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# Wind Tunnel Based Identification of Pitch Damping for a Flow-Through Model Using a Free to Tumble Rig

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## Abstract

Pitch damping identification in high-speed wind tunnels is achievable with forced vibration rigs working at small amplitudes at high technical complexity and with free to tumble rigs, potentially covering the widest possible range of angles of attack, as a simple and cost-effective alternative. Various aerospace vehicles or reentry debris can be characterized with both techniques. The focus here is on the implementation of a free to tumble rig to be used in the first instance with an interesting space debris, namely a tronconical interstage of a space launcher. Besides the rig and model, a procedure for the identification of the aerodynamic pitch damping coefficient is developed, using the interior point optimization method. The particularity of the wind tunnel model is that it is a flow-through one and therefore it cannot be properly tested on a forced vibration rig, since it requires an adaptor that would obstruct the inner flow, making it irrelevant. An experimental campaign is described, covering regimes from subsonic to supersonic, with the model placed in the horizontal plane as reported in literature, but also in vertical plane, such that the static balancing of the model could be eliminated. Conclusions are presented considering the results, with ideas for improvements.

**Keywords**: *wind tunnel, free-to-tumble, aerodynamic damping coefficient, space launcher interstage*

## Nomenclature

*Latin*

$A$ – Angle of attack amplitude

$C_{mq} + C_{m\dot{\alpha}}$ – Aerodynamic damping coefficient

$I$ – Inertia moment for pitch axis

$S$ – Body reference area

$V$ – Upstream velocity

$L$ – Body reference length

$t$ – Time

Greek

$\alpha$ – Angle of attack

$\omega$ – Angular frequency

$\delta$ – oscillation phase angle

$\rho$ – Air density

Superscripts

$\xi$ – Damping ratio

Subscripts

$ref$ – Model reference data

$i$ – Data series index

$obj$ – Refers to the objective function

## 1. Introduction

The space industry accelerated in the last years at a significant level. For private companies, a launch per week is nowadays a reality and since the launchers are not fully recoverable, space debris are growing in number. The Clean Space Initiative generated a number of research programs within ESA involving INCAS, covering activities from numerical to experimental aerodynamics, culminating with the

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development of a complex, multidisciplinary code for simulation of the destructive reentry [6]. The development of a free to tumble rig (FTT) was considered first in 2013 in a project proposal, with the intent of characterizing the stability of a probe bring-back reentry capsule. A simple device was preferred considering the complexity of a forced vibration rig that requires a long development time, together with the numerical procedures.

When looking for an interesting debris for the rig, it became obvious that many elements from launchers first or even second stage are recovered sometimes in a good condition (titanium fuel tanks) and more. Trajectory propagation of various debris requires aerodynamic databases that are almost impossible to generate, considering the irregular, evolving shapes. The uncertainties of aerodynamics in six degrees of freedom dynamics can be high. Therefore, only those debris that are known to land relatively intact worth to be considered up to the level of damping coefficients in the hypothesis of small angle of attack oscillations.

Finally, it was concluded that a generic interstage tronconical system (TC) similar to that of Vega Launcher is the best to be characterised in terms of dynamic derivative. The Mach number will range from 0.4 to 3.5, maximum achievable at INCAS Supersonic wind tunnel.

## 2. Wind tunnel experimental free-to-tumble model

The assembly configuration consists of an interstage tronconical system (TC) connected to the fork of the FTT rig by a rod, that allows for pitching the model during the experimental runs, due to the bearings placed in the fork arms. The interstage TC model of Vega launcher has been modelled using open access data and then scaled at a diameter of 100 mm and a reference area of 0.00485 m$^2$. The scale has been chosen considering the blockage in the test section of 1.2x1.2m$^2$ and the requirements of exploiting most of the facility envelope [7], from subsonic to supersonic.

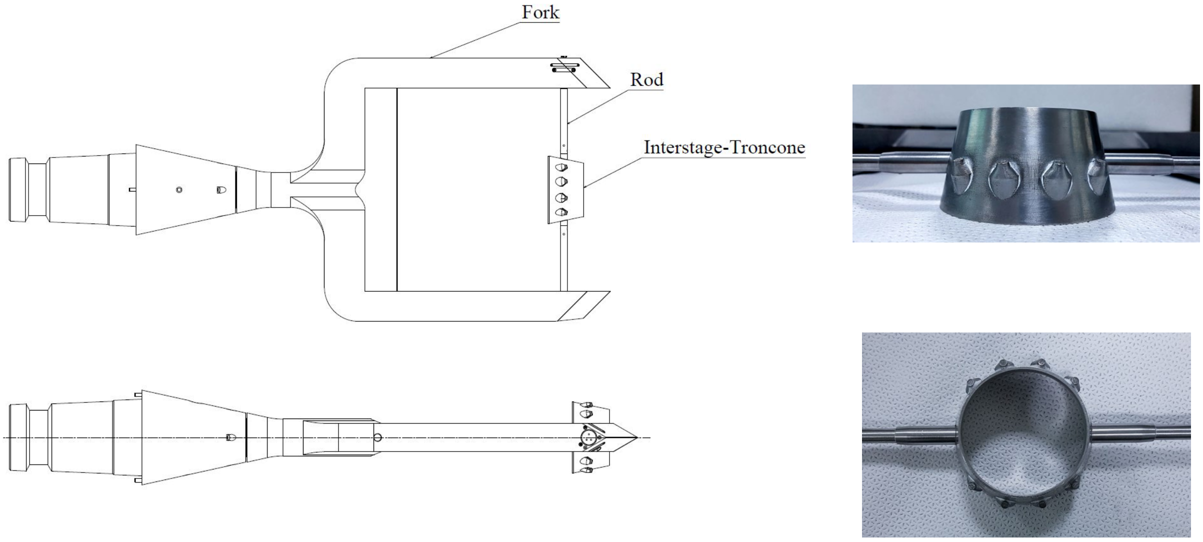


**Fig. 1** Free to tumble rig and interstage flow-through tronconical model

The distance between the arms of the rig is 300mm and the distance between the base of the rig and the axis of the rod is 250mm, with a diameter of the rod of 10mm, chosen specifically for this model. Although the model rotation center should be adjustable [1], [4], for safety reasons it was considered to have the rod firmly fixed in a single position from the manufacturing (Selective Laser Melting). This operational inflexibility has been assumed considering that no experience has been available and the startup loads of the facility are well above the established regimes loads. The limitation of movement can be easily obtained with a rod that is flow aligned, fixed on the rig support, having contact with the inner surfaces of the model in the leeside [4].

The load capacity of the rod has been calculated using the start-up forces at M=3.5, with a safety factor of 1.5, resulting a load of 600N for a static weight test, preliminary to the wind tunnel (WT) testing, according to the classical method in [3]. It is worth to mention that the rod is not monolithic, but there are two segments connected to the model with transversal pins. Fork arms bearings have been chosen from the SKF catalogue considering the same loads, from the low friction category.

The process of manufacturing of the interstage model consisted of combining the milling of the free-to-tumble (FTT) body made of stainless steel EN 1.4923 and SLM manufacturing process of the 8 protrusions representing the retro-rockets - for this geometry, Fig. 1.

An industrial potentiometer, Model 157 from Vishay [5], had been mounted in the left fork arm and fixed in place by a grip ring in order to measure the experimental pitch angle for the TC model. The FTT rig can be tested at any roll angle and this feature may be useful in assessing the eventual effect of gravity upon the dynamics.

a) b)

**Fig. 2** FTT model installed on the rig, a) roll angle 0 deg, b) roll angle 90 deg

## 3. Pitch damping coefficient identification

The dynamic stability of the TC model can be characterized by the pitch damping coefficient, that is $C_{mq} + C_{m\dot{\alpha}}$. From the motion history of the FTT model obtained after the WTT results, this pitch damping sum can be identified by considering that the motion of the angle of attack of the interstage TC can be expressed as a 2nd order differential equation [1].

$$\ddot{\alpha} - \frac{\rho V S L_{ref}^2}{4I}\left(C_{mq} + C_{m\dot{\alpha}}\right)\dot{\alpha} - \frac{\rho V^2 S L_{ref}}{2I} C_{m\alpha}\alpha = 0 \qquad (1)$$

The generic solution of the simple harmonic oscillator equation with damping, is given in Eq. 2, considering the procedure from [1].

$$\alpha = A e^{\xi t} cos(\omega t + \delta) \qquad (2)$$

Knowing the value of ξ, the pitch damping can be computed from Eq. 3. In order to identify ξ, a nonlinear curve fitting process is applied to the angle of attack history obtained from the experimental data.

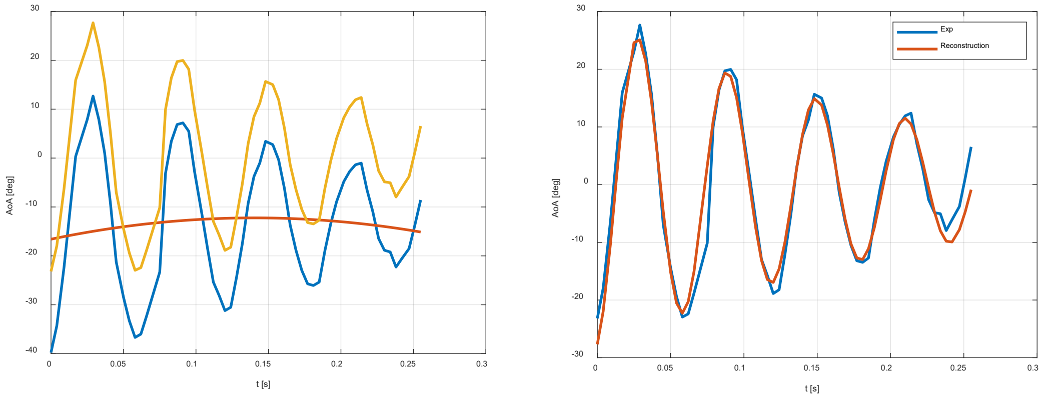
$$\xi = \frac{\rho V S L_{ref}^2}{8I}\left(C_{mq} + C_{m\dot{\alpha}}\right) \qquad (3)$$

Identification of damping coefficient is performed with a numerical optimization process, minimizing the norm of error between the measured angle and the solution from Eq. 2. Interior point optimization method from Matlab, function *fmincon* is applied in variables $A$, $\xi$, $\omega$ and $\delta$. Before optimization, the signal is prepared manually, from case to case, as in Fig. 3 and Fig. 4.

Time axis windowing is mandatory, selecting the most appropriate data segment and translating it to the origin. This is performed in an iterative manner, until repeatability of optimization results is obtained, as an engineering measure of robustness. Windowing parameters, lower and upper bounds of the solution vectors are all stored in distinct experiment related files, for proper data organization and future work revision.

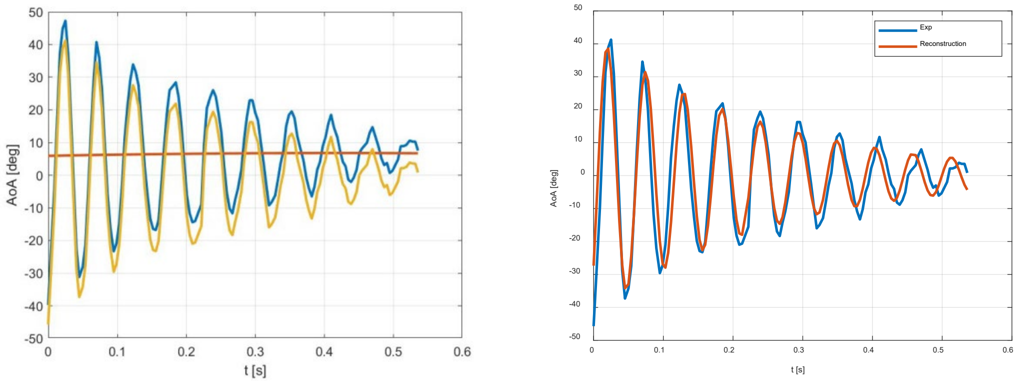
Next step is to eliminate the offset of angle history. The offset curve is built as a polynomial fit, of generally second degree, that is subtracted from the recorded data. Without the damped oscillations centering with respect to the time axis it makes no sense to try to apply data fitting. These are mandatory steps for a valid optimization process. The objective function for the optimizer is definitely the least squares sum as in Eq. 3.

$$f_{obj} = \frac{1}{n}\sqrt{\sum_{i=1}^{n}\left(A\, e^{\xi t_i}\cos(\omega t_i + \delta) - \alpha_i\right)^2} \qquad (3)$$



a) b)

**Fig. 3** Data windowing/normalization for #9288 (Mach=2.5) and normalization a), reconstruction b)

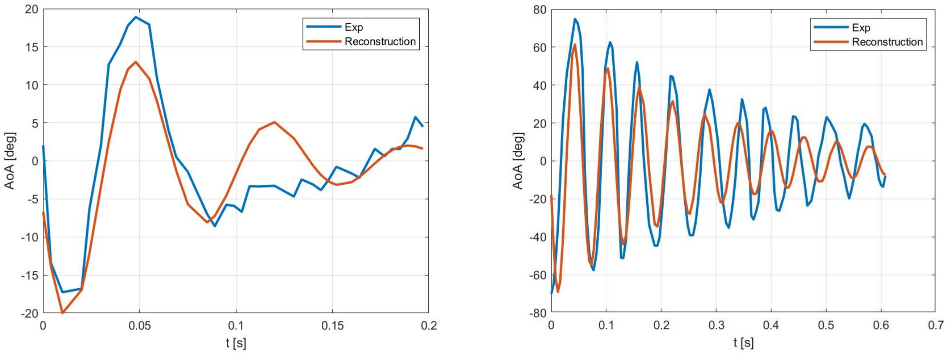


a) b)

**Fig. 4** Data windowing/normalization for #9280 (Mach=3.5) and normalization a), reconstruction b)

In a naïve approach, the Genetic Algorithm has been tested, with poor results, besides the unacceptable duration. Working with data, once decent search bounds have been identified for each case, interior method provided good results, correlated with the data quality.

Other than the successful resolutions from Fig. 3 and Fig. 4, there are cases when the process is impossible because of excessive aerodynamic damping, combined with a low sampling rate and possible other factors, Fig. 5**.**



a) b)

**Fig. 5** Failed data fitting #9286, M=1.5 a) and # 9290, M=3.5 b)

## 4. Results and conclusions

The final values of the nonlinear fitting process are in Table 1, correlated with Mach and the choice of roll angle, between 0 and 90 deg. Runs 5 and 11 are not valid, while for others, validity is also debatable. The process of conditioning the data and assessing the results is clearly related to the personal experience of the engineer.

**Table 1** Test matrix and results

| No. | Run # | Mach | Coefficient [-] | Roll angle [deg] | AoA [deg] | Remarks |
|---|---|---|---|---|---|---|
| 1 | 9280 | 3.5 | -0.224 | 90 | 0 | |
| 2 | 9289 | | -0.207 | 90 | 0 | |
| 3 | 9290 | | -0.197 | 90 | 0 | |
| 4 | 9291 | | -0.184 | 0 | 0 | |
| 5 | 9293 | | -0.350 | 0 | 10 | Uncertain fit |
| 6 | 9292 | | -0.207 | 0 | 0 | |
| 7 | 9288 | 2.5 | -0.132 | 90 | 0 | |
| 8 | 9281 | | -0.183 | 90 | 0 | |
| 9 | 9287 | | -0.147 | 0 | 0 | |
| 10 | 9294 | | -0.166 | 0 | 10 | |
| 11 | 9295 | 1.5 | - | 0 | 10 | Failed fit |
| 12 | 9282 | | -0.662 | 90 | 0 | |
| 13 | 9286 | | -0.449 | 0 | 0 | |
| 14 | 9285 | | -0.57 | 90 | 0 | |
| 15 | 9283 | 1.1 | -0.512 | 90 | 0 | |
| 16 | 9296 | 0.5 | -0.193 | 0 | 10 | |
| 17 | 9284 | | -0.130 | 0 | 0 | |

All supersonic runs have been visualized with the Schlieren system that essentially is producing a movie with the maximum resolution of 640x480. Images are then extracted for proper assessment since the dynamics of the flow is fully captured at about 2000 fps.

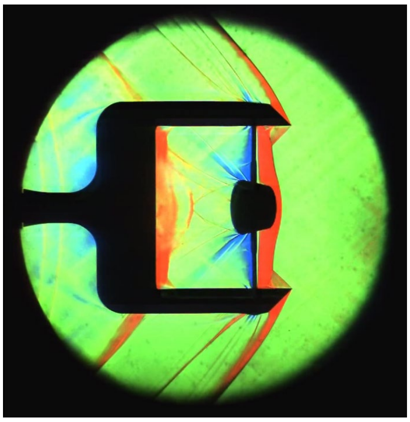


**Fig. 6** Mach 1.5, roll angle 90 deg

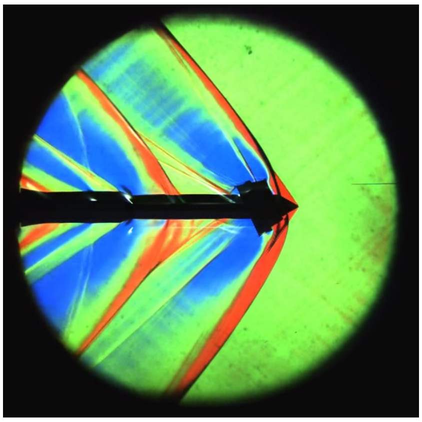


**Fig. 7** Mach 1.5, AoA=0 deg

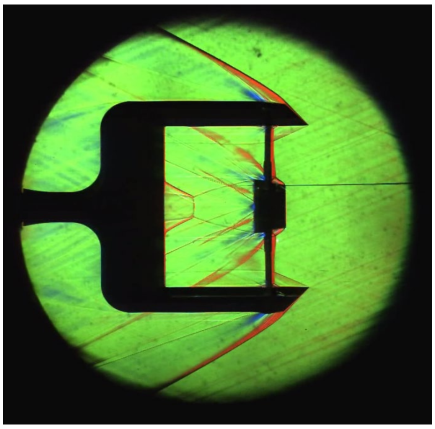


**Fig. 8** Mach 2.5, roll angle 90 deg

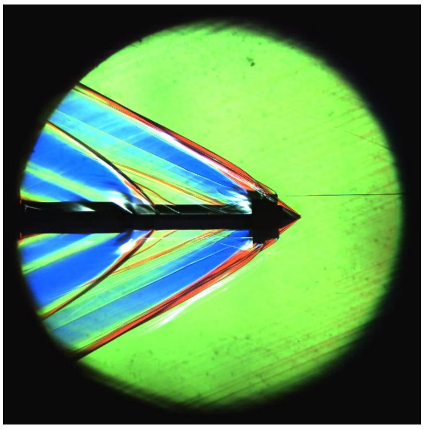


**Fig. 9** Mach 2.5, AoA=0 deg

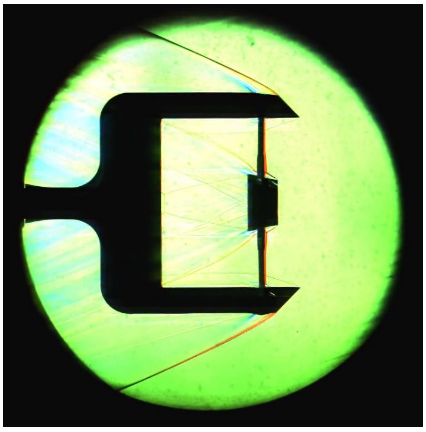


**Fig. 10** Mach 3.5, roll angle 90 deg

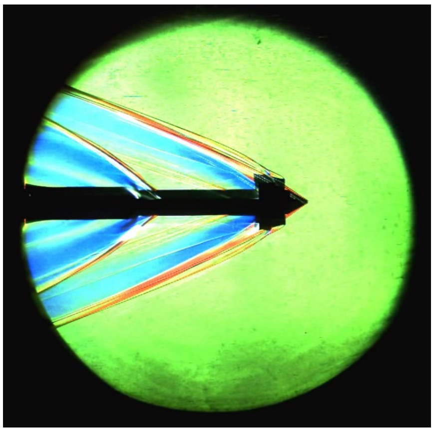


**Fig. 11** Mach 3.5, AoA=0 deg

A significant number of experiments have been repeated at M 1.5, 2.5 and 3.5, assessing the influence of roll angle positioning and angle of attack, providing overall dispersed results. At M=1.5 the influence of rod is high, Fig. 6 and Fig. 7 such that this regime should be avoided. At M=2.5 the rod generated detached shock is closer. Rod thickening near the tronconical body is showing the corresponding increased offset, Fig. 8, Fig. 9, while the flow is much better than at M=1.5. Expansion/compression cells are generated by the divergent nozzle, when stabilized. The same considerations apply for M=3.5, with the best flow, consistent with the best results in terms of damping coefficient processing, Fig. 10, Fig. 11.

The angle of attack of the rig at 10 deg seems to produce a negative influence in the attempt to perform the fitting. Runs 5 exhibits an uncertain fit with an outstanding coefficient, run 10 is not conclusive, and run 11 is numerically failed. Considering Schlieren images from Fig. 12, the conclusion is that the flow field is more complex and the influence of the rig is negative. However, this particular device it is supposed to work aligned with the stream.

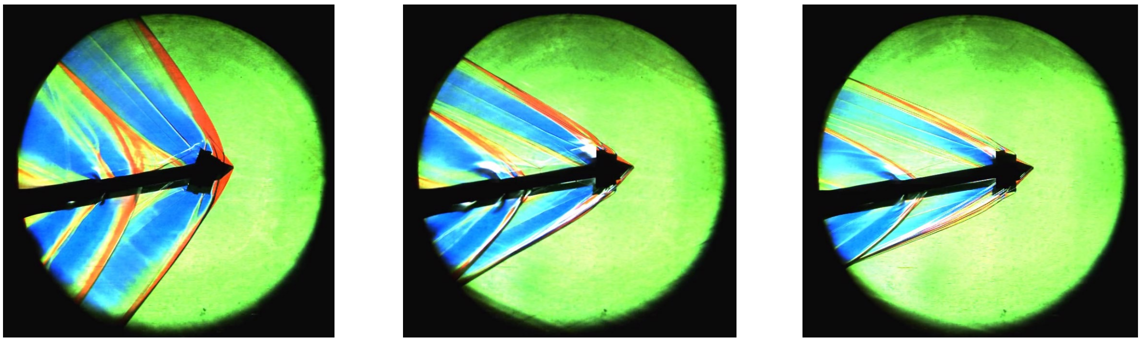


**Fig. 12** AoA=10 deg, M=1.5, 2.5, 3.5

A higher sampling rate and a higher resolution data acquisition system is required for a better data conditioning and better optimization/fitting. This issue is solved for other rigs currently under development, that have their own acquisition system, working in deterministic regime, at much higher sampling rate. The same principle can be applied for the current rig.

For the current campaign, bearings and transducers induced damping was not considered. Accurate alignment of rod segments and bearing is crucial to reduce the friction, as it can be tested by hand. It is to be noted that the bearings must be cleaned with solvent from the same reason, since they are not subject of serious wearing and fatigue. In this case bearings must be greased only for long time storage.

Future work will consider a system for proper characterization of the FTT rig, probably using a vacuum chamber. Any potential other improvements will be performed considering the requests for such services. An aerodynamic calibration model has to be identified in the literature, manufactured and tested.

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