

Robust Active Shock Control Bump Design Optimisation using Parallel Hybrid-MOGA

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Abstract: The paper investigates a robust optimisation for detail design of active shock control bump on a transonic Natural Laminar Flow (NLF) aerofoil using a Multi-Objective Evolutionary Algorithm (MOEA) coupled to Computational Fluid Dynamics (CFD) software. For MOEA, Robust Multi-objective Optimisation Platform (RMOP) developed in CIMNE is used. For the active shock control bump design, two different optimisation methods are considered; the first method is a Pareto-Game based Genetic Algorithm in RMOP (denoted as RMOGA). The second method uses a Hybridised RMOGA with Game-Strategies and a parallel computation for high performance computation. The paper not only shows how a shock control bump approach coupled to CFD improves aerodynamic performance of original transonic aerofoil but also it shows how high performance computation with applying Hybrid-Game and parallel computation increase the efficiency of optimisation in terms of computational cost and result accuracy.

Keywords: Parallelization, Computational Fluid Dynamics, Shock Control Bump, Multi-Objective Evolutionary Algorithms, Game Strategies.

1 Introduction

Computational Fluid Dynamics (CFD) has become an important tool in optimisation and has seen success in many real world applications. Most important among these is in the optimisation of aerodynamic surfaces. Most of these have been carried out for a given set of input parameters such as free stream Mach number and angle of attack. One cannot ignore the fact that Multi-Objective (MO) and Multidisciplinary Design Optimisations (MDO) in aerospace engineering frequently often deal with situations where the design input parameters and flight/flow conditions have some amount of uncertainty attached to them. This challenge can be solved by using a robust/uncertainty design approach which can produce high quality solutions in terms of magnitude of performance and its sensitivity at a variable uncertainty design parameters [1, 2, 3]. However, one major drawback of using robust design method is extensive computational cost. Therefore it is inevitable to conduct the optimisation in high performance (parallel) computation while innovating the optimisation techniques.

This paper develops a methodology for robust multi-objective design optimisation. The methodology couples CFD software, robust/uncertainty design strategy, and a parallelised hybrid evolutionary optimiser, to produce a set of reliable optimal designs which have higher performance and lower sensitivity. In this paper, an Active Flow Control (AFC) device design is considered as a robust optimisation

application.

One of important challenges in aeronautical engineering is to control flow over a transonic aerofoil/wing to reduce drag while increasing aerodynamic performance (L/D). The drag reduction can save mission operating cost, condense critical aircraft emissions and increase the performance envelope of the aircraft. Such drag reduction can be achieved by implementing a type of AFC called Shock Control Bump (SCB) [4, 5] without the need to design a new aerofoil or wing planform shape.

The approach is demonstrated on its application; robust design optimisation of SCB on the suction side of Natural Laminar Flow (NLF) aerofoil; RAE 5243 to minimise the total transonic drag at the variable Boundary Layer Transition (BLT) positions and lift coefficients (250 samples obtained by Latin Hypercube Sampling [9]). This design problem is solved by using two different Multi-Objective Evolutionary Algorithms (MOEAs); the first is the Genetic Algorithm (GA) [6, 7] in Robust Multi-objective Optimisation Platform (RMOP) (denoted as RMOGA). The second method uses a hybridised GA with Nash-Game [8] and parallel computation [10] (denoted as HPRMOGA). The paper will show;

- how to control the design quality under considering uncertain design parameters,
- how to control the transonic flow on a current aerofoil using a SCB,
- how to improve the optimisation efficiency using Hybrid-Game coupled to parallel computation.

The rest of paper is organised as follows; Section 2 considers robust design optimisation of detailed design of Active Shock Control Bump using RMOGA and HPRMOGA.

2 Robust optimisation for detailed design of Shock Control Bump

Problem Definition

The problem considers a detailed robust design optimisation of shock control bump under considering uncertainty parameters including Boundary Layer Transition (BLT) positions and lift coefficients (250 samples in total) using RMOGA and HPRMOGA. The number of CPUs usage for RMOGA (Pareto-Game) and HPRMOGA (Pareto and Nash games) are one and ten CPUs respectively in Dell PowerEdge 6850 (Intel(R) Xeon(TM) CPU 16 × 3.20GHz and 32GB RAM) machine. The objectives are to minimise the total drag and to minimise its sensitivity as shown Equations (1) and (2); HPRMOGA employs three players; Pareto-Player (considering fitness functions 1 and 2 at 250 samples for uncertainty), Nash-Player1 (considering fitness function 1 at 25 samples for uncertainty) and Nash-Player 2 (considering fitness function 2: 25 samples for uncertainty). The stopping criterion is based on the predefined elapsed time; RMOGA and HPRMOGA are stopped after 50 and 25 hours respectively.

$$f_1 = \min(\mu Cd) = \frac{1}{N \times M} \sum_i^N \sum_j^M Cd_{ij} \quad (1)$$

$$f_2 = \min(\sigma Cd) = \frac{1}{N \times M - 1} \sum_i^N \sum_j^M (Cd_{ij} - \mu Cd)^2 \quad (2)$$

Stopping Criterion;

$$ElapsedTime_{RMOGA} \leq 50Hours, ElapsedTime_{HPRMOGA} \leq 25Hours$$

at uncertainty conditions; Boundary Layer Transition positions (BLT) and lift coefficients (Cl)

$$\mu_{BLT} = 0.3782 \text{ and } \sigma_{BLT} = 0.0802 \text{ at a range of } BLT = [0.25 : 0.50]$$

$$\mu_{Cl} = 0.7462 \text{ and } \sigma_{Cl} = 0.0398 \text{ at a range of } BLT = [0.67 : 0.82]$$

where N and M are number of samples for Boundary Layer Transition positions and lift coefficients (Cl) respectively i.e. $N = 10$ and $M = 25$.

Numerical Results

Resulting Pareto front obtained by RMOGA and HPRMOGA are compared to the baseline design as shown in Figure 1. Both RMOGA and HPRMOGA produce a set of solutions which have lower mean total drag and sensitivity at variable BLT and Cl conditions when compared to the baseline design. Even though the computational cost of HPRMOGA is only half of RMOGA, Pareto member 1 (the best solution for objective 1) obtained by HPRMOGA produces lower mean total drag when compared to Pareto member 1 obtained by RMOGA. The convergence history obtained by RMOGA and HPRMOGA are plotted to compare the computational efficiency as shown in Figure 2 where x -axis is normalised by each total function evaluation. It can be seen that HPRMOGA saves upto 75% of RMOGA computational cost while producing lower converged value for fitness function 1.

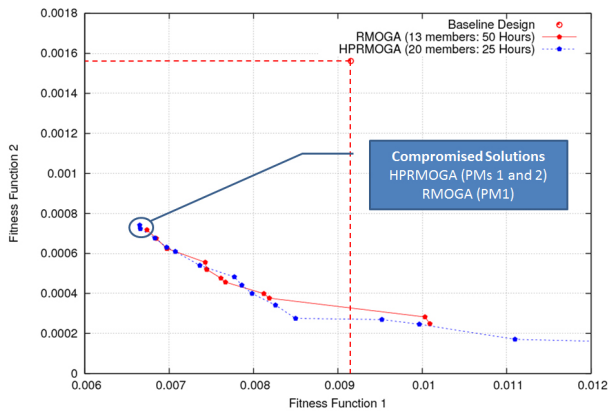


Figure 1: Pareto optimal front.

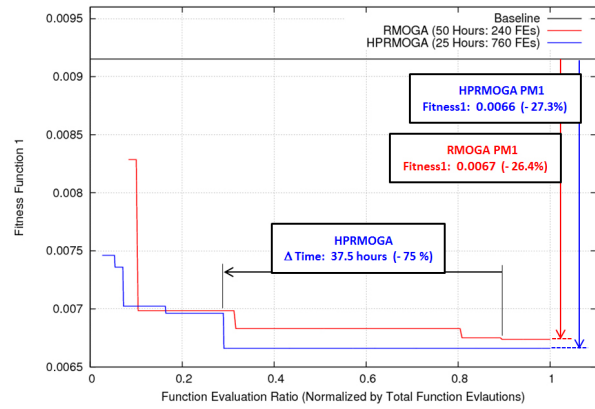


Figure 2: Computational cost comparison.

Pareto member 1 obtained by RMOGA (denoted as RMOGA PM1), and Pareto members 1 and 2 obtained by HPRMOGA (denoted as HPRMOGA PM1 and PM2) are selected as a compromised solution to proceed more detailed statistical analysis. The mean and standard deviations of total drag obtained by compromised solutions are compared using Cumulative Distribution Function (CDF) and Probability Density Function (PDF) as shown in Figures 3 and 4. It can be seen that all solutions obtained by RMOGA and HPRMOGA have lower mean total drag when compared to the baseline design. In addition, all optimal solutions obtained by RMOGA and HPRMOGA produce lower drag sensitivity when compared to the baseline design as shown in Figure 4.

Figure 5 compares the pressure contour obtained by Pareto member 1 from both RMOGA and HPRMOGA at the mean BLT and Cl i.e. $\mu_{BLT} = 0.3782$, $\mu_{Cl} = 0.7462$. It can be seen that the optimal solution obtained by HPRMOGA reduces the total drag by 26% while improving L/D by 34.2%.

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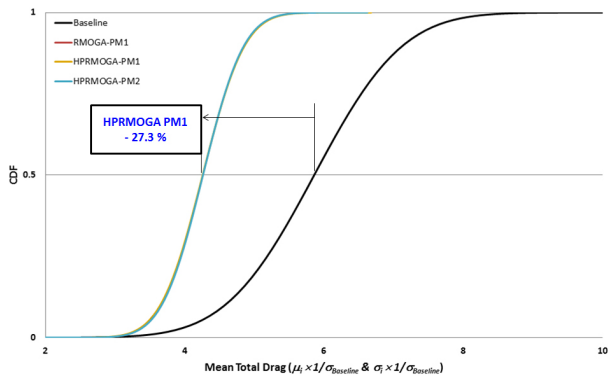


Figure 3: Pareto optimal front.

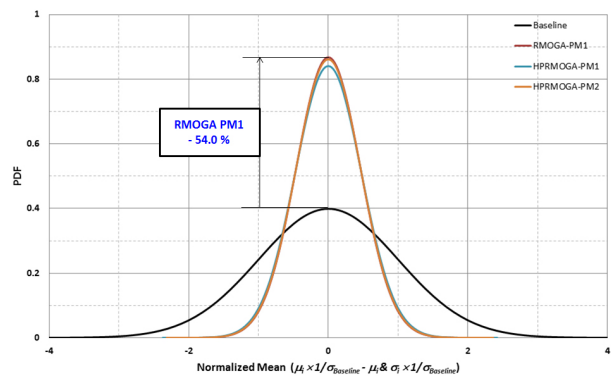


Figure 4: Computational cost comparison.

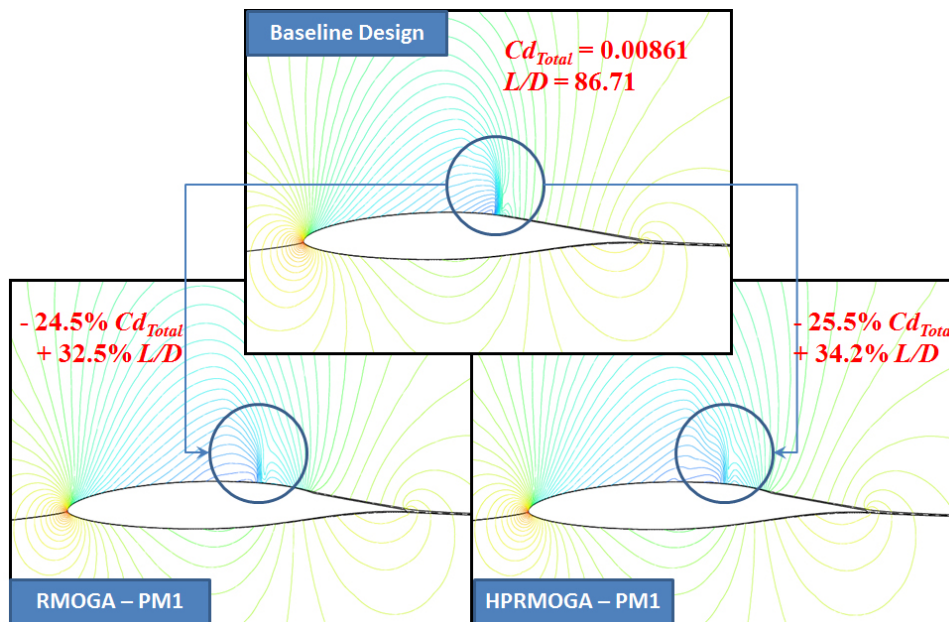


Figure 5: C_p contour comparison.

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