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An efficient surrogate-based framework for aerodynamic database development of manned reentry vehicles

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Abstract

In this study, an efficient framework is developed via surrogate modeling for aerodynamic database generation and management of reentry vehicles. For reentry vehicles with the wide range of flight envelope, a large number of coefficients are required to fulfill the aerodynamic multi-dimensional tables. To reduce the number of high-fidelity analyses without considerable accuracy loss, a proper combination of sampling, interpolation, and data fusion methods are required. The proposed framework includes a multi-dimensional nonlinear interpolation (Kriging), a data fusion (co-Kriging) and a sampling method (Latin Hypercube Sampling) in an integrated structure coupled with aerodynamic solvers. The main idea is applying Kriging interpolation method on cheap data points to estimate the aerodynamic coefficients' trends over the entire space of variables, and refining the trends with accurate sample points and data fusion. Latin hypercube sampling method is used for optimal distribution of cheap samples and initial accurate sample points. After a few high-fidelity analyses, co-Kriging data fusion method is applied for the improving aerodynamic database fidelity via augmentation of trends with the accurate data. The process iterates using new accurate sample points (located on maximum mean squared error) until the mean squared error criteria is met. Cheap data are produced by a variety of low-fidelity solvers e.g. potential and Euler solvers and high-fidelity data are calculated by full Navier-Stokes solvers (CFD). For each regime of the flight envelope, i.e. subsonic, transonic, supersonic and hypersonic and each type of reentry configurations, e.g. Apollo-type, grid studies are done separately and the optimum grid and solver settings are implemented into the framework to facilitate the automatic aerodynamic database generation and management. All parts of the presented framework are validated independently in compare to some reference test cases. To show the capabilities of the developed framework, Orion reentry capsule with complete flight envelope is assumed as a sample. Orion aerodynamic database is generated efficiently and the obtained results are in good agreement in comparison with experimental data. In conclusion, the framework accuracy, flexibility, and efficiency are demonstrated.

Keywords: Aerodynamic database; Co-Kriging data fusion; Kriging interpolation; Manned reentry vehicle; Surrogate model

1. Introduction

Atmospheric reentry flight is inevitable when we want to return a valuable payload from space. Mostly, reentry vehicles contain astronauts or important objects, consequently, their design and development must be reliable and accurate. One of the key aspects of reentry vehicle development is aerodynamic analysis as an input for other aspects of design e.g. structure, thermal, stability, simulation and control (Desai et al., 2008). For reentry vehicles, aerodynamic database generation process is challenging, time-consuming and expensive because of the vast flight envelope including hypersonic, supersonic, transonic and subsonic flow regimes. Typically, aerodynamic forces and moments of these vehicles are presented in

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Nomenclature

Symbols

C_L	lift coefficient
C_D	drag coefficient
C_M	moment coefficient
$E(I(x))$	expected Improvement function
$F(x)$	function of design variables
$\hat{f}(x)$	regression function in Kriging
Kn	Knudsen number
L	likelihood function
M	Mach number
n_{db}	total number of data to complete the database
n_i	number of values of parameter i
P_j	smoothness parameter in Kriging
p, q, r	angular rates
Re	Reynolds number
$\hat{S}(x)$	mean squared error function
x	vertex of design variables
X_c	low-fidelity sample point
X_e	high-fidelity sample point
$\hat{y}(x)$	Kriging estimator of y
Y_c	low-fidelity output
Y_e	high-fidelity output
Z_c	local features of low-fidelity data
Z_e	local features of high-fidelity data

Greek

α	angle of attack
β	side slip angle
θ	width parameter in Kriging
μ	mean of a random field
ρ	constant scaling factor
σ	standard deviation
ψ	radial basis function
ω	weighting matrix
Ψ	correlation matrix of observed data

Acronyms

B.C	Boundary Condition
CFD	Computational Fluid Dynamic
EIF	Expected Improvement Function
LHS	Latin Hypercube Sampling
MLE	Maximum Likelihood Estimate
MSE	Mean Squared Error

Indexes

c	cheap (low-fidelity)
d	desire
e	expensive (high-fidelity)
db	database

multi-dimensional tables and a large number of aerodynamic data ($\sim10^6$) is required to complete the table. For aerodynamic database construction, there are several sources and methods. The real and costly data are obtained from flight tests. Wind tunnel test is cheaper but has limitations regards scaling, blockage and measurements. CFD is another source of aerodynamic data that can predict non-linear flow physics. Another approach and the cheapest one is semi-empirical methods combined with approximate and linear aerodynamic theories. Obviously, fulfilling whole aerodynamic table with high fidelity data is very expensive and nearly impossible and therefore employing different fidelity methods is unavoidable. Also, for the fusion of multi-fidelity data and improvement of the aerodynamic table accuracy, surrogate models can be used (Ghoreyshi et al., 2010, 2011; Da Ronch et al., 2011; Vallespin et al., 2012).

Pamadi et al. (2001) developed an aerodynamic database for X-34 in reentry phase. In some flight conditions that no wind tunnel data were available, they used numerical solutions. For data completeness, they used APAS code that can cover subsonic and supersonic flow regimes calculation and for higher Mach numbers, they used MARK III (Pamadi et al., 2001). Chaderjian et al. (2003) used AERODB software to run thousands of inviscid and viscous Navier-Stokes calculations for aerodynamic database generation for an asymmetric reentry vehicle. They used 13 super-computers on 4 different sites. All processes are automated to reduce time, cost and user errors (Chaderjian et al., 2003). Prabhakar (2005) developed aerodynamic database generation algorithm for three kinds of reentry vehicle geometries using different types of solvers (Prabhakar, 2005). Rufolo et al. (2006) represented the methodology of integration of different aerodynamic sources of data for PRORA vehicle. Their main sources were wind tunnel data and computational fluid dynamics. Moreover, some methods like vortex lattice method, panel method and Datcom have been used to fill gaps in wind tunnel data (Rufolo et al., 2006). Kinney (2004, 2007, 2009) used several correction factors for refining low fidelity calculations. These correction factors were evaluated from the proportion of CFD computations to cheap calculations in some flight conditions (Kinney, 2004, 2007, 2009). Tomac and Rizzi (2010) used adaptive fidelity CFD tools ranging from vortex lattice method to URANS CFD solver to generate aerodynamic tables of the X-31 vehicle. Interpolation and data fusion methods have been used to combine data and create an even accurate database (Tomac and Rizzi, 2010).

As seen in the literature, aerodynamic studies of reentry vehicles are mainly emphasized on the direct generation of aerodynamic coefficients using costly CFD or wind tunnel