JOURNAL OF SPACECRAFT AND ROCKETS
Vol. , No. ,

Proper-Orthogonal-Decomposition-Based Leveraging of Reentry Vehicle's Surface Environment

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DOI: 10.2514/1.A33241

In the early stage of a reentry vehicle designs are often necessary tools able to perform mission and trajectory trade studies. Many works in the literature present tools able to interpolate from a numerical database of high-fidelity simulations to a target free-stream condition. In this context, the work explores the capability of a reduced-order model in extending a limited database of computational fluid dynamics simulations to the full coverage of the design space. This results in a fast physic-based tool able to generate load history experienced on a vehicle's surface during the reentry flight. The reduced-order model is based on proper orthogonal decomposition coupled with a Gaussian process for interpolations. A detailed cross-validation analysis of the model that provides a loss function map in the design space can be considered as a guide to in-fill the database with further computational fluid dynamics simulations, keeping the number of computational fluid dynamics runs at a minimum value to limit the computational budget. Main results are the history of the pressure and skin-friction coefficient of a reference trajectory related to a specific vehicle's control points. This output will be compared with a simple Gaussian metamodel based directly on the computational fluid dynamics data of such control points.

Nomenclature

c_f	=	skin-friction coefficient
c_p	=	pressure coefficient
$\boldsymbol{E}$	=	proper orthogonal decomposition information content
f	=	true function
$\hat{f}$	=	modeled function
R	=	correlation matrix
Re/m	=	freestream Reynolds number/meter
S	=	processed snapshot matrix
$\boldsymbol{s}$	=	design variables vector
W	=	snapshot matrix of computational fluid dynamics data
$\boldsymbol{x}$	=	spatial vector of coordinates (x, y, z)
z_{cfd}	=	computational fluid dynamics variables involved in Kriging metamodel
α	=	vector of scalar proper orthogonal decomposition coefficients
λ	=	vector of proper orthogonal decomposition eigenvalues
ρ	=	Pearson's coefficient
$\boldsymbol{\Phi}$	=	matrix of spatial eigenfunction or proper orthogonal decomposition modes
ψ	=	basis function of Kriging surface of interpolation

I. Introduction

THE design of hypersonic and reentry vehicles requires an assessment of the aerodynamic and aerothermodynamics environments the vehicle will experience during the reentry flight. Due to the huge amount of kinetic and potential energies of the "falling vehicle," the design and sizing of thermal protection system (TPS) play a key role, because it protects the vehicle and payload from the intense heat generated from the aerobreaking process.

For a given vehicle configuration and an associated flight trajectory, it is mandatory to determine along the trajectory the time-varying heating at the vehicle surface to enable selection and size of the material(s) of the required TPS [1]. A typical design output is the time history of loads like pressure, skin friction, and heat flux along any flight trajectory and of any point on the vehicle surface.

In the TPS design problem, an engineering code is sufficient for determining general trends and performing preliminary design trades. However, this approach loses accuracy in regions of fluid dynamic complexity. Computational fluid dynamics (CFD) can be used to compute the flowfield past the vehicle, providing high-fidelity estimates of the surface quantities involved in the TPS design. Either way, numerical simulations of high-enthalpy flows, can be time consuming due to the complex physical phenomena like separated boundary layer, shock wave impingement, and so on. Furthermore, the flow can be considered, in certain conditions, as a reacting mixture in thermochemical nonequilibrium, and thus numerically stiff [2]. Then, CFD cannot be used at each point of the descent trajectory, as would be required to assess the way in which heat loads propagate on the surfaces and in to the vehicle's structure, in a time-accurate framework.

Here, the technology introduced can be intended as a different approach to the problem of the extension of the results coming from a limited matrix of CFD solutions to the whole design space. This can be useful, especially in the preliminary design phase when a broader range of configurations, entry conditions, and then vehicle trajectories are often in a constant state of change.

In the literature, some works try to pursue this goal with some different approaches. The anchoring process is often employed [3,4] and permits a few CFD solutions to be used beyond the original flight condition, allowing for the cost-effective use of CFD solutions early in the design process. A different way was presented in [5], where directly a nonlinear interpolations in the design space (DS) variables is performed, assessing the effects of the new freestream conditions on the aerodynamic and thermal loads the vehicle has to withstand. An interesting approach could be found in [6,7], where the aerothermal environment for any trajectory was obtained by interpolation of the high-fidelity CFD solution nearest in trajectory space to a specific flight condition. The interpolation was performed using the engineering code HAVOC, which employs correlation, scaling laws, and theory to approximate surface and boundary-layer properties.

This work considers a reduced-order model (ROM) based on a proper orthogonal decomposition (POD) technique that can transform in a compact form the information coming from experimental or numerical simulations. The model can be considered as physics-based, since it considers the flow features coming from numerical evaluations.

POD is a technique able to linearize a highly nonlinear problem. In fact, it was introduced in aeronautics by Lumley [8] to extract coherent structures from turbulent flow. But, in 1987, Sirovich pulled

Received 7 January 2015; revision received 3 June 2015; accepted for publication 4 July 2015; published online XX epubMonth XXXX.

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