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A high-order sensitivity method for multi-element high-lift device optimization

L. Soulat, A. Fosso Pouangué, S. Moreau*

Mechanical Engineering Department, Université de Sherbrooke, 2500 Bd Université, Sherbrooke J1K2R1, Canada

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ABSTRACT

A complete procedure to study and optimize a multi-element high-lift device is presented and applied to the L1T2 test case. The direct Reynolds-Averaged Navier–Stokes (RANS) simulations of the reference configuration first reveal the importance of the size of the computational domain to correctly capture the potential effects generated by the L1T2 configuration. A parameterized Navier–Stokes approach based on a high-order sensitivity technique is then used as a surrogate model for solution reconstructions. This approach has the advantage to ask for only one parameterized RANS simulation around a reference configuration. The results stress the importance to account for higher derivatives and turbulence effects for such non linear parameters as the drag. They also help assess the strong coupling between certain parameters such as the flap and slat rotations. Then, the high-lift device is optimized according to two illustrative objectives: maximize the lift and minimize the drag. A genetic algorithm is applied to construct the Pareto front. Optimizations using only the geometric parameters (geometrical optimization) or the geometric parameters and the inlet flow Mach number and angle of attack (total optimization) are performed. Both optimizations show quite similar optimal geometric positions: a flap rotation inducing the maximum camber to increase the lift and an upward slat rotation to reduce the drag according to the parameter coupling study. In the total optimization, configurations with higher lift coefficients are found by setting the angle of attack and the Mach number to their maximum values. This optimization allows obtaining more important variations of the lift and the drag from the baseline configuration than the geometrical optimization.

1. Introduction

High-lift device (HLD) systems significantly increase the lift of the airfoil at low speed during take-off and landing phases. During take-off, it is also needed to keep a relatively low drag in order to reduce the thrust required. Nowadays, the design of quieter high-lift systems is also an objective as then high-lift device noise is an important contributor to noise at approach [1]. Hence the design of efficient high-lift systems is critical for the environmental impact of aircraft in terms of payload, fuel consumption and noise. The design of such systems is a complex optimization process, because of the multi-element geometry that yields an important number of independent parameters to optimize. As a matter of fact, in the optimization process, both the position and the shape of the different elements could be considered. Physical parameters, such as the flow angle and the flight Mach number are also important. Therefore, the number of HLD design variables could rapidly increase from ten to a hundred [2]. Since, there are also multiple possible constraints and objectives, HLD optimization can be very tedious and automatic optimization a helpful solution.

Different approaches have been used for airfoil aerodynamic optimization. Both single-objective optimizations with constraints [2–12] and multi-objective optimization [13] have been considered. Gradient based methods such as sensitivity equations [8,9,12], adjoint method or Newton based method [2–4,10] are the most popular. They are used to solve constrained single-objective optimizations and can be used for multi-objective optimization by decomposing them in a number of single-objective optimization. For multi-objective optimizations, some authors have also proposed to use genetic algorithms [13]. In all methods, numerous evaluations of the objective functions are needed. One evaluation generally corresponds to at least a complete simulation (using RANS equations for instance). For one single-objective optimization, the cost of these evaluations could be reasonable, but for a general multi-objective optimization, the cost might simply be unaffordable. A surrogate model is then used based on a reduced number of complete simulations. For instance, Greenman et al. [5–7] used a neural network while Kanazaki

* Corresponding author. Tel.: +18198218000; fax: +18198217163.
E-mail addresses: laurent.soulat@usherbrooke.ca (L. Soulat), arnaud.fosso@usherbrooke.ca (A. Fosso Pouangué), stephane.moreau@usherbrooke.ca, stephane.smoreau@gmail.com (S. Moreau).

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et al. [13] used the Kriging method. Other methods involve for instance variable-fidelity optimization methods which use a corrected low-fidelity model to speed up the design process [14–16].

The present work is addressing the multi-objective optimization of a HLD system using a surrogate model based on a unique parameterized Navier-Stokes solver, that has been applied to the study of different aerodynamic configurations as the flow around airfoils, fan blade cascades [17–21] and casing treatment in a compressor [22,23]. The latter approach could be considered as a high order sensitivity method involving the "exact"Jacobian matrix obtained by automatic differentiation. Indeed, to evaluate the flow field for a given set of design variables, an extrapolation by a high-order derivation of the flow around a baseline solution including cross-derivatives is used. The calculation of all derivatives is performed once and is equivalent to or faster than the calculation of one flow flow-field with a Reynolds-Averaged Navier–Stokes (RANS) numerical simulation (typically several hours on a single 2.4 GHz Xeon E5530 processor). Then, the extrapolation based on a reconstruction by a Taylor series expansion is almost instantaneous, providing a noticeable speed-up for the evaluation of configurations around the baseline [23]. To demonstrate the capabilities of the new approach, two academic cases of aerodynamic multi-objective optimization of a 3-element high-lift device are considered: one with only positioning parameters and another accounting also for two variables defining the flight conditions (the angle of attack and the Mach number). This optimization is performed using the Non-Dominated Sorting Genetic Algorithm-II (NSGA-II) of Pratap and Deb [24]. The generated Pareto front is studied using the Self-Organizing Maps (SOM) technique [13].

The paper is organized as follows: the second section presents the considered high-lift configuration and some details about the newly-developed parameterized approach. In the third section, the baseline solution is analyzed and the L1T2 slat is shown to be very sensitive to the domain size and shape for the first time. An original lens-shape grid topology is also proposed to accommodate the variations of angle-of-attack in the optimization process. A comparison is done between the high order sensitivity approach and the traditional first order sensitivity approach. The influence of turbulence in the parameterized approach is also discussed. Both effects are shown to be key to an accurate prediction of drag, and the cross-derivatives are shown to provide relevant coupling between parameters for the first time. The analysis of the Pareto front is then performed in the fourth section to highlight several possible optima to this multi-parameter multi-objective optimization.

2. Description of the optimization problem

2.1. High-lift configuration and parameterization

This study focuses on the three-element high-lift L1T2 device. This configuration was thoroughly studied both numerically and experimentally during the British National High Lift Programme and has become an ERCOFTAC benchmark [25,26]. It provides a good starting point for the sensitivity analysis and optimization. Moreover, this geometry is quite representative of actual high-lift devices, with several sharp trailing edges located within the slat- and flap-coves. The baseline configuration studied here is the configuration with both slat and flap fully deployed. The geometric and aerodynamic characteristics of this baseline configuration are briefly recalled in Table 1.

Table 1
Characteristics of the L1T2 case.

Chord c (retracted form)	0.7635 m
Slat angle (deployed)	25°
Flap angle (deployed)	−20°
Flight Mach number M	0.197
Reynolds number Re	3.52×10^6
Flow angle α	+4.01°
Ambient static temperature	290° K
Ambient static pressure	101 300 Pa

The configuration and the corresponding flow are assumed to be two-dimensional, but the optimization process presented here could be extended without any problem to a three-dimensional case. The baseline configuration is represented in Fig. 1. The present optimization focuses on the positioning of the slat and flap with respect to the main airfoil (geometric parameters), and on the flow angle-of-attack and Mach number (flow parameters). The positioning of the slat or the flap is parameterized by two translations in the horizontal and vertical directions, and one rotation. Without precise knowledge of the actual kinematics on such a high lift system, the rotation centers were chosen at the upper trailing edge of the slat, and at the leading edge of the flap. These positions could also be varied to assess the impact of a given kinematics on both the aerodynamic and acoustic performances. The present eight parameters, along with the position of the rotational centers are illustrated in Fig. 1. This problem is actually quite similar to the recent optimization of multi-element trawl doors for fishing boats, but with more variables as the flow conditions are varied in the present investigation. [16].

The objectives of the L1T2 optimization are to increase the lift and to decrease the drag. The lift is measured with the lift coefficient C_L defined by:

$$C_L = \frac{1}{\frac{1}{2}\rho_\infty U_\infty^2} \int_S F_y \mathrm{d}S, \tag{1}$$

where ρ_∞ and U_∞ are the upstream flow density and speed respectively, S the surface of the airfoil and F_y is the component of the aerodynamic force orthogonal to the upstream flow direction. The drag is measured with the drag coefficient C_D defined by:

$$C_D = \frac{1}{\frac{1}{2}\rho_\infty U_\infty^2} \int_S F_x \mathrm{d}S, \tag{2}$$

where F_x is the component of the aerodynamic force following the upstream flow direction.

2.2. Numerical optimization procedure

The optimization process is constructed in three successive phases [23]. In the first phase, the steady flow-field in the baseline configuration is simulated numerically with a classical RANS flow solver. Once the baseline flow-field is known, the derivatives of the flow variables (i.e. the conservative and turbulent variables) are calculated for every parameter of the study with a dedicated solver. The last step is the optimization itself with a genetic algorithm on the

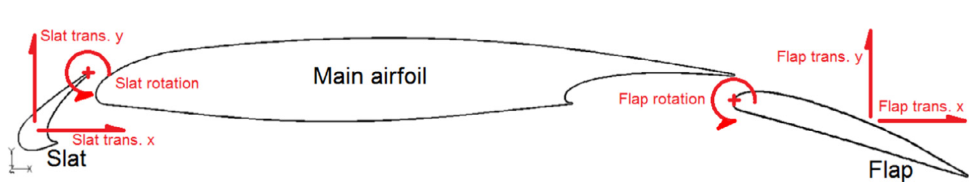

Fig. 1. L1T2 high-lift and positioning parameterization.