An Adaptive N-Fidelity Metamodel for Design and Operational-Uncertainty Space Exploration of Complex Industrial Problems

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ABSTRACT

Ship performance depends on design and operational (including environmental) parameters. The accurate prediction of significant design metrics (such as resistance and powering requirements; seakeeping, maneuverability, and dynamic stability; structural response and failure) requires prime-principle-based high-fidelity computational tools (e.g., for computational fluid/structural dynamics, CFD/EFD), especially for innovative configurations and off-design conditions. These tools are generally computationally expensive, making the exploration of design (such as in simulation-based design optimization, SBDO) and operational-uncertainty (such as in uncertainty quantification, UQ) spaces a technological challenge.

The objective of the present work is to develop and demonstrate an adaptive generalized N-fidelity metamodel to reduce the computational effort in both SBDO and UQ of complex industrial problems, while maintaining highly accurate predictions. The model can be also used to fuse together heterogeneous sources, such as CFD and EFD data.

Consider $\mathbf{x} \in \mathbb{R}^n$ as the design and/or operational-uncertainty vector. Define the function of interest provided by the highest-fidelity level as f_1, the lowest-fidelity as f_N, and arbitrary intermediate fidelity levels as $\{f_i\}_{i=2}^{N-1}$. The N-fidelity approximation $\hat{f}(\mathbf{x})$ of the desired function $f(\mathbf{x})$ reads

$$\begin{cases} \hat{f}(\mathbf{x}) = \tilde{f}_N(\mathbf{x}) + \displaystyle\sum_{i=1}^{N-1} \tilde{\varepsilon}_i(\mathbf{x}) \\ \varepsilon_i(\mathbf{x}) = f_i(\mathbf{x}) - f_{i+1}(\mathbf{x}) \end{cases} \quad \text{and} \quad U_{\hat{f}}(\mathbf{x}) = \sqrt{U^2_{\tilde{f}_N}(\mathbf{x}) + \sum_{i=1}^{N-1} U^2_{\tilde{\varepsilon}_i}(\mathbf{x})} \tag{1}$$

where ε_i is the intra-level error and "$\sim$" denotes metamodel prediction based on a stochastic ensemble of radial basis functions, which also provides the prediction uncertainty U. Assuming the uncertainty associated to the prediction of the lowest-fidelity $U_{\tilde{f}_N}$ and intra-level errors $U_{\tilde{\varepsilon}_i}$ as uncorrelated, the N-fidelity uncertainty $U_{\hat{f}}$ can be evaluated by Eq. 1. The contribution of each fidelity level to $U_{\hat{f}}$ is assessed and used to refine adaptively the training set as the sampling of the design/operational space progresses.

The proposed N-fidelity metamodel extends authors previous work [1, 2] and is applied here to: (i) the shape optimization of a destroyer hull (DTMB 5415) and (ii) a RoPAX ferry, and (iii) the UQ of a NACA airfoil. The DTMB 5415 and RoPAX problems are studied by a Reynolds-averaged Navier-Stokes equation solver. The NACA airfoil is assessed by an inviscid aerodynamic solver coupled with an integral boundary layer equation near the body and the wake. For all problems, $N \geq 3$ is selected and solutions from different computational grids are used as different fidelity levels.

REFERENCES

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