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Progress in Inverse Finite Element Method for Shape- and Stress-Sensing of Shell Structures

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Abstract

Structural Health Management (SHM) systems are designed to mitigate accidents due to structural failures and are envisioned as integral technologies of the next-generation aerospace vehicles. Advanced sensor arrays and signal processing technologies are being developed to provide distributed, real-time sensor monitoring of states of strain, temperature, and aerodynamic pressure. When properly integrated within robust and computationally-efficient physics-based algorithms, the ensuing massive quantities of measured data will help infer physically admissible structural behavior, provide real-time feedback to the actuation and control systems, and assess internal loads and structural integrity.

This lecture will address the latest advances in the inverse Finite Element Method (iFEM), which represents a significant step toward bringing SHM closer to the realm of higher technology readiness. The iFEM enables reconstruction of full-field displacements, strains, and stresses, using measured strain data provided by in-situ strain sensors. Various applications of this computational technology have already been demonstrated for beam, frame, plate, and shell structures using numerically generated as well as experimentally measured strain data, both for linear and geometrically nonlinear deformations and small strains. Unlike most other methods for deformed shape reconstruction, iFEM is general enough to be applicable to complex geometries, boundary conditions and loadings, with and without inertial effects. The latest iFEM formulation produces stable and accurate solutions for those practical cases when the measured strain data are incomplete; both in the sense of spatial distribution with respect to the underlying iFEM mesh, as well as with respect to the lack of completeness of the measured strain data. In this regard, the iFEM reconstruction is examined using tri-axial strain data, characteristic of strain-rosette measurements, as well as uniaxial strain data, commonly available by way of Fiber Bragg Grating (FBG) sensors. FBGs produce uniaxial, albeit high-density, strain measurements along the fibers.

Two iFEM formulations for application to shell structures are discussed. The first formulation utilizes First-order Shear Deformation Theory (FSDT) as its analytic basis, whereas the second uses Refined Zigzag Theory (RZT). This new structural theory is well suited for laminated composite and sandwich structures. Both formulations are based upon a weighted-least-squares variational principle that uses the complete set of strains corresponding to the respective theory. The error functional uses the least-squares-difference terms comprised of the strain components that are expressed in terms of the assumed element displacements and the corresponding strains that are measured experimentally. All strain-displacement relations are enforced explicitly, whereas the analytic and measured strains are matched in the least-squares sense. By virtue of these assumptions, all strain compatibility relations are explicitly satisfied and thus ensure integrability of the strain field to derive a compatible displacement field across the entire structural domain. The discretization of a complex shell structure is accomplished by way of simple and efficient three-node inverse-shell elements that are based upon -continuous, anisoparametric shape functions.

Finally, the lecture will highlight several numerical examples that demonstrate the unique modeling capabilities of the latest iFEM formulations. These include problems in which measured strains are only provided along sparsely distributed lines to simulate strain data from FBG arrays. In addition, large-displacement (geometrically nonlinear) problems will be discussed in which iFEM is applied using incremental strain measurements, while updating the deformed geometry following the incremental reconstructions. Results for problems with numerically simulated and experimentally measured strains will be discussed.

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A Brief Biography of Alexander Tessler

- Dr. Alexander Tessler (PhD, UCLA, 1979) has been employed by the U.S. aircraft industry, Army research, and, currently, NASA Langley Research Center (since 1991). He has also served as an adjunct professor at Northeastern University, Old Dominion University, George Washington University, and University of Virginia.
- Dr. Tessler is a recognized international authority in applied mechanics and finite element methods and is credited with the development of techniques and finite element methods used in commercial, university, and government software. Many of his methods and formulations have been documented in the state-of-the-art textbooks on finite element methods. To date, he has contributed over two hundred technical papers, book chapters, and reports, and has made numerous presentations at national and international conferences, industry workshops, and universities.
- Dr. Tessler is a NASA Floyd Thompson Fellow. He has received numerous awards for his technical excellence and outstanding contributions. His biography has been published in Marquis Who's Who in Science and Engineering, Who's Who in America, and Who's Who in the World.

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January, the 16st, 2017 at 12:00
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