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Efficient optimization procedure in non-linear fluid-structure interaction problem: Application to mainsail trimming in upwind conditions

Matthieu Sacher[a,*], Frédéric Hauville[a], Régis Duvigneau[b], Olivier Le Maître[c], Nicolas Aubin[a], Mathieu Durand[d]

[a] Naval Academy Research Institute, IRENAV CC600, 29240 Brest Cedex 9, France
[b] INRIA Sophia Antipolis, 2004 Route des Lucioles, 06902 Valbonne, France
[c] LIMSI - CNRS, Rue John Von Neumann, 91400 Orsay, France
[d] K-EPSILON, 1300 Route des Crêtes, 06560 Valbonne, France

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ABSTRACT

This paper investigates the use of Gaussian processes to solve sail trimming optimization problems. The Gaussian process, used to model the dependence of the performance with the trimming parameters, is constructed from a limited number of performance estimations at carefully selected trimming points, potentially enabling the optimization of complex sail systems with multiple trimming parameters. The proposed approach is tested on a two-parameter trimming for a scaled IMOCA mainsail in upwind sailing conditions. We focus on the robustness of the proposed approach and study especially the sensitivity of the results to noise and model error in the point estimations of the performance. In particular, we contrast the optimization performed on a real physical model set in a wind tunnel with a fully non-linear numerical fluid-structure interaction model of the same experiments. For this problem with a limited number of trimming parameters, the numerical optimization was affordable and found to require a comparable amount of performance estimation as for the experimental case. The results reveal a satisfactory agreement for the numerical and experimental optimal trimming parameters, considering the inherent sources of errors and uncertainties in both numerical and experimental approaches. Sensitivity analyses have been eventually performed in the numerical optimization problem to determine the dominant source of uncertainties and characterize the robustness of the optima.

1. Introduction

Research on sailing yachts has fostered the advancement of methods to predict and improve the performances of racing yachts. Yacht performance is usually assessed using so-called Velocity Prediction Programs (VPPs) (Oossanen, 1993), which by equilibrating loads on hull, appendages and sails, determine several performance indicators, such as Boat Speed (BS) and Velocity Made Good (VMG). The loads estimation in VPPs can be based on empirical formulas, experimental data and/or numerical models of various complexity level (Hansen et al., 2003; Korpus, 2007). Due to the complexity and multi-physics character of yacht dynamics, performance studies are often separated in hydrodynamic (Huetz and Guillerm, 2014) and aerodynamic (Augier et al., 2012;

* Corresponding author.
E-mail address: matthieu.sacher@ecole-navale.fr (M. Sacher).

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Trimarchi, 2012; Menotti et al., 2013) aspects. In the present work, we focus on the aerodynamics optimization for the performance of a sail system; however, the procedure developed below can be applied to hydrodynamic optimization and even fully coupled (hydro-aero) yacht performance optimization.

The physics of sail systems involves very complex phenomena, such as nonlinear Fluid-Structure Interaction (FSI) effects and aero-elastic instabilities. Moreover, the modeling of real sailing conditions is still an open challenge because of the large uncertainties in the prediction of wind and sea states. To our knowledge, the sails optimization has thus been limited so far to idealized situations. For instance, sail shape optimizations (without accounting for the full FSI problem) were reported in Rousselon (2008), while the numerical trimming of two-dimensional sails was considered in Chapin et al. (2008). Regarding three-dimensional FSI problems, the authors of Ranzenbach et al. (2013) mention an optimization of the trimming of sails, but within an inviscid flow approximation and few details are provided on the actual optimization procedure used.

The present work aims toward the development of efficient numerical optimization procedures, capable of dealing with complex sail systems with realistic physical models (e.g. nonlinear FSI and turbulent flows) and large number of optimization variables (i.e. trimming parameters). Abstractly, the optimization problem can be expressed as

$$\mathbf{x}_{\text{opt}} = \underset{\mathbf{x}\in\Omega}{\text{argmin}} - \mathcal{P}(\mathbf{x}), \tag{1}$$

where $\mathbf{x}$are the optimization variables, Ω the domain of variation of the optimization variables, and $\mathcal{P}: \Omega \mapsto \mathbb{R}$ is the measurement of performance to be maximized. The main difficulty in solving problem (1), in the context of sail-trimming, is related to the cost of numerically estimating the performance $\mathcal{P}$ at tentative values $\mathbf{x}$of the parameters.

Indeed, the estimation of $\mathcal{P}(\mathbf{x})$ involves the resolution of a complex nonlinear FSI problem, with typically several convergence iterations between the nonlinear elastic and flow solvers. Further, adjoint-based techniques are hardly amenable to non-linear FSI problems, particularly when the resolution is based on the coupling of distinct solvers. This fact precludes the use of efficient gradient-based optimization methods, and favors the use of derivative free optimization algorithms such as the simplex based (Nelder and Mead, 1965) and evolutionary (Bäck and Schwefel, 1993; Hansen, 2006) methods. These approaches classically require many performance evaluations of $\mathcal{P}(\mathbf{x})$, making applications to sail systems very costly as a single evaluation of $\mathcal{P}$ can routinely require several hours of CPU-time even on modern parallel computers.

From these observations, we advocate the use of meta-models to mitigate the large computational cost of optimizing the trimming parameters of sail systems. Meta-models-based optimization methods have been experiencing a growing interest for the last years, and are currently used in several other disciplines, such as aerodynamic drag reduction (Laurenceau and Sagaut, 2008; Jeong et al., 2005), vibration minimization for rotating aircrafts (Glaz et al., 2009), civil engineering for the design of water distribution network (di Pierro et al., 2009) and geological carbon sequestration (Espinet and Shoemaker, 2013), or FSI problems (Aghajari and Schäfer, 2015; Degroote et al., 2012). Specifically, we rely in this work on Gaussian Process (GP) to approximate the mapping $\mathcal{P}: \Omega \mapsto \mathbb{R}$. This statistical approach uses a coarse set of performance evaluations at some selected parameters values $\mathbf{x} \in \Omega$ to infer a GP $\mathcal{G}(\mathbf{x}) \approx \mathcal{P}(\mathbf{x})$. Given the GP approximation one can apply his favorite optimization procedure substituting $\mathcal{G}$ to $\mathcal{P}$ in (1), and obtain an approximation of $\mathbf{x}_{\text{opt}}$. This surrogate-based optimization procedure is embedded in an iterative scheme, where new evaluations of the performance at carefully selected new points $\mathbf{x}$ are introduced in order to refine the GP approximation in regions of Ω of interest, that is susceptible to include the optimum. The GP approach is then expected to improve the direct optimization of $\mathcal{P}$ by a) requiring an overall lower number of performance evaluations, compared to direct gradient-free approaches, and b) enabling the use of efficient global optimization tools.

Another interest of GP-based optimization is that it naturally accommodates for errors and noise in the performance evaluation. This feature is especially attractive in the case of optimizations relying on complex numerical simulations, where both modeling and numerical errors are expected to be significant and hardly reducible. To illustrate the interest of the robustness of the GP-based optimization to inherent error, this work focuses on the optimization of a scaled IMOCA mainsail in upwind conditions. The objective is to find the optimal trimming of the sail, for a performance criterion combining the drive and side aerodynamic force coefficients. The GP-based optimization is performed first on a physical model using measurements of $\mathcal{P}(\mathbf{x})$ performed in the wind tunnel of the Yacht Research Unit (the University of Auckland), for the sequence of trimming points $\mathbf{x}$requested by the iterative optimization procedure. In this case, the error in the observed values of the performance is due to the imperfections in the experimental apparatus and the inherent noise in the measurements. This experiment shows that the significant error in the measurements of $\mathcal{P}(\mathbf{x})$ compromises the convergence of descent methods (Saul'ev and Samoilova, 1975) without its implicit account in the GP reconstruction.

The experimental optimization is subsequently used to assess the relevance of numerical optimizations, where a non-linear FSI solver is used to compute the performance. To this end, a high fidelity numerical model was created from measurements of the experimental model (e.g. dimensions, and sail geometry, mechanical characteristics of mast and boom, wind tunnel inflow conditions, ...). A state of the art FSI solver is then used to solve the numerical model at the sequence of trimming points requested by the GP-based optimizer. The FSI solver involves a nonlinear structural solver coupled to a finite volume flow solver with an Unsteady Reynolds-Average Navier-Stokes Equations (URANS) model. The comparison of the experimental and numerical optimal trimming parameters shows a significant discrepancy, as expected from both numerical modeling and experimental errors. However, it is found that the agreement between the numerical and experimental optimal performances is consistent with the error and noise levels estimated by the GP constructions. This observation has motivated further uncertainty quantification studies to determine the dominant source of model error affecting the optimal trimming parameters and the performance. Because of the highly non-linear and coupled nature of the FSI solver, the uncertainty analyses rely again on local surrogates of the performance, using a Polynomial