

# PROGRESS ON INVERSE ESTIMATION TECHNIQUE OF NON-LINEAR PITCH DAMPING COEFFICIENT CURVES USING FREE-FLIGHT CFD GENERATED TRAJECTORIES

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Characterization of entry vehicle pitch damping coefficient curves is crucial to ensure appropriate re-entry and overall mission success. The pitch damping coefficient ( $C_{m_q} + C_{m_{\dot{\alpha}}}$ ) is used to encapsulate the oscillatory growth or decay of a body during a trajectory. The inverse estimation technique utilizes an existing Free-Flight CFD (FF-CFD) dataset and wraps a reconstruction algorithm in an optimizer. The reconstruction integrates the planar equations of motion derived by Schoenenberger, Queen [1] using Python's *scipy.integrate.solve\_ivp*. The optimizer's objective function is the normalized  $L_2$  residual of the angle of attack peaks between the reconstructed trajectory and the original data produced with FF-CFD. Inclusion of the peak times in this residual calculation allows for simultaneous optimization of the pitch moment coefficient,  $C_{m_{\alpha}}$ . This residual equation is shown below in Eq. 1.

$$R = \sum_{\alpha_0}^{\max \alpha_0} \sqrt{\sum_{\alpha_i=peak,0}^{\alpha_i=peak,n} \left( \left( \frac{\hat{\alpha}_i - \alpha_i}{\alpha_i} \right)^2 + \left( \frac{\hat{t}_i - t_i}{t_i} \right)^2 \right)} \quad [1]$$

The optimizer *scipy.optimize.minimize* was used with the gradient-based Powell method for the analysis presented, however the differential evolution method was investigated as means of comparison, and was found to produce marginally lower residual values with prohibitively longer run times. Further, the pitch damping curve is found by fitting a cubic interpolation function to a set of  $(\alpha, (C_{m_q} + C_{m_{\dot{\alpha}}}))$  control points, where the  $\alpha$  points are held constant and the  $(C_{m_q} + C_{m_{\dot{\alpha}}})$  values are the optimized parameters. The pitch moment curve uses a linear interpolation between the minimum and maximum  $\alpha$  in the dataset. FF-CFD generated trajectories using the Dragonfly capsule geometry with the Genesis ballistic range model parameters were simulated and used for this analysis. These FF-CFD trajectories simulate planar motion, as restricted by the equations of motion, of three different cases: 1-

DoF (free-to-pitch), 2-DoF (free-to-pitch and heave), and 3-DoF (free-to-pitch, heave, and decelerate). Pitch damping coefficient curves generated using this inverse estimation curve technique with FF-CFD 1-DoF Dragonfly data are found in Fig. 1. Preliminary results reconstructing ballistic range shots using these FF-CFD derived predictions of the pitch damping curve (Fig. 1) are shown in Fig. 2. It should be noted that the ballistic range shot used a Genesis model whereas the FF-CFD data used a Dragonfly geometry, however these geometries are similar.

[1] Schoenenberger, M. and Queen, E. (2008) *NATO RTO Symposium AVT-152*.

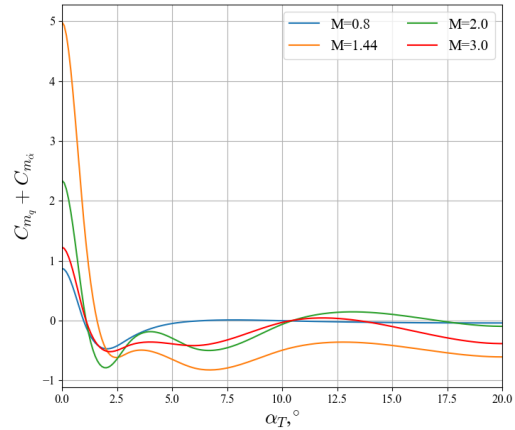


**Figure 1: Inverse estimation derived pitch damping coefficient curve from 1-DoF FF-CFD Dragonfly data**

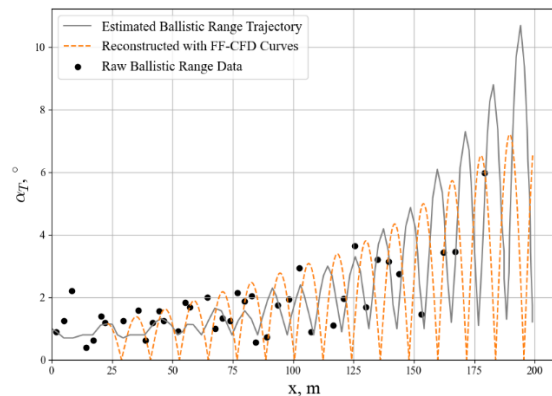


**Figure 2: Genesis ballistic range shot r990495**