectory, reducing Eq. (2) to just the contribution of lift. The system then becomes

$$\begin{aligned} &\ddot{\alpha} + \left(\frac{\rho V S}{2m}\right)^2 C_D C_{L_\alpha} \alpha + \frac{\rho V S}{2m} C_{L_\alpha} \dot{\alpha} \\ &\quad = \frac{\rho V^2 S D}{2I} \left(Cm_q \frac{\dot{\theta} D}{2V} + C_{m_{\dot{\alpha}}} \frac{\dot{\alpha} D}{2V} + Cm_\alpha \alpha \right). \end{aligned} \tag{5}$$

The second term on the LHS of Eq. (5) is responsible for slightly modifying the oscillating frequency of the capsule, but since its small for this kind of cases, its contribution is neglected. From Eq. (3), the pitch rate $\dot{\theta}$ can be expressed as

$$C_{m_q} \frac{\dot{\theta} D}{2V} = C_{m_q} \left(\frac{\dot{\alpha} D}{2V} + \frac{\rho S D C_L}{4m} \right), \tag{6}$$

where the constant term is small compared to the $\dot{\alpha}$ one. Finally, Eq. (5) becomes

$$\ddot{\alpha} - \frac{\rho V S}{2m} \left[-C_{L_\alpha} + \frac{m D^2}{2I} \left(C_{m_q} + C_{m_{\dot{\alpha}}} \right) \right] \dot{\alpha} - \frac{\rho V^2 S D}{2I} C_{m_\alpha} \alpha = 0, \tag{7}$$

which is the an approximate solution of the coupled system mentioned above. This shall be the starting point of most experimental analysis performed on the domain of re-entry capsule's dynamic stability.

Following *Routh's Criteria* [8] one can state the necessary conditions for stability to be

$$\begin{cases} \frac{\partial C_m}{\partial \alpha} < 0 \\ \frac{\rho V S}{2m} \left[-\frac{\partial C_L}{\partial \alpha} + \left(C_{m_q} + C_{m_{\dot{\alpha}}} \right) \frac{d^2 m}{2I} \right] < 0. \end{cases} \tag{8}$$

The first condition obviously concerns the static stability. The derivative must be negative as the pitch moment must counteract the angle of attack change about the trim angle. The second condition concerns the dynamic stability and involves the pitch damping coefficient $C_{m_q} + C_{m_{\dot{\alpha}}}$.

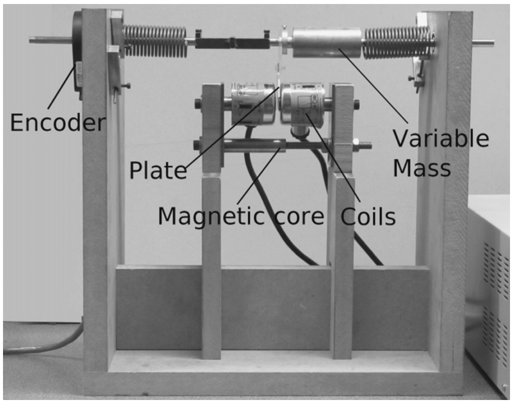

Fig. 2. Dedicated experimental setup for calibration of electromagnetic damping.

3. Dynamic analysis

3.1. Experimental setup preliminary analysis

Following the previous research activities developed at VKI [9,10], a *forced oscillation* technique is employed in order to perform a dynamic characterization of the capsule's pitch damping parameter.

During the wind-tunnel testing, the model will be put to a forced oscillation state causing an aerodynamic moment, which will change with the angular position of the model, constructing an univocal relation. This relation can be mathematically processed in order to extract the value for the aerodynamic damping acting on the capsule. Though this is standard procedure, well documented in literature [11,12], most of it lacks an in-deep analysis of the accuracy of the findings, meaning there's no validation of both the experimental and mathematical method used to convert the results obtained from the wind-tunnel testing to a damping value. Consequently, there is a need to implement a structured process to access the magnitude of the error and uncertainty associated with the experiment. This project defines a two stage process, starting with (1) a *calibration* phase in which a dedicated experimental setup, based on electromagnetic damping and free oscillations, is used (Fig. 2) with the objective of univocally relate the value of damping generated the pair of coils to the supplied current. This pair of coils is mounted on the dynamic stability forced oscillations experimental setup during (2) the *validation* phase, in which the system is put to oscillation outside of the wind-tunnel, meaning no presence of aerodynamic damping.

Instead an electromagnetic damping is applied to the setup, using the referred pair of coils. The moment acting on the capsule and its angular position are recorded. Using the calibration of phase (1) it is possible to know exactly the value of the damping we are applying to the oscillating plate, as it is directly related to the coils' supplied current. In the end, the objective is to evaluate the difference between this known damping and the one obtained with the mathematical method used to extract the damping from the recorded moment/angular position.

3.2. Theoretical aspects

3.2.1. Energy method

According to [13] several data processing approaches may be employed in order to obtain a value of damping from the recorded moment/forces and angular position. In the context of this research project only the *Energy Method* is used, has it has proven to be efficient and relatively straightforward in several previous VKI research projects in the field of dynamic stability.