Pitch damping identification in high speed regimes with a free-to-tumble rig

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DOI: 10.13111/2066-8201.2020.12.4.24

Received: 25 September 2020/ Accepted: 21 October 2020/ Published: December 2020

Abstract: *Many re-entry bodies, even if they are debris or not, have nonlinear dynamic stability characteristics that produce oscillations in flight. The free-to-tumble techniques can be used to extract damping coefficient of specific body for planetary entry. The curve fitting approach is used to predict oscillatory behavior and the damping coefficient for the various test conditions of the wind tunnel obtained after the experimental data. The analysis presented provides an overview of the free-to-tumble test techniques and illustrates the effects of dynamic stability of the inter-stage tronconical system. It is proposed that these test techniques and curve fitting solution be refined in the future to better define the dynamic stability curves for the re-entry bodies.*

Key Words: *free-to-tumble, damping coefficient, dynamic stability, inter-stage tronconical system*

1. INTRODUCTION

It is known that some space hardware can survive the travel through the atmosphere. For example, this is the case of structural parts of a spacecraft like nozzle and propellant tank, but not only, which are made of materials with a high melting temperature. On the other hand, there are many objects in space in low orbits that slowly degrade and eventually end their lives falling to Earth [1]. This paper focuses on the study of a generic inter-stage tronconical system (TC) similar to that of Vega Launcher, during the re-entry stage, by characterizing its dynamic stability in terms of dynamic derivatives assessment. The prediction of the dynamic stability using experimental data is quite challenging and important for determining the dynamic stability of such configurations in supersonic and transonic flight regimes, and they are used for better understanding the ablation processes.

2. WIND TUNNEL EXPERIMENTAL FREE-TO-TUMBLE MODEL

The assembly configuration consists of an interstage tronconical system (TC) connected to the fork of the WTT rig by a rod, that allows for pitching the model during the experimental runs, due to the bearings placed in the fork arms. The inter-stage TC model, based on the VEGA geometry, has a diameter of 100 mm.

The scale of the model was chosen after a series of numerical analysis performed on the interstage shape, in order to validate the regimes, as presented in Table 1.

The process of manufacturing the inter-stage model consisted of combining the milling of the free-to-tumble (FTT) body made of stainless steel EN 1.4923 and 3D printing manufacturing process of the 8 protrusions for this geometry (Figure 1).

Figure 1. Inter-stage tronconical model

The fork length (Figure 2) has a rectangular axial section for the front arms and chamfered at 60^0 and 45^0 at the tip.

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.

The load capacity of the rig for the FTT model was calculated using the start-up forces at 3.5 Mach, multiplied by a safety factor of 1.5, resulting a load of 600N for a static weight test, preliminary to the wind tunnel (WT) testing.

An industrial potentiometer, Model 157 [2], had been mounted in the 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)

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

3. PITCH DAMPING COEFFICIENT

The dynamic stability of the TC model can be characterized by the pitch damping coefficient, C_{mq}, also known as the pitch-damping sum $C_{mq} + C_{m\dot{\alpha}}$. From the motion history of the FTT model obtained after the WTT results, this pitch damping sum can be computed by considering that the motion of the angle of attack of the inter-stage TC can be expressed as a 2nd order differential equation [3]:

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

Consequently, equation (1) can be simplified based on the assumption of constant velocity, free to oscillate and without heave, which means that the oscillation center related to the freestream flow is fixed, equation (1) resulting in a simple harmonic oscillator with damping, having the classic solution:

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

where:

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

Knowing the value of ξ, the pitch damping sum can be computed from equation (3). In order to evaluate the parameter ξ, a curve fitting process is applied to the angle of attack history, obtained from the WT experimental data.

4. CURVE FITTING PROCESS

Identification of damping coefficient is performed with a numerical optimization process, minimizing the norm of error between the measured angle and the solution from equation (2). Before optimization, the signal is prepared manually, from case to case, as in Figure 3 and Figure 4.

Time axis windowing is mandatory, selecting the most appropriate data segment and translating it to the origin.

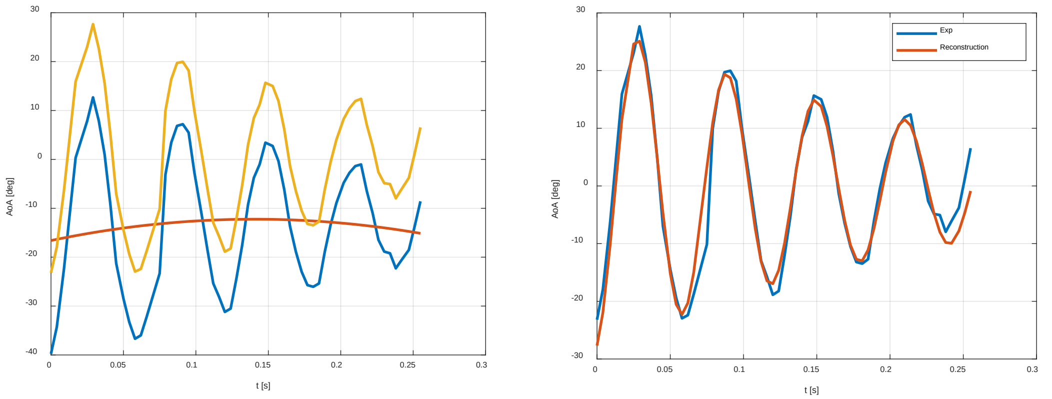
This is performed by working repeatedly with the data repeatedly, until repeatability of results is obtained, as a measure of robustness.

Next step is to eliminate the offset of angle (Figure 3 *a*)). The offset curve is built as a polynomial fit, of generally second degree, that is subtracted from the recorded data. These are mandatory steps for a valid optimization process:

$$f_{obj} = \frac{1}{n}\sqrt{\sum_{i=1}^{n}\left(A e^{\xi t_i}\cos(\omega t_i + \delta) - \alpha_i\right)^2} \tag{4}$$

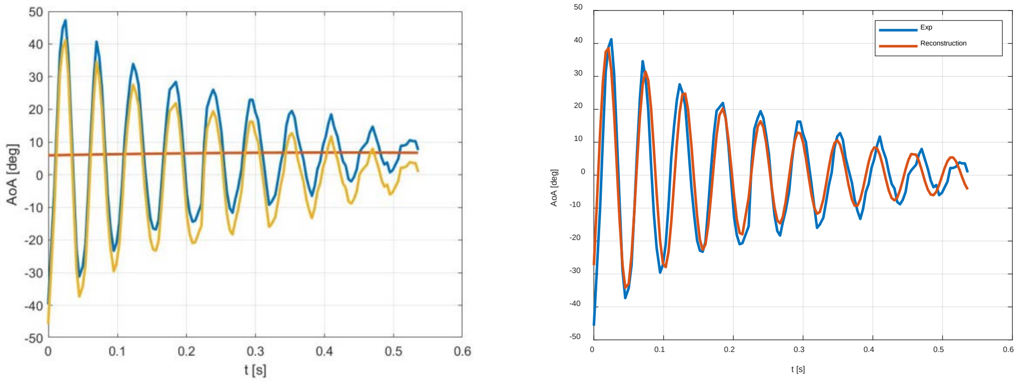
Optimization is performed in two steps, with the Genetic Algorithm and then with Non Linear Programming, from Matlab Optimization Toolbox.

Amplitude A, absolute damping ξ, pulsation ω and phase angle δ are computed. 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.



a) b)

Figure 3. Data windowing/normalization for Run #7 (Mach=2.5) and normalization a), reconstruction b)



a) b)

Figure 4. Data windowing/normalization for Run #1 (Mach=3.5) and normalization a), reconstruction b)

5. RESULTS AND CONCLUSIONS

The final values of the fitting process indicated by the Solver can be a solution for the TC model tests (Figure 3 b), Figure 4 b)). Results of this fitting process are given as damping coefficient (C_{mq}), found in Table 1.

Table 1. Results of damping coefficient (C_{mq})

No.	Mach	$C_{mq} + C_{m\dot{\alpha}}$	roll angle $0^0/90^0$	AoA of the FTT rig [deg]	Remarks
1	3.5	-0.224	90	0	
2		-0.207	90	0	
3		-0.197	90	0	
4		-0.184	0	0	
5		-0.350	0	10	**Uncertain**
6		-0.207	0	0	
7	2.5	-0.132	90	0	
8		-0.183	90	0	
9		-0.147	0	0	
10		-0.166	0	10	
11	1.5	-	0	10	**poor conditioning**
12		-0.662	90	0	

13		-0.449	0	0	
14		-0.57	90	0	
15	1.1	-0.512	90	0	
16	0.5	-0.193	0	10	
17		-0.130	0	0	

In order to properly evaluate the damping coefficient for cases with Mach = 3.5, the curve fitting process was not applied from the start of the experimental data, due to the unsteady initialization phase of the WT at the beginning of the tests.

Fitting process was feasible for the cases with Mach = 2.5 and 1.5, in order to determine a properly damping coefficient, due to the experimental curve data obtained from the WTT campaign.

A good agreement of the curve fitting is obtained for a partial time range; thus, a more accurate damping coefficient can be extracted, minimizing the factors that influence the FTT rig, starting with the bearing friction coefficient, the precision of the potentiometer and the influence of the WT on the resulting data acquired during the experiment.

A higher sampling rate is desired for a better damping coefficient identification, but this is possible only with a faster acquisition system. For the current campaign, bearings and transducers induced damping was not considered. Future work will consider a system for proper characterization of the FTT rig.

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