A NONPARAMETRIC PROBABILISTIC APPROACH FOR MODELING AND QUANTIFYING MODEL-FORM UNCERTAINTY IN CFD WITH TURBULENCE MODELING

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ABSTRACT

An innovative, computationally tractable approach for modeling and quantifying model-form uncertainty in viscous computational fluid dynamic (CFD) models is presented. It distinguishes between two sources of uncertainty: those associated with turbulence modeling; and all other sources such as those related to wall and/or far-field boundary conditions. Accordingly, the proposed approach consists of two complementary methods for performing uncertainty quantification (UQ): one that targets the uncertainty associated with modeling the Reynolds stress; and one that targets all other sources of model-form and/or parametric uncertainty. The former method decomposes the Reynolds stress tensor into a trace-vanishing deviatoric component and a spherical part [1]; constructs a hyperparameterized probability model of the eigenvalues of the deviatoric component based on its spectral algebraic properties; and performs additional probabilistic modeling to obtain a complete hyperparameterized probabilistic model for the Reynolds stress. Each realization of this probabilistic model corresponds to an admissible turbulence model of a certain family. The latter method adapts the recently developed nonparametric probabilistic method for modeling and quantifying model-form uncertainty [2,3] to the context of this work and its objectives: it is grounded in a stochastic, projection-based model order reduction (PMOR) technique that is also hyperparameterized; and that guarantees the computational tractability of the resulting approach for performing UQ. The hyperparameters of both components of the overall approach are simultaneously determined by formulating and minimizing an appropriate data-driven stochastic loss function. Its unique features also include the accounting for the uncertainty associated with PMOR, which is performed to ensure the computational tractability of the incurred Monte Carlo simulations. The potential of the overall methodology for the UQ of large-scale CFD computations with turbulence modeling is demonstrated for the Reynolds-averaged Navier-Stokes (RANS)-based aerodynamic analysis in the transonic flow regime of a rigid NASA Common Research Model configuration for which wind tunnel data is available.

REFERENCES

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