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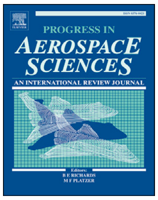

A review on design of experiments and surrogate models in aircraft real-time and many-query aerodynamic analyses

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ABSTRACT

Full scale aerodynamic wind tunnel testing, numerical simulation of high dimensional (full-order) aerodynamic models or flight testing are some of the fundamental but complex steps in the various design phases of recent civil transport aircrafts. Current aircraft aerodynamic designs have increase in complexity (multidisciplinary, multi-objective or multi-fidelity) and need to address the challenges posed by the nonlinearity of the objective functions and constraints, uncertainty quantification in aerodynamic problems or the restrained computational budgets. With the aim to reduce the computational burden and generate low-cost but accurate models that mimic those full order models at different values of the design variables, Recent progresses have witnessed the introduction, in real-time and many-query analyses, of surrogate-based approaches as rapid and cheaper to simulate models. In this paper, a comprehensive and state-of-the art survey on common surrogate modeling techniques and surrogate-based optimization methods is given, with an emphasis on models selection and validation, dimensionality reduction, sensitivity analyses, constraints handling or infill and stopping criteria. Benefits, drawbacks and comparative discussions in applying those methods are described. Furthermore, the paper familiarizes the readers with surrogate models that have been successfully applied to the general field of fluid dynamics, but not yet in the aerospace industry. Additionally, the review revisits the most popular sampling strategies used in conducting physical and simulation-based experiments in aircraft aerodynamic design. Attractive or smart designs infrequently used in the field and discussions on advanced sampling methodologies are presented, to give a glance on the various efficient possibilities to a priori sample the parameter space. Closing remarks foster on future perspectives, challenges and shortcomings associated with the use of surrogate models by aircraft industrial aerodynamicists, despite their increased interest among the research communities.

1. Introduction

In aircraft aerodynamic design teams, the computational burden linked with the preliminary or conceptual design phases is in general very prodigious and is characterized by high computational costs, high fidelities or sensitivity analyses. Identifying and screening multiple aircraft configurations (cruise/high lift, control surface deflections, etc) and flight conditions (Mach number, angle of attack, etc) in order to analyze the most promising ones require to generate fast and efficient methods. Commonly, high dimensional aerodynamic design models - HDAMs (discretization in more than 3 spatial dimensions), also know as full order aerodynamic models (FOAMs), require time consuming and computationally expensive simulations or physical experiments to evaluate the complex objective functions and constraints for analysis and optimization. Solving aerodynamic problems generally require real-time or many-query settings; a real-time analysis consists of instantaneous solutions under restricted resources and give the possibility to respond to evolving conditions as the phenomenon unfold (e.g. in routine analysis or control and nondestructive evaluation/parameter estimation). A many-query scenario arise when the FOAM is solved repeatedly for various configurations and design variables (e.g. in design optimization, optimal control or uncertainty analysis). As an example, while designing a new aircraft, a CFD (Computational Fluid Dynamics) campaign provides the aerodynamicists with flow solutions from only few selected flight conditions because it will be time-consuming and costly to evaluate all of them. To circumvent these burdens and enable a wider exploration of the

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Nomenclature

(L)CVT	(Latinized) Centroidal Voronoi Tesselation
(N)OA	(Nearly) Orthogonal Arrays
(N)OLH	(Nearly) Orthogonal Latin Hypercube
AIC	Akaike's Information Criterion
AMSE	Adjusted Mean Square Error
ANN	Artificial Neural Networks
ANOVA	Analysis Of Variance
APR	A Priori Model Reduction
BIC	Schwarz's Bayesian Information Criterion
BK	Blind Kriging
BPOD	Balanced Proper Orthogonal Decomposition
CCD	'Box-Wilson' Central Composite Designs
CDoE	Classical Design of Experiments
CFD	Computation Fluid Dynamics
CPOD	Compact Proper Orthogonal Decomposition
DACE	Design and Analysis of Computer Experiments
DEIM	Discrete Empirical Interpolation Method
DFM	Data-Fit Models
DNS	Direct Numerical Simulations
DoE	Design of Experiments
DR	Dimensionality Reduction
EDK	External Drift Kriging
EIM	Empirical Interpolation Method
EI	Expected Improvement
FAST	Fourier Amplitude Sensitivity Test
FO(A)M	Full Order (Aerodynamic) Model
FT	Flight Test
GEK	Gradient Ehance Kriging
GNAT	GaussNewton with Approximated Tensors
GPOD	Gappy Proper Orthogonal Decomposition
HD(A)M	High Dimensional (Aerodynamic) Design Models
HM	Hybrid Models
IMSE	Integrated Mean Square Error
ISC	Infill Sampling Criteria
Isomap	Isometric Mapping
LCB	Lower Confidence Bounding
LDR	Linear Dimensional Reduction
LES	Large Eddies Simulations
LHS	Latin Hypercube Sampling
LOO	Leave-One-Out Cross Validation
LSM	Least Square Method
MAE	Mean Absolute Error
MARS	Multivariate Adaptive Regression Splines
MCMC	Markov Chain Monte Carlo Sampling
MDoE	Modern Design of Experiments
MDO	Multidisciplinary Design Optimization
MDS	Multidimensional Scaling
MES	Maximum Entropy Sampling
MFIS	Multifidelity Importance Sampling
MFM	Multidifelity Model
MLE	Maximum Likelihood
MLP	Multilayers Perceptrons
MOR	Model Order Reduction
MPE	Missing Point Estimation
NLDR	Nonlinear Dimensionylity Reduction
ODE	Ordinary Differential Equations
OFAT or OVAT	One Factor/Variable At a Time
OK	Ordinary Kriging
PCA	Principal Component Analysis
PDE	Partial Differential Euqations
PGD	Proper Generalized Decomposition
PI	Probability of Improvement
POD	Proper Orthogonal Decomposition
PRESS	Prediction Error Sum of Squares
RAE	Relative Accuracy Error
RANS	Reynolds Navier Stokes Equations
RBF(NN)	Radial Basis Neural Network
REES	Regional Error Measures
RK	Regression Kriging
ROB	Reduced Order Basis
ROM	Reduced Order Model
SB(A)O	Surrogate Based Analysis and Optimization
SCF	Spatial Correlation Function
SIAM	Society for Industrial and Applied Mathematics
SK	Simple Kriging
SMMM	Surrogate Model Management Methods
SSA	Stochastic Spectral Approximations
SUMO	Surrogate Model
SVD	Singular Value Decomposition
SVM	Support Vector Machines
SVR	Support Vector Regression
TPWL	Trajectory Piecewise Linear Approximation
TRMM	Trust-Regions Management Methods
UK	Universal Kriging
VAM	Variable Accuracy Model
VCM	Variable Complexity Model
VFM	Variable Fidelity Model
VRM	Variable Resolution Model
WRMSE	Weighted Root Mean Square Error
WTT	Wind Tunnel Test

design space, researchers introduced cheap-to-evaluate models (surrogates models- SUMOs) to accurately and speedily predict the values of the model objectives and constraints at new design points, without a need to necessarily repeat the original expensive physical or simulation-based experiment.

Optimization through the use of surrogates models is called Surrogate-Based Optimization (SBO). Gaining a good insight into SBO requires a knowledge in Design of Experiments (DoE) (spatial distribution of the samples, training set), simulation-based models (e.g. CFD) or physical models (e.g. Wind Tunnel Testing) and optimization. Moreover, SBO frameworks are heavily dependent on the design objectives and constraints. They should quantify for the uncertainties (sensitivity analysis) within the surrogate models, deal with 'noisy' data and pare down the problems posed by the high-dimensionality of the data (dimensionality reduction). A vast number of papers have addressed SBO methods. Popular releases are the ones from Booker et al. [1], Queipo et al. [2], Forrester et al. [3], Forrester and Keane [4], Ahmed et al. [5], Koziel et al. [6], Viana et al. [7] or more recently Leifsson and Koziel [8]. However, it is not clear from the readings if the approaches and frameworks presented in the above-mentioned papers are suitable for aerodynamic analysis and optimization, and could fit the needs of the aircraft industry. Motivated by the lack of a review considering industrial outlooks proper to aircraft aerodynamic design analysis and optimization, the present paper is a broad up-to-date survey that differs from its existing counterparts by the wide range of DoEs and SUMOs methodologies introduced, its aircraft industrial emphasis, recent SBO applications in aircraft aerodynamic design, etc.

The outline of the paper is as followed: Section 2 revisits the classical DoE (CDoE) and the modern DoE (MDoE or Design and Analysis of Computer Experiments (DACE)). Section 3 provides a comprehensive summary on existing surrogate modeling techniques employed in aircraft aerodynamics, including data-fit models (DFM), reduced-order models