A GENERALIZED CONDENSATION METHOD FOR FIELD-BASED STRUCTURES

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ABSTRACT

Structural condensation is widely employed in aeroelastic analysis to efficiently model nonlinear structural dynamics. For a conventional finite element model, condensation is relatively straightforward; a subset of the nodes in a finite element model that follow major load-paths is selected to partition the system of linear equations with regards to loaded (master) and unloaded (slave) degrees of freedom. The master nodes form the beam elements of the reduced model to which the mass and stiffness properties are fit to the full finite element model.

In more recent years, feature-mapping methods[1] have enabled topology optimization with high-level, parameterized geometry by mapping the design to an implicit field representation and solving the displacements on a fixed, non-conforming mesh. This implicit representation naturally and robustly transforms topological operations into inexpensive arithmetic operations. Although feature mapping has been applied to circumvent the reconstruction or perturbation of analysis meshes in an aeroelastic analysis[2], implicit field-based structural representations are incompatible with existing condensation schemes that rely on nodal partitioning.

This work introduces a generalized condensation method for field-based structural representations. First, a beam geometry is extracted by skeletonizing the field representation of the structure. Crucially, the resulting skeleton is generated automatically and need not conform to the nodes that discretize the field representation. The conventional master-slave partitioning scheme is replaced with a generalized deformation map between the beam-element skeleton and the surrounding volume. Then the geometrically linear stiffness and mass properties of the field-based representation are employed similarly to those of a conventional large-scale finite element model[3] to fit the mass and stiffness properties of a beam model based on Hodge's intrinsic theory.

We demonstrate the efficacy and efficiency of the proposed condensation method for several 3D configurations with a prescribed outer mold line and with an internal structure implicitly represented by a density field. Our generalized condensation strategy automates the process of obtaining a structural beam model that approximates a density-based structural representation, thereby enabling condensation methods to efficiently model the nonlinear structural dynamics of field-based structural models. This work marks a major step towards employing condensation methods to efficiently model geometrically nonlinear aeroelastic effects in the context of a topology optimization.

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[1] Fabian Wein, Peter D Dunning, and Julián A Norato. "A review on feature-mapping methods for structural optimization". In: *Structural and multidisciplinary optimization* 62.4 (2020), pp. 1597–1638.

[2] Hollis A Smith and Joshua D Deaton. "A Feature-Based Approach to Aeroelastic Topology Optimization". In: *AIAA SCITECH 2025 Forum*. 2025, p. 0972.

[3] Rafael Palacios and Alvaro Cea. "Nonlinear modal condensation of large finite element models: application of Hodges's intrinsic theory". In: *AIAA Journal* 57.10 (2019), pp. 4255–4268.