High-Order Vibroacoustic Modal Analysis of Fluid-Loaded Plates with Simply-Supported and Free Edges

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High-Order Vibroacoustic Modal Analysis of Fluid-Loaded Plates with Simply-Supported and Free Edges

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Abstract. A higher-order Carrera Unified Formulation is presented for fluid-loaded slender plates, employing orthogonal Lagrange and total-degree Taylor polynomials to capture cross-sectional kinematics. Comparison with three-dimensional finite-element models shows that moderate-order Lagrange expansions predict coupled eigenfrequencies with an error of less than 1%. In contrast, fourth- and fifth-order Taylor models achieve engineering accuracy with approximately 100 times fewer degrees of freedom. Parametric studies reveal that changing the lateral boundaries from simply supported to free lowers the fundamental frequency by approximately 3% and accentuates in-plane motion, especially in the mid-frequency range where plate and cavity modes coalesce. The method thus offers an efficient and validated alternative to complete 3-D analysis, with future extensions envisioned for nonlinear effects, damping layers, and gradient-based design optimization.

Introduction

Lightweight aircraft panels and launch-vehicle fairings often operate in strong fluid-structure interaction (FSI) regimes where classical first-order theories become inaccurate [1][2]. Recent Carrera Unified Formulation (CUF) studies have demonstrated rapid convergence for composite beams and shells [3][4]. By adopting a structured ML pipeline, a reliable predictive methodology for structural health monitoring was derived, following the strategy proposed by Magliacano *et al.* [5]. Nevertheless, realistic edge constraints and mid-frequency validation remain open issues [6][7][8]. This comprehensive framework represents a natural evolution of the authors' previous studies on FS systems with clamped or cantilever boundary conditions [9] and delivers a self-contained, substantially novel contribution.

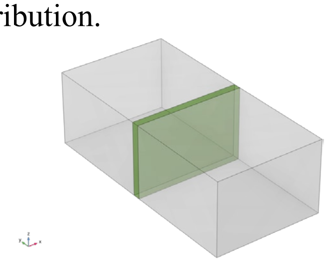

Figure 1: Schematic of the model domains; the aluminum plate is green, while the air volumes are gray.

Methodology

Cross-sectional displacements and pressure fields are approximated by linear, quadratic, or cubic Lagrange polynomials, or, for the uncoupled domains, by total-degree Taylor polynomials up to

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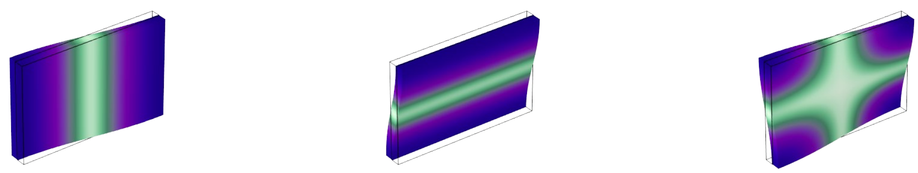
fifth order. The axial field employs one-dimensional Lagrangian elements, allowing the formulation to recover three-dimensional behavior hierarchically [10].

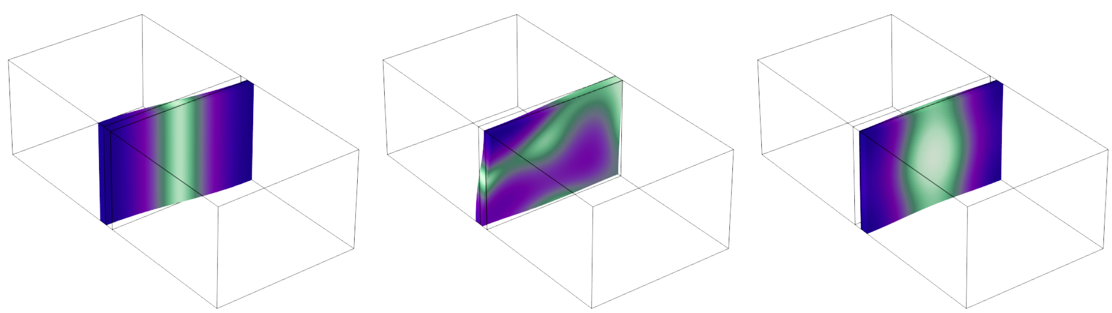
A 15[cm]×10[cm] aluminum plate of thickness 1[cm] is surrounded by 15[cm] air layers on both faces, as illustrated in Figure 1, following ISO 9613-1 guidelines. Reference three-dimensional solutions are obtained with Comsol Multiphysics 6.2.

Results and Discussion

The predictive capability of the higher-order scheme is assessed by juxtaposing *in-vacuo* solutions with those of the fully coupled fluid–structure model. The analysis focuses on (i) the global downshift of the eigenvalue spectrum caused by added mass, and (ii) the preservation of modal shape integrity, paying special attention to the influence of realistic edge constraints. The Lagrange LE9B3 expansion is singled out because it reproduces the three-dimensional benchmark while keeping the numerical cost moderate.



2nd modal shape of the in vacuo *model, 1079[Hz].* *3rd modal shape of the* in vacuo *model, 2408[Hz].* *4th modal shape of the* in vacuo *model, 3454[Hz].*



2nd modal shape of the coupled model, 1079[Hz]. *3rd modal shape of the coupled model, 2138[Hz].* *4th modal shape of the coupled model, 2139[Hz].*

Figure 2: Comparison of the first three non-rigid modal shapes between in vacuo (displacement) and coupled (displacement-pressure) models. Aluminum material, simply supported structural, and absorbing fluid boundary conditions.

Acoustic loading produces a mode-dependent frequency reduction: the fundamental pair remains virtually unchanged, whereas higher modes experience a drop of up to 20%. Mode shapes plotted in Figure 2 retain their nodal patterns, confirming that the hierarchical CUF kinematics accurately captures fluid–structure coupling without sacrificing shape fidelity.

Releasing the lateral restraints lowers the first significant eigenfrequency from 2140[Hz] to 2073[Hz], a reduction of roughly 3% in line with the expected loss of bending stiffness. Despite

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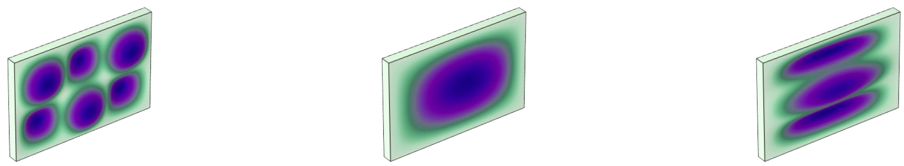
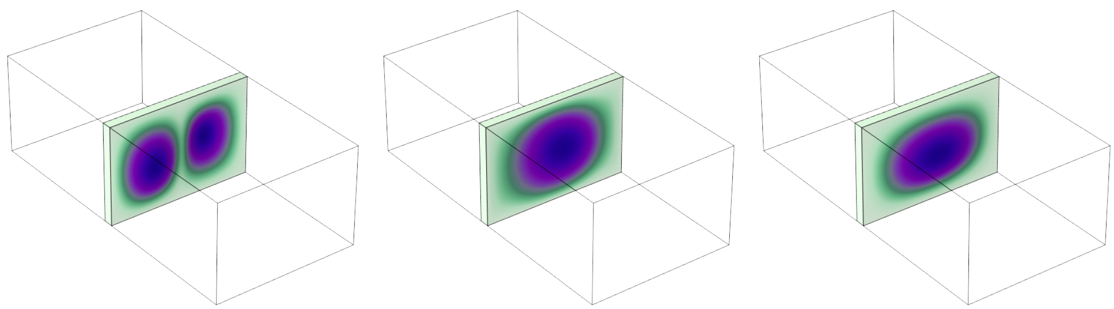
this shift, Figure 3 shows that the modes remain bending-dominated; only a mild intensification of in-plane displacements is observed near the free edges.



7th modal shape of the in vacuo *model, 2081[Hz].*

8th modal shape of the in vacuo *model, 2298[Hz].*

9th modal shape of the in vacuo *model, 4742[Hz].*



7th modal shape of the coupled model, 2079[Hz].

8th modal shape of the coupled model, 2138[Hz].

9th modal shape of the coupled model, 2140[Hz].

Figure 3: Comparison of the first three non-rigid modal shapes between in vacuo (displacement) and coupled (displacement-pressure) models. Aluminum material, free structural, and absorbing fluid boundary conditions.

The fluid medium produces a pronounced added-mass effect, shifting the plate's eigenfrequencies to lower values compared with the *in vacuo* case and activating additional hybrid resonance modes. Numerical results confirm that the CUF-based formulation retains high fidelity while achieving marked computational savings: high-order cross-sectional expansions cut the number of required degrees of freedom by up to two orders of magnitude yet still yield mesh-independent predictions. This approach makes it attractive for large-scale or high-frequency analyses under stringent resource constraints. Across all test cases, the model reproduces benchmark data with excellent accuracy, displays robust convergence, and faithfully captures the essential physics of fluid-structure interaction.

Conclusions

The present research confirms that high-order CUF elements [11], when combined with a weak interface coupling, provide a numerically parsimonious yet accurate tool for fluid-loaded plate analysis. Frequency errors stay below 1% with two orders of magnitude fewer unknowns than complete three-dimensional meshes. This efficiency paves the way for integration into multi-disciplinary optimization loops.

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