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Uncertainty based MDO of UAS Using HAPMOEA

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CFD has been successfully used in the optimisation of aerodynamic surfaces using a given set of parameters such as Mach numbers and angle of attack. While carrying out a multidisciplinary design optimisation one deals with situations where the parameters have some uncertainty attached. Any optimisation carried out for fixed values of input parameters gives a design which may be totally unacceptable under off-design conditions. The challenge is to develop a robust design procedure which takes into account the fluctuations in the input parameters. In this work, we attempt this using a modified Taguchi approach. This is incorporated into an evolutionary algorithm with many features developed in house. The method is tested for an UCAV design which simultaneously handles aerodynamics, electromagnetics and maneuverability. Results demonstrate that the method has considerable potential.

1 Introduction

This paper develops a methodology for uncertainty based Multidisciplinary Design Optimisation (U-MDO) and is an extension to Lee et al. [1], and Srinivas et al. [2]. It couples a CFD software, a Radar Cross Section (RCS) analysis tool, an advanced evolutionary optimiser and the concept of robust/uncertainty strategy [3] to produce a set of optimal -stable designs. The approach is demonstrated on its application to Unmanned (Combat) Aerial Vehicle (UAV/UCAV) to maximise its performance and survivability. UCAVs have high industrial demands in the area of military and natural disaster monitoring (forest fire, flood, earthquake, etc.). For this optimisation, four main objectives are considered; the first is to maximise an aerodynamic performance at cruise condition, the second is to produce a low observability at mono and bi-static radar signature aircraft against enemy radar system. The third is to have extreme manoeuvrability. Finally the fourth is to have a robust design that has good characteristics in terms of performance and sensitivity at variable flight conditions and frequencies.

2 Methodology

The method couples the Hierarchical Asynchronous Parallel Multi-Objective Evolutionary Algorithms (HAPMOEA software) with several analysis tools. The HAPMOEA [7] is based on the well known Darwinian principle and implemented with Evolution Strategies [4]. The core of this method incorporates the concepts of Covariance Matrix Adaptation, CMA [5], Distance Dependent Mutation, DDM [4]. At the top level of this method, the asynchronous parallel computation [6], multi-fidelity hierarchical topology and Pareto tournament selection are implemented. In the bottom level, the method does two major search operations (Mutation and combination) under Pareto-game strategy. In the middle level, the method couples evolutionary optimiser (HAPMOEA), analysis tools and statistical design tool taking into account uncertainty.

3 Real World Design Problem

Analysis and Formulation

The vehicle considered is a Joint Unmanned Combat Air Vehicle (J-UCAV) that is similar in shape to Northrop Grumman X-47B [9]. The wing planform is assumed to be of an arrow shape with jagged trailing edge. The aircraft maximum gross weight is approximately 21,045 kg and empty weight is 16,955 kg. The wing design parameters for the baseline wing configuration are illustrated in Fig. 1. In this test case, the fuselage extends from 0 to 25% of the half span. The crank positions are at 46.4% and 75.5% of half span. The inboard and outboard sweep angles are 55^o and 29^o, while the taper ratios are 20 and 2% of c_{Root}. It is assumed that the baseline design contains three types of aerofoils at root (NACA 66-021), crank1 (NACA 67-1015), crank2 (NACA 67-008) and tip (NACA 67-008). The mission profile of UCAV considers Reconnaissance, Intelligence, Surveillance and Target Acquisition (RISTA) is as illustrated in Fig. 2 and is divided into eight sectors.

Problem Definition

Objective 1 refers to aerodynamic quality (eq. 1) at the variability of flight conditions and is expressed in terms of mean and variance of inverse L/D ratios. The mean and variance of the turning radius (r) at 45^o bank angle formulate the quality of manoeuvrability (eq. 2). Electro-magnetic (RCS) quality (eq. 3) at the variability of radar frequencies is in terms of mean

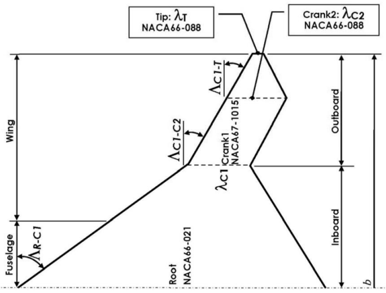

Fig. 1. Wing Geometry.

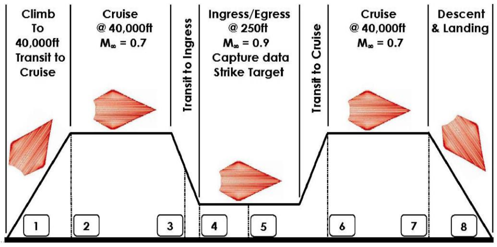

Fig. 2. Mission profile

and variance of mono ($Sector2$) and bi-static ($Sector4$) radar signatures. The fitness functions for objectives are;

$$f_1 = min\left(\frac{-1}{Aerodynamic_{Quality}}\right) \tag{1}$$

where $Aerodynamic_{Quality} = \left(\ln\left(\overline{1/(L/D)}\right) + \ln\left(\delta\left(1/(L/D)\right)\right)\right)$,

$$\overline{1/(L/D)} = \frac{1}{K}\left(\sum_{i=1}^{K}\left(\frac{1}{(L/D)_i}\right)\frac{M_{\infty i}^2}{M_s^2}\right)$$

$$\delta 1/(L/D) = \frac{1}{K-1}\sum_{i=1}^{K}\left(\frac{1}{(L/D)_i}\frac{M_{\infty i}^2}{M_s^2} - \overline{\frac{1}{(L/D)}}\right)^2$$

$$f_2 = min\left(Maneuverability_{Quality}\right) = min\left(\overline{r} + \delta r\right) \tag{2}$$

where r is the instantaneous turning radius at bank anlge 45^o and defined as; $r = {}^{V_\infty}\!/_{\omega}, \ \ \omega = {}^{\left(g\sqrt{n^2-1}\right)}\!/_{V_\infty}, \ \ n = {}^{qC_L}\!/_{(W/S)}$.

$$f_3 = min\left(RCS_{Quality}\right) \tag{3}$$

where $RCS_{Quality}$ can be defined as;

$$RCS_{Quality} = \left(\overline{RCS_{Mono}} + \delta RCS_{Mono}\right) + \left(\overline{RCS_{Bi}} + \delta RCS_{Bi}\right)$$

Mono-static Radar conditions: $\theta = [0^o : 3^o : 360^o] \ \ and \ \phi = [0^o : 0^o : 0^o]$.
Bi-static Radar conditions: incident angles are $\theta = 135^o, \ \phi = 90^o$

$$\theta = [0^o : 3^o : 360^o], \ \phi = [0^o : 0^o : 0^o]$$

The variable flight and radar frequency conditions are;

$$M_{\infty i} \in [0.8195, \ 0.8295, \ M_s = 0.8395, \ 0.8495, \ 0.8595] \ \ and \ \alpha = 4.3^o$$

$$F_{\infty i} \in [1.0, \ 1.25, \ F_s = 1.5, \ 1.75, \ 2.0]$$

Design Variables

Four aerofoils at root, crank 1, crank 2 and tip sections are considered for optimisation and the Control Points (CPs) for aerofoil design are sixty eight (4 sections × 17 CPs). The wing planform shape is parameterised by considering eight design variables including three wing sectional areas, three sweep angles and two taper ratios are considered and the upper and lower bounds of these variables are described in table 1 where the sectional areas (S) are in m^2 and one geometrical constraints is applied $\lambda_{C2} \leq \lambda_{C1}$. These lead to the different span length (b) and Aspect Ratio (AR).

Table 1. UCAV wing design variables

Variables	S_1	S_2	S_3	λ_{C1}	λ_{C2}	Λ_{R-C1}	Λ_{C1-C2}	Λ_{C2-T}
Lower	50.46	10.09	5.05	0.15	0.15	49.5^o	25^o	25^o
Upper	63.92	16.82	10.09	0.45	0.45	60.5^o	35^o	35^o

Results

The algorithm was run approximately for 945 function evaluations and took 150 hours on two 2.4 GHz processors. The resulting Pareto set is shown in Fig. 3 where the best solution (Pareto member 1) for fitness functions 1 is marked as inverse triangle and triangle is the best solution (Pareto member 3) for fitness function 2. Square represents the best solution (Pareto member 10) for fitness function 3. It can be seen that the baseline UCAV dominates Pareto member 10 in the aspect of maneuverability quality as shown in Section-A and Section-C. However, all Pareto members dominate the baseline UCAV in aspect of the quality of cruise aerodynamics and electro-magnetics in terms of performance (mean) and sensitivity/stability (variance).

The best solutions (Pareto members 1, 3 and 10) and Pareto member 4 are selected to compare the aerodynamic, maneuverability and RCS quality to the baseline UCAV in table 2. All Pareto members exhibit improved quality in aerodynamic parameters. With regards to maneuverability quality, Pareto member 10 is dominated by the baseline design while Pareto member 10 has 32% less chance to be detected to enemy radar system when compared to the baseline UCAV. Pareto member 4 is selected as a compromised solution for further evaluation since it makes an improvement at all aspects of aerodynamic, maneuverability and electro-magnetic qualities.

Figure 4 shows the comparison of mono-static RCS at the standard design frequency (1.5GHz) between Pareto member 4 (compromised solution), Pareto member 10 (best solution for fitness function 3) and the baseline design. Pareto member 4 and 10 produce 25 and 35% lower mono-static radar

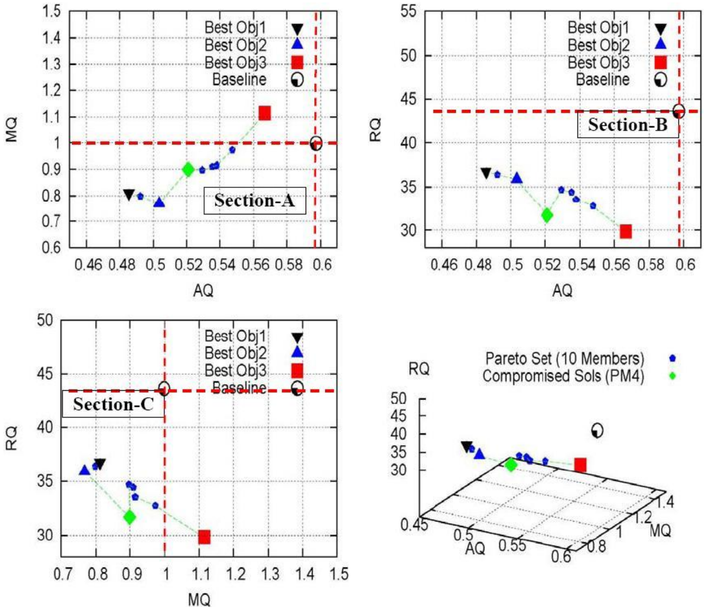

Fig. 3. Pareto non-dominated solutions for U-MDO of UCAV

Table 2. Comparison of the objectives

Description	Baseline	ParetoM1	ParetoM3	*ParetoM4*	ParetoM10
AQ	0.597	0.485 (-19%)	0.503 (-16%)	0.521(−13%)	0.566 (-5%)
MQ	0.998	0.822 (-18%)	0.768 (-23%)	0.899(−10%)	1.114 (+12%)
RQ	43.63	36.77 (-8%)	35.86 (-18%)	31.68(−27%)	29.83 (-32%)

signature when compared to the baseline design. The bi-static radar signatures obtained by Pareto members 4, 10 and the baseline design is shown Fig. 5. The results show that the Pareto members 4 and 10 has lower observability by 17 and 20% when compared to the baseline design. Therefore, they will have less chance to be detected to enemy radar systems at *Sector* 2 and *Sector* 4.

4 Conclusions

HAPMOEA coupled to CFD and robust design technique has capabilities to generate a set of useful Pareto non-dominated solution that has unique character in the aspects of aerodynamic performance, manoeuvrability and electromagnetics. The numerical results show a broad applicability of methodology for MDO design problems and benefit of using CFD, and the importance of integrating robust/uncertainty concepts. Future work will focuses on game

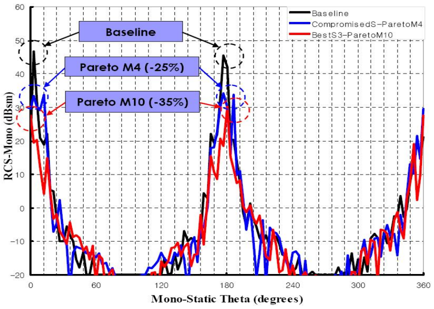

Fig. 4. Mono-static radar signature

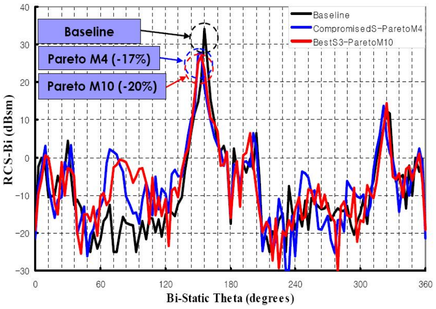

Fig. 5. Bi-static radar signature

strategies including Nash and Pareto to speed up optimisation convergence of MO and MDO with uncertainty design problems.

References

[1] Lee, D.S., Gonzalez, L.F., Srinivas, K., Auld, D.J., Periaux, J.: MultiObjective and Multidisciplinary Design and Optimisation of Blended Wing-Body UCAV using Hierarchical Asynchronous Evolutionary Algorithms, 45th AIAA Aerospace Sciences Meeting and Exhibit, Grand Sierra Resort Hotel (Formerly Reno Hilton)Reno, Nevada 8 - 11 Jan. (2007)

[2] Srinivas, K., Lee, D.S., Gonzalez, L.F., Periaux, J., Multidisciplinary Design Optimisation Of Joint UCAV Using HAPMOEA with Uncertainty. WEHSFFC and ECCOMA. Moscow, Russia. 19-22. November (2007)

[3] Clarich, A., Pediroda, V., Padovan, L., Poloni, C., Periaux, J.: Application Of Game Strategy In Mulit-Objective Robust Design Optimisation Implementing Self-Adaptive Search Space Decomposition By Statistical Analysis., European Congress on Computational Methods in Applied Sciences and Engineering. 24-28. July. (2004)

[4] Michalewicz, Z.: Genetic Algorithms + Data Structures = Evolution Programs. Artificial Intelligence, Springer-Verlag. (1992)

[5] Hansen, N., Muller, S.D., Koumoutsakos, P.: Reducing the Time Complexity of the Derandomized Evolution Strategy with Covariance Matrix Adaptation (CMA-ES). Evolutionary Computation, 11(1), pp. 1-18, (2003)

[6] Van Veldhuizen, D.A., Zydallis, J.B., Lamont, G.B.: Considerations in Engineering Parallel Multiobjective Evolutionary Algorithms, IEEE Transactions on Evolutionary Computation, Vol. 7, No. 2, pp. 144–173, April (2003)

[7] Lee, D.S., Gonzalez, L.F., Whitney, E.J.: Multi-objective, Multidisciplinary Multi-fidelity Design tool: HAPMOEA - User Guide. (2007)

[8] Lee, D.S.: Uncertainty Based Multiobjective and Multidisciplinary Design Optimization in Aerospace Engineering, The Univ. of Sydney, Sydney, NSW, Australia, section 9.3, p.p. 269-307 (2008)

[9] Northrop Grumman.: http://www.is.northropgrumman.com/systems/nucasx47b.html