

DIRECTLY-PHYSICAL SUBSPACE IDENTIFICATION FOR STRUCTURE-PRESERVING AEROSERVOELASTIC MODEL UPDATING

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ABSTRACT

Accurate aeroservoelastic (ASE) models are essential for flutter prediction, stability assessment, and control-law development, yet in practice they often require extensive manual tuning due to structural uncertainty, unsteady aerodynamic modeling errors, and actuator/sensor dynamics not fully captured by nominal analysis models. Due to the inherent assumptions of the theory, the ASE models comprised of previously mentioned subsystems always contain a degree of modeling error and uncertainty, i. e. in practice, these models are useful for predicting the aircraft aeroelastic response, but they are not perfect. Thus, ASE models have to be updated on the basis of available input-output data from ground and flight tests until there is a satisfactory correlation between model predictions and experimental results. In practice, model updating remains labor-intensive because standard identification methods either (i) fit low-order black-box models that do not map cleanly back to physical parameters, or (ii) perform output-error tuning on high-order models with weak identifiability and limited robustness to sensor and actuator dynamics. This paper addresses the research question: *How can a low-order, data-driven subspace model identified from wind-tunnel tests be used to update a high-order, physically structured ASE model while enforcing physical consistency and stability?*

We propose *Directly-Physical Subspace Identification* (DPSI), a structure-preserving model updating methodology that uses subspace identification only to extract a black-box state-space model from measured data, and then estimates a compact set of physical parameters by constrained nonlinear optimization. First, a discrete-time subspace model $(\hat{A}, \hat{B}, \hat{C}, \hat{D})$ is identified from measured data and converted to Markov parameters

$$\hat{H}_0 = \hat{D}, \quad \hat{H}_k = \hat{C}\hat{A}^{k-1}\hat{B}, \quad k = 1, \dots, L,$$

which serve as noise-filtered, similarity-invariant summaries of the measured MIMO dynamics. Second, a high-order ASE model is parameterized by a low-dimensional vector θ that modifies physically meaningful quantities (selected modal frequencies and damping ratios, grouped unsteady-aerodynamic coupling/residue scalings with fixed stable lag poles, actuator gains/time constants, and sensor-delay parameters). From the parameterized state-space realization $(A_d(\theta), B_d(\theta), C(\theta), D(\theta))$, model-based Markov parameters

$$H_0(\theta) = D(\theta), \quad H_k(\theta) = C(\theta)A_d(\theta)^{k-1}B_d(\theta)$$

are computed over the same horizon. DPSI then solves a weighted least-squares matching problem

$$\theta^* = \arg \min_{\theta} \sum_{k=0}^L \|W_y(\hat{H}_k - H_k(\theta))W_u\|_F^2$$

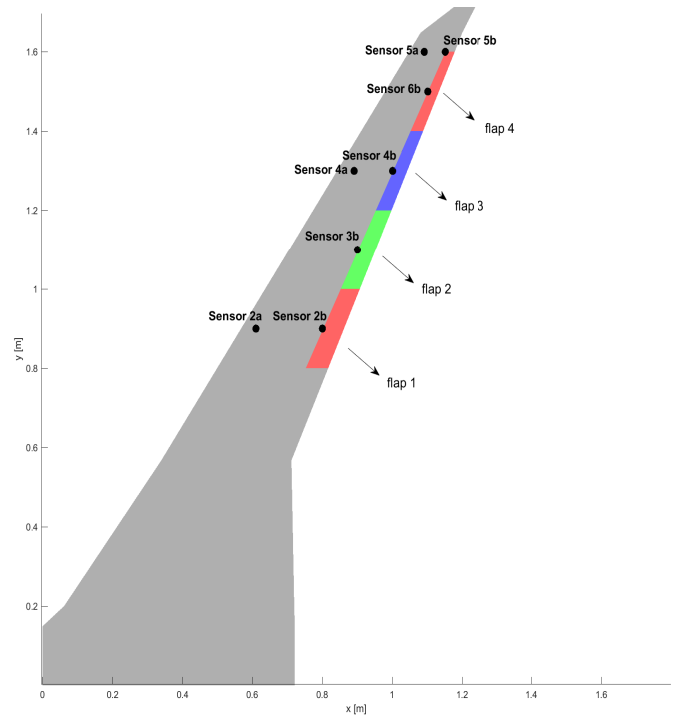
subject to physics-based constraints: positivity/bounds on updated modal parameters, stability of aerodynamic lag and actuator subsystems, and global discrete-time stability (e.g. spectral-radius margin on $A_d(\theta)$). This formulation yields a direct mapping from data to updated physical

parameters without estimating a similarity transform or fitting unstructured high-order matrices.

The method is demonstrated on a wind-tunnel benchmark consisting of a rigidly mounted aeroelastic wing demonstrator, Fig.1, excited by four independently actuated control surfaces using repeated chirp inputs at different freestream velocities of 30, 40 and 50 m/s, with eight vertical accelerometers as outputs ¹.



(a) Experimental setup for the aeroelastic wing demonstrator used for subspace system identification



(b) Sensor positions on the planform of the aeroelastic wing demonstrator

Figure 1: Aeroelastic wing demonstrator

The physical linearized ASE model retains its intended block structure consisting of flexible modes, unsteady aerodynamic lag states, actuator states, and first-order Padé sensor-delay states, while DPSI updates only a small subset of parameters. The proposed updating method via DPSI has been successfully applied on the linearized ASE model including the use of the wind-tunnel data. Using residual analysis by means of Theil's inequality coefficient (TIC) we assess the quality of the updated model for each of the output variables where TIC is a measure for fit error between measured and model outputs. $TIC = 0$ (case of equality) implies a perfect match, whereas $TIC = 1$ indicates the scenario of maximal inequality [2].

Preliminary results depicted in Figure 2 demonstrate that DPSI generates a structure-consistent updated ASE model that more accurately reproduces measured time histories across all eight output channels than the nominal model, while maintaining stability and delivering physically interpretable parameter corrections. Overall, DPSI provides a practical and scalable route to high-order ASE model updating driven by wind-tunnel (and potentially flight) data, enabling

¹The experimental data used in this research were acquired from the test campaigns conducted as part of the SAFER² [1] project at the DNW-NWB, a low-speed wind tunnel of Göttinger type, situated at the DLR site in Braunschweig and operated by the German-Dutch Wind Tunnels (DNW).

improved flutter-margin assessment and control-oriented model refinement while preserving physical realizability.

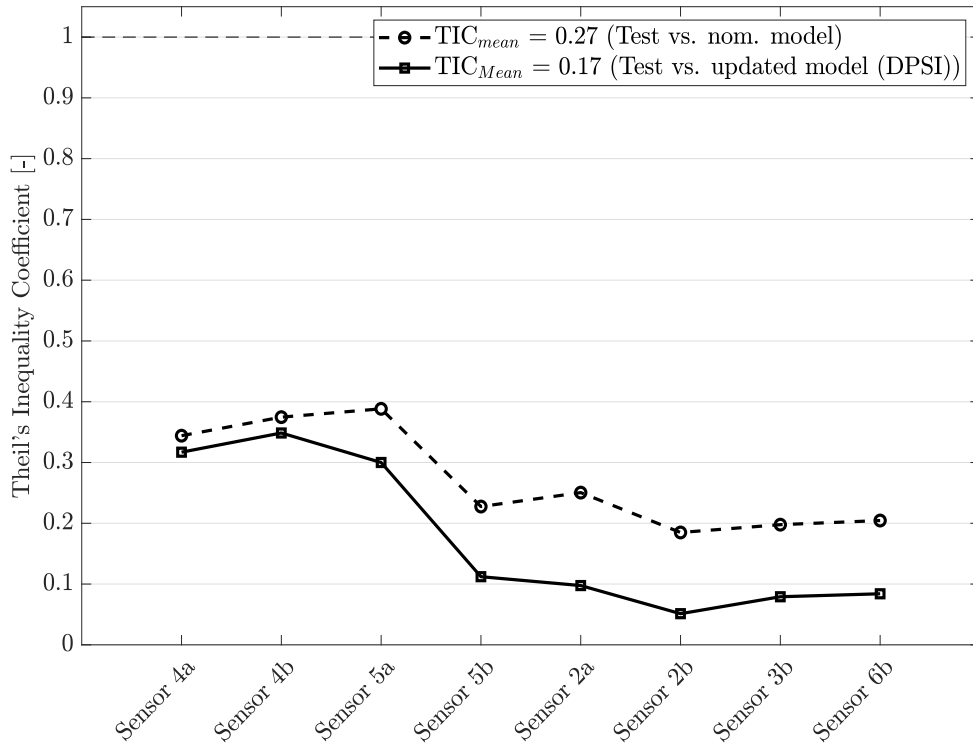


Figure 2: Fit error distribution between test and model (nominal and updated) outputs at $U_\infty = 50$ m/s

References

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