Coherent solutions to roll damping derivatives evaluation for a generic rocket model

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Abstract: *This paper presents a coherent approach to evaluate the roll damping derivatives for the standard Basic Finner Model. The study compares and analyses the results obtained through a range of techniques, including experimental testing, numerical simulations and semi-empirical models. The study aims to evaluate the reliability and accuracy of these methods and to identify the factors that contribute to their sensitivity. The paper concludes by summarizing the findings of the study and discussing the implications of the results for the design and operation of rockets. The experimental and numerical analysis used in this study provides a robust and comprehensive evaluation of the roll damping coefficient.*

Key Words: *aerodynamics, roll damping coefficient, Basic Finner Model, semi-empirical methods, panel methods, CFD methods, experimental methods*

1. INTRODUCTION

The prediction of the aerodynamic stability coefficients of aerospace vehicles presents considerable importance in design activities. The most important aerodynamic stability coefficients are the damping derivatives which are very difficult to obtain due to their dynamic character. The roll damping coefficient represents the roll moment coefficient derivative with reduced rotation and it is important for lateral-directional stability of rockets, missiles or aircrafts. This coefficient can be obtained in an experimental way (using flight tests or wind tunnel tests) or in a numerical way (using CFD or analytical models), but both ways present several advantages and disadvantages. The experimental determination involves a large cost, the existence of an experimental infrastructure, special equipment and sensors, correction methods, compliance with some similitude criteria, large times for model manufacturing and instrumentation, limited application field, specialized operation team and others, but that kind of tests offer accurate results, short testing times, possibility to study complex models and complex phenomena. Otherwise, the numerical prediction involves the existence of an HPC, large time for computing, a specialized operation team, reduced accuracy for complex problems and others, but that kind of simulation presents smaller costs, no correction methods, no compliance with some similitude criteria and a large application field.

This paper continues the studies performed in the papers [1], [2], [3], [4], [5], [6], [7], [8] [9] and [10] on the determination of the roll damping coefficient considering both numerical and experimental methods.

Although many methods for roll damping coefficient prediction already exist, this study focuses on their operational costs, applicability and accuracy. The paper presents a comparison between several coherent solutions to roll damping derivatives evaluation considering a standard dynamic model.

The methods analyzed in this paper are: the *semi-empiric method* presented in the reference [1], the *panel method* presented in references [11] and [12], which is based on the potential flow model, the *Multiple Reference Frame and Sliding Mesh Technique* presented in references [4] and [5] ,which are based on URANS model, and the *free and forced rotation methods* presented in reference [10], which are experimental methods.

1.1 Calibration Model

The model used to perform the mentioned studies is known as Basic Finner Model or as Army-Navy Finner and it is a common research model for dynamic application proposed by STAI and AGARD organizations [8].

This model represents a calibration model because it is intensely used for experimental testing or numerical simulations in validation test cases. The figures below present the technical drawing of the Basic Finner Model with relative-to-caliber dimensions (Fig. 1), and the isometric view of the model (Fig. 2), respectively.

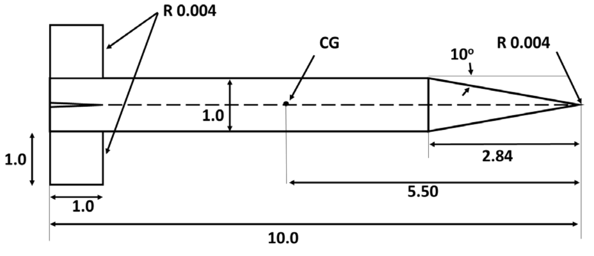

Fig. 1 Basic Finner Model - technical drawing

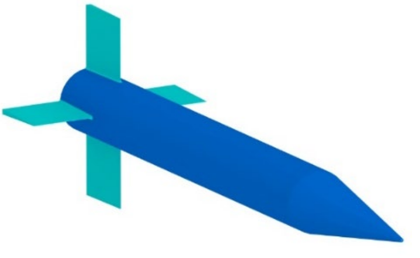

Fig. 2 Basic Finner Model - isometric view

The caliber of the model used is 60mm and the length of the model is 600mm as shown in Fig. 1. The considered reference area is the cross-section fuselage area (2827.43mm^2) and the model moment of inertia around the Ox axis is I_{xx}=0.0073 kg m^2.

1.2 Flow parameters

Each determination method considered presents limitations in analysis, so Table 1 shows the flow parameters considered for each method used:

Table 1 – Flow parameters

Methods	Flow parameters
Semi-empirical	Mach = 0.1 .. 3.5 at AoA = 0°
Panel Method	Mach = 0.1 .. 0.5 at AoA = 0° – 20°
CFD	Mach = 0.4 .. 3.5 at AoA = 0° & Mach = 0.4, 2.5 at AoA = 0° .. 50°
Experimental	Mach = 0.4 .. 3.5 at AoA = 0° & Mach = 0.4, 2.5 at AoA = 0° .. 20°

2. DETERMINATION METHODS

Some of the early papers, [13] and [14], related to the estimation of the roll damping coefficient for an aerospace vehicle, present semi-empirical methods based on experimental data for generic configurations.

In the same period, experimental ballistic studies [15] were performed to determine the roll damping coefficient, followed by experimental studies in wind tunnels using different techniques [6], [7], [8], [9] and [10]. Also, in addition to experimental investigations, numerical methods, presented in: [2], [16], [17], [18], [19], [4] and [5], have been developed to predict the roll damping coefficient as an alternative to experimental testing.

Nowadays, although there are many methods to evaluate the roll damping derivative, they differ in accuracy, applicability or required resources, so this study focuses on their performances. Below are briefly presented the determination methods considered.

2.1 The semi-empirical method

The semi-empirical method used to determine the roll damping coefficient is based on the analytic approach of interferences and on the extrapolation of experimental data obtained for general configurations. The expression of the roll damping coefficient for the considered model is:

$$\boldsymbol{C_{l_p} = 4\chi\sqrt{\vartheta_f}(K + K_F)k_1 C_z^\alpha} \tag{1}$$

where: χ and k_1 are coupling parameters, which creates side force and yaw moment in roll motion, ϑ_f is the air flow braking factor, K and K_F are the interference factors for wing and fuselage, and C_z^α is the lift slope with incidence.

The interference factors K includes trapezoidal correction, boundary layer correction, compressibility correction, anterior and posterior fuselage length correction and air flow breaking correction. The expression of each factor from equation (1) is presented in references [1] and [20].

2.2 The potential flow analysis

The pressure distribution on the surface S for Basic Finner configuration, from the Fig. 3, is evaluated by analysing a perfect incompressible fluid flow in an external volume.

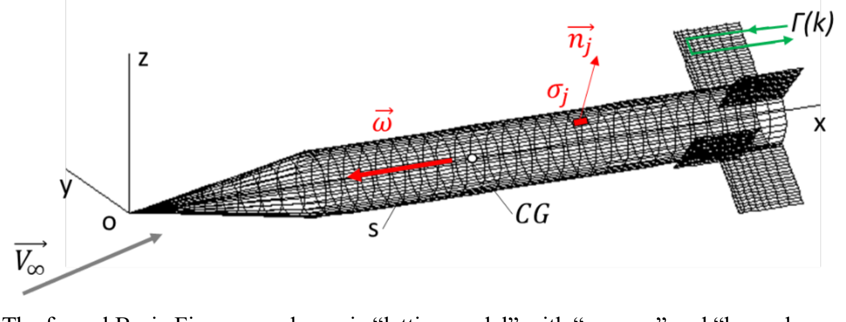

Fig. 3 The formal Basic Finner aerodynamic “lattice model” with “sources” and “horseshoe vortices”

It is convenient to describe potential $\varnothing$ in two components $\varnothing = \varnothing_\infty + \varphi$, where $\varnothing_\infty$ is the potential of the unperturbed flow and φ is the perturbation potential due to the presence of the body.

If the boundary conditions are applied to the perturbation potential φ, we obtain a Neuman Problem applied to the potential flow:

$$\begin{cases} \boldsymbol{\Delta\varphi = 0}, \text{ in the region R} \\ \left(\frac{\boldsymbol{\partial\varphi}}{\boldsymbol{\partial n}}\right)_{\boldsymbol{S}} = \vec{\boldsymbol{n}}\boldsymbol{\nabla\varphi} = -\vec{\boldsymbol{n}}\vec{\boldsymbol{V}}_{\infty}, \text{ on the surface S} \\ \boldsymbol{\varphi = 0}, \textbf{a}\text{t the great distances, when } r \to \infty \end{cases} \tag{2}$$

Considering an angular rotation speed $\boldsymbol{\omega}(p,q,r)$ around the center of gravity *CG*, the local undisturbed speed $\boldsymbol{V}_{\infty i}$ has the form:

$$\vec{\boldsymbol{V}}_{\infty \boldsymbol{i}} = \vec{\boldsymbol{V}}_{\infty} + \vec{\boldsymbol{\omega}} \times \vec{\boldsymbol{r}}_{\boldsymbol{i}} \tag{3}$$

System (2) is numerically solved with particular solutions: distribution of sources $\sigma_j(q)$ on non-lifting panels, and horseshoe vortices of intensity $\Gamma(k)$ on lifting zones, written in the discrete form. This robust approach is an in-house “Lattice Method” called VSLM (Vortex Sources Lattice Method). [11]

2.3 The RANS flow analysis

For the high-fidelity CFD analysis, the RANS model coupled with a turbulence model are used. The RANS (Reynolds Averaged Navier-Stokes) model represents a system of equations developed to solve the turbulent flows proposed in [21]. The turbulence model used is the k-ε realizable proposed in paper [22] to solve the deficiencies of the standard model. The k-ε realizable model was considered because it presents good results for aerodynamic flows with roll motion as shown in papers [4] and [10].

To obtain the roll damping coefficient, two techniques were considered: the first technique is the multiple reference frame which offer a quasi-steady solution, and the second technique is the sliding mesh which perform an unsteady analysis rotating a small domain with the model into a large domain.

The multiple reference frame approach represents a common way to model a rotating field into a fluid flow due to its simplicity and low resources required. This method transforms the components of velocity in the rotating domain considering the rolling motion, so instead of the model rotating physically through the air, the air flows around the model with a corresponding velocity. The MRF approach is also known as „frozen rotor model” and its mathematical model is presented in [23]. Although the MRF approach is frequently used for industrial applications, it presents several constraints which limits its applicability:

- The rotating domain must be axisymmetric;
- The rotating axis must be concentric with rotating parts;
- The rotating parts must be completely included in the rotating domain.

The sliding mesh method is the most physically correct approach for CFD analysis of rotating bodies, although this method requires large computational resources due to unsteady characters of the fluid flow. This approach requires a distinct rotating domain and uses the interfaces to transfer information from the moving to stationary domain. In order to ensure a proper information transfer over the interface, the rotating angle per time step was imposed at 1.2^{o}.

Both considered approaches use the same grid with a rotating domain and a stationary domain as shown in Fig. 4. The first layer height of the boundary layer enables y+ values around 30, recommended for the k-ε realizable turbulence model. The final grid, presented in Fig. 5, was obtained after a grid convergence study and it includes 9 million of polyhedral cells.

Fig. 4 presents the CFD domains considered, where the diameter of the stationary domain is D = 100m, and the rotating domain presents a length L = 0.75m with a diameter d = 0.2m.

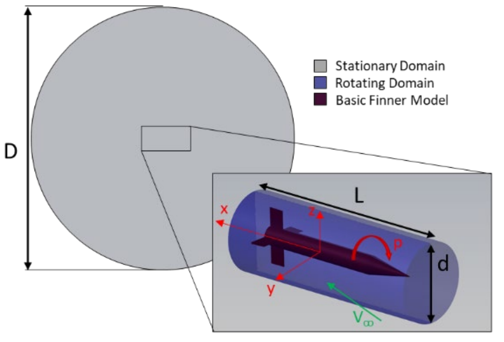

Fig. 4 CFD domains

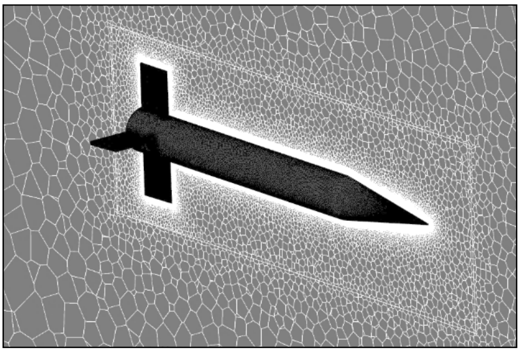

Fig. 5 CFD mesh grid

2.4 The experimental testing

The experimental testing in wind tunnels presents the best accuracy for aerodynamic forces and moments, but it implies large operational costs and large time frames for the manufacturing and instrumentation of the model. The available techniques for roll damping coefficient determination through experimental testing are the forced rotation method and the free rotation method, both presenting advantages and disadvantages. [24]

To obtain the aerodynamic roll damping coefficient, a special rig for the dynamic testing in the wind tunnel was used. The Roll Damping Rig (RDR), presented in [10], allows using of both free and forced rotation methods, independently. Fig. 6 presents the Basic Finner Model installed on Roll Damping Rig in the INCAS Trisonic Wind Tunnel for the experimental campaign.

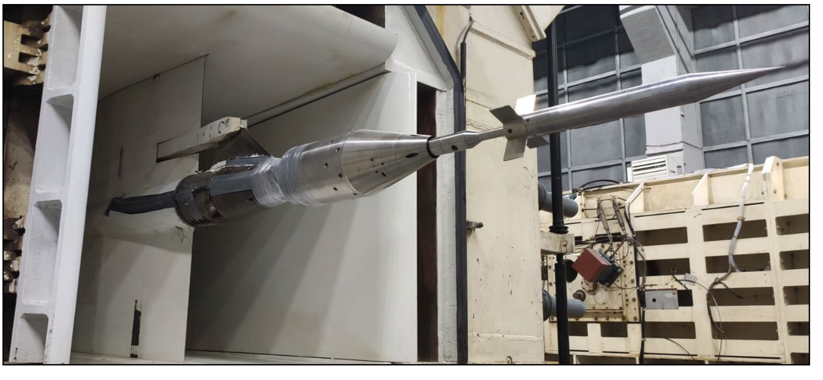

Fig. 6 The BFM installed on RDR in INCAS TWT

The forced rotation method can be used by spinning the model with constant angular velocity (p_s) and measuring the roll moment (M_i) which opposes the rolling motion, so the division of the measured roll moment and the angular velocity represents the roll moment derivative as shown in relation (4). [24]

$$\boldsymbol{M_{x_p}} = -\frac{\boldsymbol{M_i}}{\boldsymbol{p_s}} \tag{4}$$

To obtain accurate results, the tare correction and geometry deviation correction are applied on the data sets:

$$\boldsymbol{M_{x_p}} = \frac{1}{2}\left[\left(\frac{\boldsymbol{M_i}}{\boldsymbol{p_s}}\right)^{\boldsymbol{CW}} + \left(\frac{\boldsymbol{M_i}}{\boldsymbol{p_s}}\right)^{\boldsymbol{CCW}}\right]_{\boldsymbol{WT}} - \left[\frac{\boldsymbol{M_i}}{\boldsymbol{p_s}}\right]_{\boldsymbol{VC}} \tag{5}$$

The tare correction consists of subtraction of the mechanical damping measured in a vacuum chamber (VC) from the total damping measured in the wind tunnel (WT) obtaining the aerodynamic roll damping derivative. The geometry deviation correction consists in averaging of data obtained by spinning the model clockwise (CW) and counter-clockwise (CCW).

The free rotation method can be used by measuring the angular velocity (p_1, p_2) of the model at different times (t_1, t_2) when the model is free released to damp from an initial angular velocity, so the product between the moment of inertia and the logarithmic decay of angular velocity in time represents the roll moment derivative as shown in (6). [24]

$$\boldsymbol{M_{x_p}} = \boldsymbol{I_{xx}} \frac{\ln \frac{\boldsymbol{p_1}}{\boldsymbol{p_2}}}{\boldsymbol{t_2 - t_1}} \tag{6}$$

The tare correction and geometry deviation procedures are performed for a higher accuracy of results using equation (7).

$$\boldsymbol{M_{x_p}} = \boldsymbol{I_{xx}} \left\{ \frac{1}{2} \left[\left(\frac{\ln \frac{p_1}{p_2}}{t_2 - t_1} \right)^{CW} + \left(\frac{\ln \frac{p_1}{p_2}}{t_2 - t_1} \right)^{CCW} \right]_{WT} - \left[\frac{\ln \frac{p_1}{p_2}}{t_2 - t_1} \right]_{VC} \right\} \tag{7}$$

Fig. 7 presents the variation of the electric current in time used by the motor to spin the model; the blue highlighted zone represents the time interval necessary to measure the current consumption in order to determine the roll damping coefficient using the forced rotation method.

In this figure it can be observed that the data acquisition for the forced rotation method last for 12 seconds (four seconds for each angular speed). Fig. 8 presents the variation of the angular speed in time; here it can be observed the three angular speed steps followed by a speed damping which is used for the free rotation method.

In this case, the roll damping coefficient can be determined at any angular speed between the initial speed and the parasitic speed, though the speed damping takes about one second for each case.

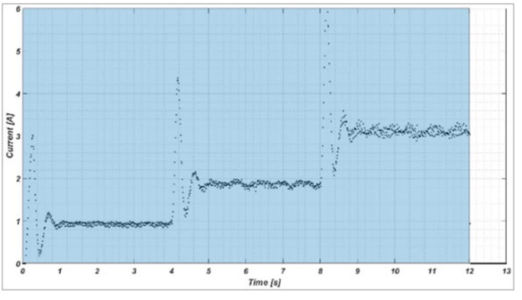

Fig. 7 The variation of electric current at each angular speed

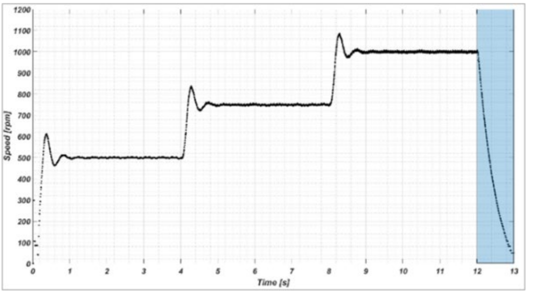

Fig. 8 The variation of model's angular speed in time

3. RESULTS AND DISCUSSIONS

The results of the study are obtained using different methods to identify their limitations, computation resources requested and accuracy. To compare the results of the study, the variation of the roll damping coefficient with different parameters (e.g. Mach number, angle of attack and angular velocity) is analyzed.

3.1 Roll damping coefficient variation with Mach number

The variation of the roll damping coefficient with Mach number represents the most studied case due to its utility for aerospace vehicles which fly at small incidence over a wide Mach number interval.

Fig. 9 presents the variation of Clp with Mach number obtained using the semi-empirical method, the panel method, numerical methods (MRF and SMT) and experimental methods (free and forced rotation method). To compare the obtained data with a reference, a calibration data set extracted from papers [6], [7] and [8] are considered.

The results obtained with the semi-empirical method cover the entire Mach range from 0.1 to 3.5, the results obtained with the panel method cover just the subsonic Mach range, with a good accuracy for incompressible and low compressible flow. The CFD results obtained using MRF technique and Sliding Mesh technique cover the entire Mach regime from 0.4 to 3.5, also the experimental results obtained using both forced and free rotation methods cover the entire Mach regime.

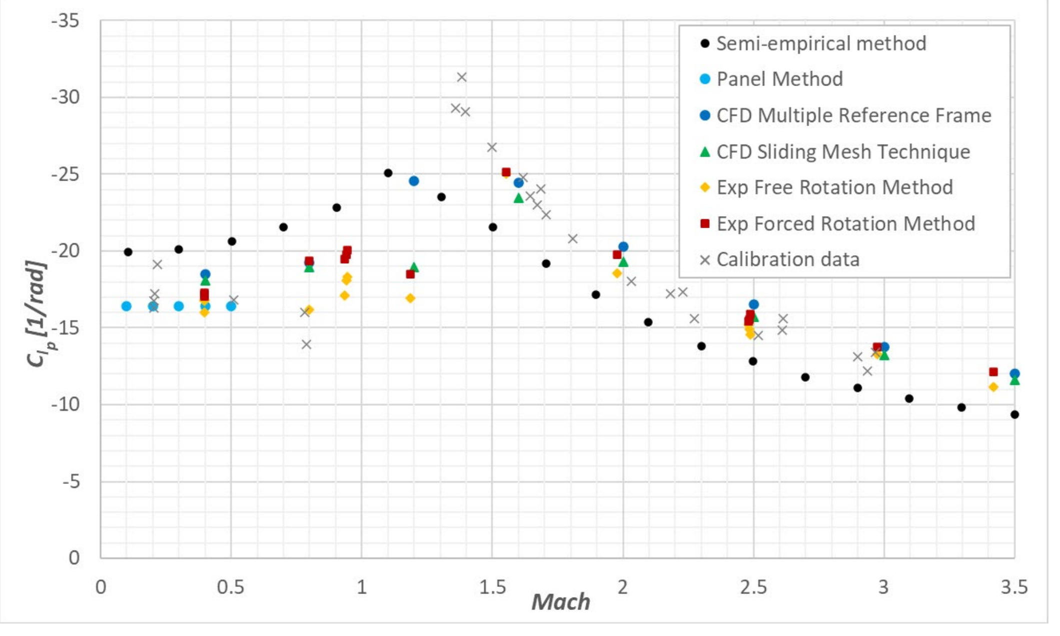

Fig. 9 The roll damping coefficient variation with Mach number

In Fig. 9 it can be observed that all the methods considered give results with very good accuracy with respect to the Mach variation at 0° incidence, except for the semi-empirical method which tends to overpredict the roll damping coefficient in the subsonic and transonic regime, and to underpredict the coefficient in the supersonic regime, but the results obtained are close to calibration data and respect the variation trend.

The values of the roll damping coefficient are very good predicted in the subsonic (incompressible and low compressible) and supersonic regimes by panel method, CFD and experimental testing, but in the proximity of the transonic regime, the data obtained presents small differences between obtaining methods.

So, though the determination methods present different complexity and accuracy, the obtained results respect the variation trend and present a very good accuracy being close to calibration data.

3.2 Roll damping coefficient variation with angle of attack

Another very important variation in the roll damping coefficient is the variation with angle of attack, which is generally non-linear and difficult to predict with accuracy. The incidence of the vehicle in roll motion produces very complex phenomenon (flow separation and reattachment, high interferences between body and wings and shock-wave interactions).

The semi-empirical method cannot predict the variation of the roll damping coefficient with the incidence, and the panel method can predict this variation with low accuracy due to the viscosity model missing. Considering the CFD method, the results depend strongly on the turbulence model which must be able to quantify the swirl flow around a body, also the MRF method cannot provide accurate data, because the phenomenon is strongly unsteady. Considering the experimental testing, the problem is the aerodynamic tare damping (the effect of the aerodynamic loads on the bearings) which is difficult to estimate and subtract, the only solution in this case is to spin the model with a large velocity to obtain a very large roll moment, bigger than the bearings friction moment.

Fig. 10 presents the roll damping coefficient variation with incidence obtained using the panel method, CFD with Sliding Mesh method and experimental testing with free and forced rotation methods. To analyze the roll damping coefficient variation with incidence, two relevant Mach regimes (0.4 and 2.5) were considered. A calibration data set for the 2.5 Mach regime [4] is present for results comparison.

The maximum incidence in experimental testing is 20°, due to the limited wind tunnel pitch system, and in CFD, the maximum incidence in 50°, because the turbulence model used starts to lose accuracy at higher angles of attack.

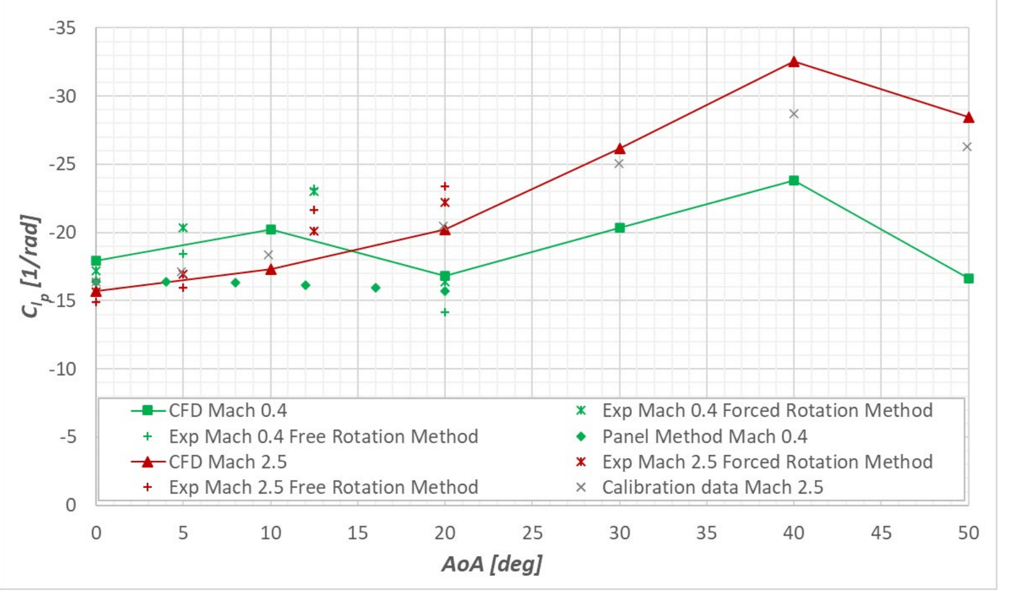

Fig. 10 The roll damping coefficient variation with angle of attack

In Fig. 10, can be observed that the CFD results at Mach=2.5 fit very well with the calibration data, also the experimental results respect the variation trend and these are close to calibration data with a small increment which is the aerodynamic tare damping contribution. The same effect of the aerodynamic tare damping is present in the subsonic regime at Mach=0.4, where the experimental data tends to overpredict the roll damping coefficient. Also, can be observed that, for both Mach cases, at 0° incidence, the experimental data fit very well with the CFD, because at this incidence the normal force on the model is zero (due symmetry) and the aerodynamic tare damping is negligible.

The results obtained with the panel method present a constant variation of the roll damping coefficient with incidence because the method considers the potential flow (irrotational and inviscid).

3.3 Roll damping coefficient variation with angular velocity

The variation of the roll moment coefficient with angular velocity is very important for the similarity criteria. If the model presents symmetry, at 0o incidence, the rolling moment coefficient exhibits a linear variation with angular velocity, which means that the roll damping coefficient is constant with angular velocity [4], [7].

For this analysis, four representative Mach regimes (0.4, 0.95, 1.6 and 2.5) were considered and the angular velocity varies from 200 rpm to 1000 rpm.

The results were determined considering experimental testing and CFD. The semi-empirical method cannot predict the angular speed effect and the panel method cannot perform analysis in transonic and supersonic Mach regimes.

Fig. 11 presents the variations of the roll moment coefficient with angular velocity for four Mach regimes. The dash-lines represent the variation trends for each Mach regimes and it can be observed that obtained data fit with the linear variation trends.

The results obtained with the forced rotation method (experimental testing) and Sliding Mesh Technique (CFD) present very accurate data with the linear dependence between roll moment coefficient and angular velocity.

The results obtained with the MRF method tend to overpredict the values of the roll moment coefficient and the results obtained with the free rotation method present small deviations from the linear variation due to the sensitivity of the moment with registered angular velocity.

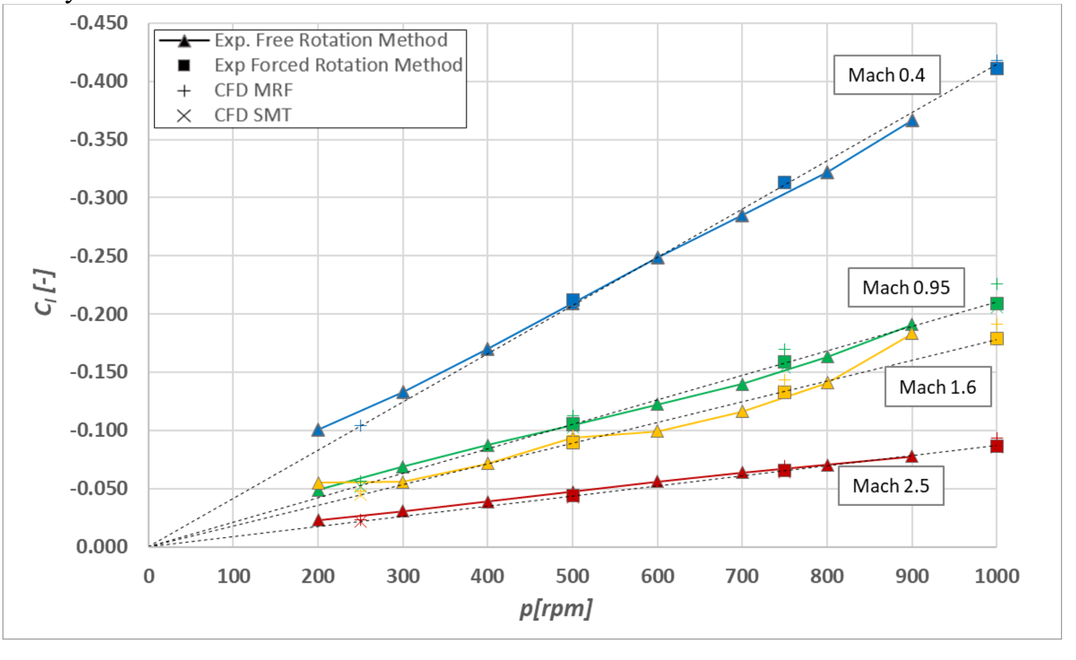

Fig. 11 The roll damping coefficient variation with angular velocity

3.4 Discussions

The analysed methods provide results with good accuracy with respect to reference data set, so all methods are suitable for aerodynamic characterization of an aerospace vehicle but with several limits. The semi-empirical method offers approximative values for roll damping coefficient and it is suitable for conceptual design of a vehicle; the results obtained with this method present decent accuracy and capture the Mach variation. The limits of this method are related to geometry, incidence variation and angular velocity variation, while the main advantage of this method is that the computation resources and computing time are very short.

The panel method provides also approximate values for the roll damping coefficient and it is suitable for advanced conceptual design because it considers the entire geometry of the model. The results obtained with this model presents good accuracy for subsonic incompressible and low-compressible regimes. The limits of this model are related to viscous effects, incidence variation and Mach variation (for compressible subsonic, transonic and supersonic regimes). The main advantage of this method is related to small computation resources and short computing time, which make it suitable for an optimization process.

The CFD methods (MRF and SMT) offer high accuracy results for the roll damping coefficient and capture the effect of Mach number, angular velocity and angle of attack (only for SMT), thus these methods are suitable for preliminary design. These methods have the disadvantage of high computation resources and high computing time (3600 CPU-hours for SMT, 150 CPU-hours for MRF). The main advantages of this method are related to the accuracy of results and complete characterization of flow field.

The experimental methods (forced rotation method and free rotation method) present also high accuracy results for the roll damping coefficient capturing the effect of Mach number, angle of attack and angular velocity. These methods are suitable for advanced design and analysis because the results obtained under similitude conditions are the real ones. The determination time are very short in this case, except for the wind tunnel model design and manufacturing, but the inconvenience is related to the wind tunnel facility which is very expensive to operate.

4. CONCLUSIONS

In conclusion, different methods for the roll damping coefficient determination were presented as coherent solutions for conceptual, preliminary or advanced design of an aerospace vehicle.

Though there are simplified models for aerodynamic analysis (semi-empirical method or panel method), their results can offer useful information if are applied properly; their main advantage are the reduced computational resources and time which make them suitable for optimization or parametric analysis.

To obtain more confident results or the effect of a parameter (e.g. Mach number, Reynolds number, reduced rotation, angle of attack and others) it is suitable to use more complex methods like CFD methods or experimental methods even though the requested computational/ experimental resources and time are larger.

However, the simple methods and complex methods should be used in their limits and with caution according to the application. Not only the simple methods like semi-empirical and panel methods are limited, also the CFD and experimental testing present issues. The CFD needs a pre-testing of the turbulence model, grid sensitivity analysis and convergence criteria, and the experimental testing requires calibration of devices, flow control, data correction, post-processing and more.

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