PHYSICS-INFORMED GROUND VEHICLE TEST MODE EXPANSION FOR FLUTTER ANALYSIS

Eui-Cheol Chung, Younggeun Park, Sangmin Lee, and SangJoon Shin*

Seoul National University
1 Gwanak-ro, Gwanak-gu, Seoul, 08826
Republic of Korea

ABSTRACT

High-aspect-ratio (HAR) wing structure has been increasingly adopted for high-altitude long-endurance (HALE) aircraft to improve its performance. Owing to its structural flexibility and aeroelastic sensitivity, accurate flutter prediction will be critical to ensure the safety of the aircraft.

In reality, structural dynamic characteristics predicted by finite element method (FEM) often deviate from those obtained by the ground vehicle test (GVTs). Therefore, to ensure accurate flutter prediction**,** a model-tuning process, such as MAC-based optimization or sensitivity-based updating, will be typically performed to relieve the inaccuracy. However, those procedures require substantial computational cost and time, and they face inherent challenges in representing the complex stiffness characteristics of an aircraft structure.

As an alternative, ZAERO version 9.3 [1] provides a GVT2FEM feature, which enables direct interpolation of GVT-derived mode vectors onto FEM grid via the spline-based mapping (Eq. (1)), followed by the construction of the generalized structural matrices and subsequent flutter analysis (Eqs. (2)–(3)). Nevertheless, because the mapping in Eq. (1) is purely geometric, relying on the surface splines such as TPS or IPS, it will show limited ability for capturing the anisotropic stiffness characteristics of the composite material layup and the complex dynamic interaction of the control-surface component in HAR wing.

$$[\phi_{FEM}] = [SPLINE][\phi_{GVT}] \tag{1}$$

$$[M_h] = [\phi_{FEM}]^T[M_{gg}][\phi_{FEM}],\ [K_h] = [\omega_n^2][M_h] \tag{2}$$

$$[s^2\,[M_h] + [K_h] - q_\infty[Q_{hh}]]\{\xi\} = 0 \tag{3}$$

To overcome the limitations of the geometry-only interpolation while enabling rapid and accurate flutter analysis, this abstract will adopt an adaptive geometric moment descriptor (AGMD)–kriging data-driven framework proposed in [2] (illustrated in Fig. 1). Specifically, this abstract proposes an integrated framework that expands sparse GVT result into a full-field representation via AGMD–kriging, enabling the extraction of complete mode vectors for flutter analysis.

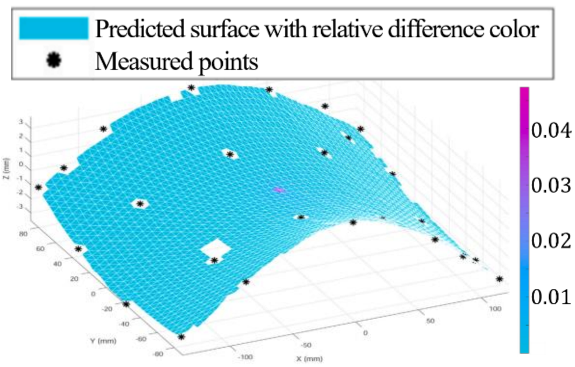

Figure 1: AGMD–kriging full-field prediction [2].

The proposed methodology will be demonstrated using the mAEWING1 aircraft research result by the University of Minnesota, which provides a comprehensive dataset including GVT [3], flight test, and FEM information. In the offline stage, displacement result will be extracted through the forced vibration analysis of an initial (untuned) FEM, and the high-dimensional dataset will be compressed using AGMD basis function to extract the essential structural shape features. In the online stage, the GVT result regarding the mAEWING1 aircraft is expanded into a full-field representation via AGMD/Kriging interpolation, from which the complete mode vectors are extracted for flutter analysis. The resulting flutter analysis will then be comparatively evaluated against ZAERO GVT2FEM and MAC-tuned FEM result. The overall workflow of the proposed methodology is schematically illustrated in Fig. 2.

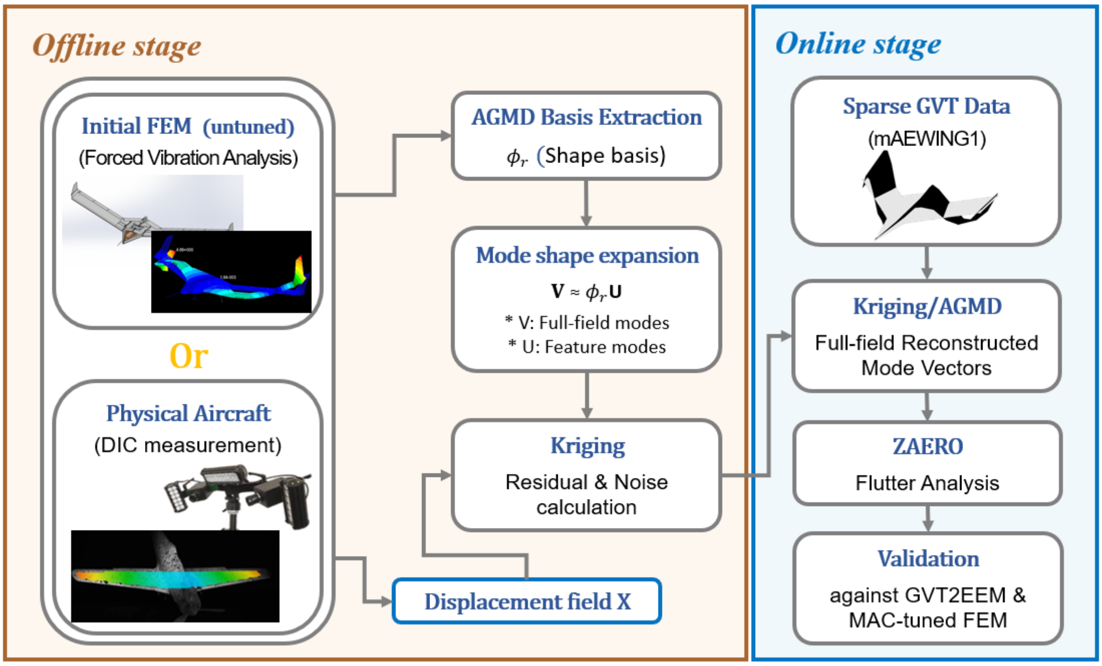

Figure 2: Physics-informed data-driven framework

The proposed method reconstructs the full-field mode vectors by reflecting physics-informed, data-driven characteristics rather than relying solely on the geometric proximity, enabling flutter analysis without extensive FEM update. Furthermore, the proposed workflow will be effective for optimal sensor placement (OSP) and offers significant computational efficiency when iteratively expanding sparse online data into the full-field representation. This abstract will be extended to construct AGMD basis function using the high-resolution experimental result obtained via the digital image correlation (DIC) and to perform flutter analysis by expanding GVT result based on the constructed representation.

REFERENCES

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[3] Gupta, A., Seiler, P., and Danowsky, B., "Ground Vibration Tests on a Flexible Flying Wing Aircraft," *AIAA SciTech Forum*, San Diego, CA, Jan. 2016.