Aerospace Science and Technology ••• (••••) •••–•••

Contents lists available at ScienceDirect

Aerospace Science and Technology

www.elsevier.com/locate/aescte

Surrogate models and mixtures of experts in aerodynamic performance prediction for mission analysis

Rhea P. Liem [a,1], Charles A. Mader [b,2], Joaquim R.R.A. Martins [b,3]

[a] University of Toronto, Institute for Aerospace Studies, Toronto, ON, Canada
[b] University of Michigan, Department of Aerospace Engineering, Ann Arbor, MI, United States

ARTICLE INFO

Article history:
Received 8 October 2014
Received in revised form 22 December 2014
Accepted 24 February 2015
Available online xxxx

Keywords:
Surrogate models
Mixture of experts
Kriging
Radial basis functions
Adaptive sampling
Mission analysis
Aerodynamics
Aircraft design

ABSTRACT

The accurate evaluation of aircraft fuel burn over a complete mission is computationally expensive and may require millions of aerodynamic performance evaluations. Thus, it is advantageous to use surrogate models as approximations of high-fidelity aerodynamic or aerostructural models. Conventional surrogate models, such as the radial basis function and kriging, cannot model these functions accurately, especially in the transonic regime. To address this issue, we explore several ways to improve the accuracy of surrogate models. First, we employ an adaptive sampling algorithm to complement a traditional space-filling algorithm. Second, we improve the kriging surrogate performance by including gradient information in the interpolation (a form of gradient-enhanced kriging—GEK) and by introducing a known trend in the global model component (kriging with a trend). Lastly, we propose a mixture of experts (ME) approach, which is based on the divide-and-conquer principle. We validate our surrogate models using aerodynamic data for conventional and unconventional aircraft configurations, and we assess their performance in predicting the mission ranges by analyzing ten mission profiles. Our results show that the proposed ME approach is superior to the traditional models. Using a mixture of GEK models to approximate the drag coefficients gives approximation errors of less than 5% with fewer than 150 samples, whereas the adaptive sampling fails to converge when training a global model. However, when we have a simple function profile, such as the lift and moment coefficients, using a conventional surrogate model is more efficient than an ME model, because of the added computational complexity in the latter. The range estimation errors associated with the ME models are less than 2% for all the benchmark mission profiles considered, whereas some traditional models yield errors as high as 20–80%. We thus conclude that the ME technique is both necessary and sufficient for modeling the aerodynamic coefficients for surrogate-based mission analysis.

1. Introduction

Fuel efficiency has become an increasingly important metric in aircraft design because of increases in the cost of fuel and environmental concerns [44,66]. However, evaluating aircraft fuel burn accurately is not an easy task. Several disciplines contribute to the calculation, including the aerodynamic performance of the aircraft, the aircraft's weight distribution, and the performance of the engines. The calculation is also affected by the speed of the aircraft and the atmospheric conditions at the altitude where the aircraft is flying. To account for the coupling in such a multidisciplinary system, multidisciplinary design optimization (MDO) should be used since it can automatically perform the optimal interdisciplinary trade-offs [54]. While effective, MDO frameworks can be computationally expensive. Completing such a computation in an optimization process (which requires many iterations, prior to reaching optimality) using pure physics-based models quickly becomes computationally intractable. The most common approaches for reducing the cost of aircraft fuel-burn computations involve a simplification of either the physics in the model or the mission profile considered. The classical Breguet range equation is a popular example of such an approach [43,74,81]. Kenway and Martins [33] used this equation to analyze the aircraft performance at each operating point in multipoint high-fidelity aerostructural optimization problems to minimize fuel burn and takeoff gross weight.

E-mail address: rhea.liem@mail.utoronto.ca (R.P. Liem).

[1] Ph.D. Candidate.
[2] Postdoctoral Research Fellow.
[3] Associate Professor.

http://dx.doi.org/10.1016/j.ast.2015.02.019
1270-9638/

Please cite this article in press as: R.P. Liem et al., Surrogate models and mixtures of experts in aerodynamic performance prediction for mission analysis, Aerosp. Sci. Technol. (2015), http://dx.doi.org/10.1016/j.ast.2015.02.019

The multipoint objective is the weighted combination of the objective functions evaluated at five operating points (perturbations of the nominal cruise condition), assuming an equal weight for each point. Other simplified models use fuel fractions to represent the individual segment fuel-burn values [81] or include simplified analytical or empirical models [102] to represent the physics. These simplifications and assumptions reduce the computational time, albeit at the expense of accuracy and generality.

Recent work has shown that surrogate models can significantly reduce the computational cost of performing a detailed fuel-burn computation in a design optimization setting. Surrogate models, or metamodels, are commonly used as simpler approximations of the physical systems to reduce the cost of computationally intensive analysis and optimization tasks [87–89]. Surrogate models have previously been shown to assist various optimization procedures in aerospace engineering. Chung and Alonso [9,10] used a gradient-enhanced kriging (GEK) method in a supersonic business jet design optimization, Toal and Keane [93] used a cokriging method to perform a multipoint drag minimization, Zimmermann and Görtz [105] developed a proper orthogonal decomposition (POD) subspace restricted least squares model to solve the governing fluid flow equations, and Amsallem et al. [2] performed offline precomputations to construct fluid reduced order bases (ROB) and structural reduced order models (ROM) for aeroelastic computations. Fossati and Habashi [18] employed an ROM approach, based on POD and kriging interpolation, to reduce the computational cost in steady and unsteady three-dimensional viscous turbulent aero-icing simulations. In the context of mission analysis, Koko [37] used a Lagrangian interpolation as a surrogate to model the aerodynamic forces at different points along the flight mission of interest in a trajectory optimization problem aiming to minimize the fuel consumption of morphing wingtip devices.

The authors have previously used kriging models to approximate the aerodynamic data required in a detailed mission analysis procedure, to give an accurate estimation of the amount of fuel burned during a mission [47,48]. This surrogate-based mission analysis approach reduces the number of aerodynamic performance evaluations from millions to the number of samples required to build the kriging models, thus enabling the integration of mission analysis in aerostructural optimization cases. Using this procedure, a new strategy was derived to formulate multipoint design aerostructural optimization problems to maximize the aircraft performance over a large number of different missions [47]. This strategy was demonstrated in a fuel-burn minimization problem for a long-range wide-body aircraft configuration, where only the cruise portion was modeled in detail. In this multipoint optimization strategy, the number of high-fidelity aerostructural solutions at each optimization iteration is reduced from millions to 25. A similar approach was demonstrated in a direct operating cost (DOC) minimization problem for a 100-passenger regional jet configuration [48]. In this DOC minimization problem, a shorter range mission was considered. This necessitated the inclusion of the climb and descent segments in the mission, since the cruise segment was no longer the dominant mission segment.

Expanding the input space of the surrogate model to include the flight conditions involved in climb and descent makes training the surrogate model significantly more challenging. In addition to requiring a larger input space, the model needs to capture the high-drag-gradient region outside the cruise regime, which causes problems for some of the simpler surrogate modeling techniques. Unconventional configurations such as blended-wing-body (BWB) configurations present a similar challenge. In these cases, the challenge comes from a higher degree of correlation between drag and trim, causing more nonlinearity in the drag profile with respect to the tail-rotation angle variable that is used to trim the aircraft [52].

To address these challenges we develop a surrogate modeling technique that is sufficiently general to handle the full range of flight conditions and aircraft configurations that may be of interest to an aircraft designer. Specifically, we explore and analyze the performance of various surrogate models in the context of surrogate-based mission analysis. Based on our specific requirements, which are discussed in Section 3, we limit our selection of surrogate models to kriging and radial basis function (RBF) models. We consider several variants of kriging models, in particular those that allow the incorporation of extra knowledge to fine tune the surrogate models.

First, we consider the GEK model, which incorporates gradient information at the sample points so the surrogate model can have better approximations of the curvature around the sample points. GEK is a well-established technique and has been shown to improve kriging performance; see [9,10,41,40,42] for some aerospace applications of GEK.

Second, we consider the "kriging with a trend" model, where we specify the basis functions for the global model of kriging [30]. Instead of using the commonly used low-order polynomials, we select the basis functions based on the system physics, e.g., by setting a quadratic trend in a certain direction. This second approach has been demonstrated in a previous work by the authors [48].

Third, we consider multiple surrogate models in the input space instead of a single global model. The main rationale for this approach is that we let each local surrogate model perform well in a smaller subset of the input space, instead of forcing one model to approximate the entire problem domain, which might have different profiles in the input space (e.g., when the function profile in one region is more nonlinear than in others). We adopt an explicit mixture-of-experts (ME) approach [26], which uses a cluster-based preprocessing step first proposed by Tang et al. [92]. In this approach, the problem domain is first partitioned into several subregions via clustering algorithms, and this is followed by local expert training in each subregion. In this case, the local experts are surrogate models. The local predictions are then combined probabilistically to yield the final prediction.

In this work, we compare the performance of these surrogate models in approximating the aerodynamic lift, moment, and drag coefficients of two Boeing-777-size aircraft configurations: one conventional and one unconventional. We then assess the amount of error that this introduces into the estimated values of the range across ten benchmark missions to assess how well the various techniques work for the surrogate-based mission analysis. This work is a refinement of a previously presented conference paper [46].

We describe the surrogate-based mission analysis procedure in Section 2. In Section 3, we first discuss the surrogate modeling classification, selecting the techniques that are suitable for our purpose. We then explain and compare the selected techniques (kriging and RBF models). Our proposed ME model is presented in Section 4, and we describe our case studies in Section 5. We then discuss our results and findings in Section 6 and present the conclusions in Section 7.

2. Surrogate-based mission analysis

The classical Breguet range equation is commonly used to compute the amount of fuel required to fly a given range [43,74,81]. This equation was derived and published independently in 1920 by Coffin [11] and in 1923 by Breguet [6]. It has since become a basic model for describing the physics of aircraft. It contains terms representing the three dominant disciplines in aircraft design: propulsion (the thrust-specific fuel consumption, or TSFC), aerodynamics (the lift-to-drag ratio, L/D), and structures (the structural weight). However, it is applicable only under the assumption that the prod-

Please cite this article in press as: R.P. Liem et al., Surrogate models and mixtures of experts in aerodynamic performance prediction for mission analysis, Aerosp. Sci. Technol. (2015), http://dx.doi.org/10.1016/j.ast.2015.02.019