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Surrogate-enhanced simulation of aircraft in trimmed state

Andreas K. Michler *, Ralf Heinrich

German Aerospace Center (DLR), Institute of Aerodynamics and Flow Technology, Lilienthalplatz 7, 38108 Braunschweig, Germany

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ABSTRACT

This paper presents a surrogate-enhanced methodology for high-fidelity simulation of aircraft in trimmed state. Surrogates of the aerodynamic loads are used to increase robustness and reduce the number of costly high-fidelity simulations necessary during trim simulations. This is accomplished in two steps: (1) by finding a suitable estimate for the solution by global and fast local searches performed on surrogates, and (2) by applying a hybrid local search to check the potential solution and to further increase its quality if necessary. For the local searches in both steps, a Newton method is employed, whereas a genetic algorithm is used only in the first step. For the Newton method, the entries of the Jacobian are provided by means of finite difference approximations and the complex-step derivative method (CSD) based on the surrogates, and it is shown how to make CSD applicable to surrogates based on radial basis functions (RBFs). In the hybrid search, the derivatives are calculated by means of surrogates, while high-fidelity simulations are used for the main calculations of the Newton method. Updating the surrogates with the results of the latter is found to significantly accelerate the convergence of the hybrid local search. The methodology is applied to challenging trim test cases, in which several of the control surfaces of a generic fighter aircraft are deflected during trim simulation. Control surface deflection is performed via RBF-based mesh deformation, and RBFs are also used for surrogate modeling, thereby fostering code modularity and re-use.

1. Introduction

The trimmed state of an aircraft is of a steady nature: an aircraft flying, e.g., in steady level flight has zero accelerations. Since Newton's second law holds, this translates into a balance of forces and moments acting on the aircraft: the aircraft is in a state of equilibrium. This is important for a statically stable aircraft such as a transport aircraft, since it automatically returns to this state after a disturbance (e.g., a gust).

The forces and moments to be considered are due to gravity, external forces such as thrust and due to the surrounding flow. Trimming therefore involves a coupling between flight mechanics and aerodynamics or, in case elasticity is considered, aeroelasticity.

Due to increased computational resources, more efficient numerical methods and advances in physical modeling, high-fidelity simulation of aircraft involving CFD has gained importance in aircraft design [1–5]. The same holds true for trim simulations: for a current design, it has to be verified that trimmed states can be reached; otherwise, extensive design modifications may have to take place. Consequently, trim simulations with coupling to high-fidelity solvers have been undertaken in recent years [6–13]. To this end, however, different techniques have been employed to tackle the challenges of trim simulations, as described in the following.

In order to obtain a trimmed state, a trim simulation usually involves frequent changes of variables such as angle of attack, sideslip angle or deflection angles of control surfaces. For a change in the angle of attack, Prananta and colleagues have rotated the whole mesh, while a deflection of the horizontal tail was effectuated via mesh deformation involving blending [8]. Others have modified the angle of attack and the sideslip angle by changing the angles of the onflow, i.e., by modifying the farfield boundary conditions [6,9–12]. The deflection of the control surfaces is considerably more involved, since it requires the adaptation of the computational mesh. The use of efficient techniques for handling control surfaces is therefore of great importance. Besides mesh deformation, the deflection of control surfaces has also been realized by using overlapping meshes, i.e., the Chimera technique (see [8,12] and [7,9–11], respectively, and [14,15] for the Chimera technique). Both techniques avoid the regeneration of the whole mesh. But while mesh deformation techniques are applicable to the existing mesh, the Chimera technique usually requires additional efforts in defining auxiliary geometrical features (boundaries of the overlapping mesh blocks, gaps, etc.), for which the CAD description has to be resorted to, and in generating the Chimera mesh blocks.

In trimmed state, the values of certain variables of interest are known. Therefore, trim simulations may be regarded as goal-seeking or root-finding processes. The Newton technique may be

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* Corresponding author. Tel.: +49 (0) 531 295 3344; fax: +49 (0) 531 295 2914.
E-mail addresses: andreas.michler@dlr.de (A.K. Michler), ralf.heinrich@dlr.de (R. Heinrich).

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employed for the latter, even for cases featuring a multi-dimensional search space, and its convergence rate, which is quadratic in theory, is compelling [16,17]. Consequently, it has been used by many of the authors cited above [6–9,11]. Typically, for cases with symmetric onflow conditions such as steady level flight, a few high-fidelity simulations and changes of variables suffice.

Applying the Newton method to trim simulations is, however, not straightforward. Derivatives are necessary, and they are usually not readily available. Adjoint methods and automatic differentiation tools are rather involved to use for a code which has evolved over a long period of time. Therefore, finite difference approximations (FDs) are typically employed, since they are straightforward to implement. They are, however, not efficient, since at least the same number of high-fidelity simulations have to be performed as there are variables for which gradients are to be computed, Furthermore, their inaccuracies may slow down or even hinder convergence altogether. Instead of FDs, approximations based on linear aerodynamic derivatives have been used successfully by Raveh et al. [6,7], although this approach may suffer from similar difficulties. Due to the difficulties associated with the gradients, Wellmer and colleagues have resorted to a gradient-free method which solves the coupled aeroelastic and trim problem concurrently in an iterative fashion [13].

The success of the Newton method further depends on a good starting point. Although the choice is not obvious in cases with, e.g., unsymmetrical onflow conditions, a special procedure for finding a suitable starting point has been employed by none of the above mentioned researchers.

Moreover, due to non-linearities in the aerodynamics and flight mechanics, multiple local optima may exist (that is, states in which the trimmed conditions are not quite met), and a gradient-based search technique such as the Newton method may get trapped. Raveh and colleagues have integrated the trim conditions into an optimization problem to minimize, e.g., the wing's root bending moment [10]. They successfully used a simplex method. To the authors knowledge, a non-deterministic optimization method such as a genetic algorithm (GA) has not been used so far for trim problems. GAs are known to be able to find the global optimum, but at the price of many high-fidelity simulations.

Surrogate models have the potential to remedy many of the difficulties mentioned above. They are build with data of high-fidelity models and provide analytical input-output relationships predicting the behavior also away from the known data points. They can be queried at negligible cost and are therefore used as replacements or *surrogates* (hence the name) of the costly high-fidelity simulations (or costly experiments, etc.). They are also known as surrogate approximations, approximation models, or metamodels. They facilitate design space exploration, reliability analysis and sensitivity studies, and have been frequently employed for optimization involving high-fidelity simulations (see [18–21] for an overview and [22] for recent advances in surrogate-based optimization; for examples of using surrogates in aerodynamics, see [23–26]).

In the current work, surrogates are used extensively to enhance trim simulations of aircraft in complex trimmed states. Surrogates make the use of global search techniques for trim simulations affordable. Using a GA as a global and a Newton method as a fast local search technique, trim simulations based on the surrogates are conducted, with the aim of finding a *potential* or *candidate solution* to the trim problem. For the Newton technique, gradients have to be supplied. In addition to FDs, which are straightforward to implement, the complex-step derivative method (CSD) is used (see, for example, [27–29]), which does not suffer from the step size dilemma inherent to FDs and which is known to be able to provide gradients of machine accuracy. It is shown how CSD can be used in a framework which relies on radial basis function (RBF) surrogates. Finally, a *hybrid search* is performed with a Newton method to verify the candidate solution and, if necessary, to conduct further Newton steps. That means that a search on surrogates is used to provide a suitable starting point for an ensuing local search for the *true solution*, thereby increasing its robustness and accelerating its convergence. The term *hybrid* refers to the use of both high-fidelity simulations and surrogates: The former are used for the main calculations of the Newton method, whereas the latter are employed to obtain derivative information at negligible cost. This hybrid approach further offers the opportunity to use the results of the high-fidelity simulations to update the surrogates *online*, that is, during the trim simulation, and thereby enhance the accuracy of the derivatives.

For the efficient deflection of control surfaces, mesh deformation techniques based on RBFs are employed, which have been shown to be effective for these purposes [30]. Here, they are applied to deflecting ailerons, rudder and horizontal tails of the generic fighter aircraft configuration of [31]. RBF-based mesh deformation techniques are appealing for these tasks in that they preserve mesh connectivity and element numbering. As trim input parameters are likely to change only moderately, restarts drawing upon converged solutions with previous settings can be employed, thus reducing the CPU time necessary for CFD simulations. In the present work, a unified approach is adopted by employing RBFs also for surrogate modeling, thus enabling code reuse and modularity.

The trim strategy presented in this paper is applied to three trim problems, ranging from the standard steady level flight with symmetric onflow conditions to the more challenging trim problems of steady level flight with jammed rudder and steady level coordinated turn, which both exhibit unsymmetrical onflow conditions and require the simultaneous deflection of multiple control surfaces.

The outline of this paper is as follows. Section 2 recalls RBF interpolation, which is the basis for both the mesh deformation techniques and the surrogate models used here, and supplies details relevant to each application. Section 3 illustrates how derivative information based on surrogates are obtained via FDs and CSD. Section 4 states the trim problem and describes the Newton method and the GA used to solve root-finding and goal-seeking problems, respectively. It also details the barebones structure present in both solution techniques, and explains the trim strategy employed in the present work. The applications are described in Section 5. In Section 6, conclusions are drawn and an outlook is given.

2. Interpolation by radial basis functions

In the present work, radial basis functions (RBFs) are used for surrogate modeling as well as for mesh deformation for control surface deflection. Both applications are basically multi-variate interpolation problems. Therefore, Section 2.1 briefly presents the theory of RBF interpolation (for further details, the reader is referred to the books by Buhmann [32] and Fasshauer [33]). Section 2.2 focuses on the intrinsics of surrogate modeling and the choices made for the present work. Techniques for the efficient use of RBF-based mesh deformation for control surface deflection have already been detailed in [30]. Section 2.3 therefore concentrates on how to apply these techniques to cases in which multiple control surfaces have to be deflected simultaneously and several times during a single simulation, as is the case for trim simulations.

2.1. Theory of RBF interpolation

RBF interpolation can be divided into two distinct parts: *solution* and *evaluation*. In the solution part, linear systems are set up and solved for the unknown coefficients of an ansatz for the function(s) to be modelled by RBFs; in the evaluation part, the coefficients are