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Robust Multidisciplinary Optimization for Wing of a Low Subsonic UAV

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Abstract

Low subsonic unmanned air vehicles (UAVs) have a high demand in the market comparatively and they can be manufactured economically compared with other flying vehicles. Innovations are constantly emerging in this field and the need for optimized systems is on a rise. Since the wing of an aircraft is one of the most important parameters, this research focuses on the multidisciplinary optimization of the wing. Multidisciplinary optimization (MDO) is an emerging field for designing of complex aero-structures, especially in preliminary/conceptual design phase since it can compute the relative effect of important parameters of a component e.g. Weight (Structures), Lift/Drag (Aerodynamics) and Range/Endurance (Flight Dynamics). All the above mentioned parameters are highly important and should be kept into considerations while designing an aircraft. In this research three disciplines are used to calculate the parameters of optimum wing for a particular fixed wing UAV. Flight dynamics, structures, and aerodynamics are highlighted. Research in the field of optimization technique and their comparison is important as MDO is a time costly procedure so using an appropriate optimization technique is important. Very few research examples of MDO have gone in the direction in which flight dynamics, is also of concern but in doing so, the complexity of the implementation of other disciplines is slightly compromised. In this research, MDO is carried out with three disciplines having the objective function associated with flight dynamic's parameters i.e. Range and Endurance.

Keywords: Multidisciplinary optimization; Genetic algorithm; UAV; Wing design

Introduction

The coupling which is inherently present in MDO imposes additional challenges which are beyond those that are encountered in single-discipline optimization. The additional computational burden increases the overall complexity; furthermore, it creates challenges for implementing coupling of disciplines within software systems [1-3]. As solution times for analysis and optimization increases at a linear rate, the overall computational cost of MDO is relatively quite higher than compared with the sum of costs of single-discipline optimization of the presented disciplines with the MDO module. Additionally, even if every discipline present in MDO employs linear methods, the combined system may require costly nonlinear methods and analysis. Finally, if one discipline is considered for optimization, we can use a single-objective function, but for the MDO problem we need to have multiple objectives with an increase in optimization cost, or a single objective function which depends on the output of each discipline [3].

In some of the research the MDO of a system is carried out at the conceptual level by employing simple analysis tools. For aircraft design, the ACSYNT [4,5], and FLOPS [6], programs represent this type of MDO application. Due to the simplicity of analysis tools, it is usually possible to merge various disciplines and their analysis in a single modular computer program thus avoiding huge computational costs. References [7-9] provide instances of such approaches. During the detailed design process, the complexity level of analysis employed at the conceptual level increases gradually, due to which, some of these beginner codes start facing organizational challenges which are encountered when MDO is employed at a comparatively advanced stage of detailed design. Due to the overall importance of computational budget, MDO focuses on the tradeoff between accuracy and computational cost linked with alternative methods with variant levels of complexity for considering same phenomena.

In single-discipline optimization it is common to have an "analysis model" which is more accurate and more costly than an "optimization model". The trade-off between accuracy and cost is exercised in various ways in MDO. For the first technique, optimization models can use the same theory with a lower level of detail. As an example, the FE models used for combined aero-elastic analysis of the high-speed civil transport in reference [10], is relatively quite detailed than the models typically used for combined aerodynamic-structural optimization as in reference [11]. Secondly, models which are used for MDO are usually less complex and accurate than models used for a single disciplinary optimization problem.

An example of which is that the structural models used for airframe optimization of the HSCT [10], are relatively more refined than those used for MDO. Aircraft MDO programs, such as FLOPS [6] and ACSYNT [4,5], use basic aerodynamic models and use weight equations to estimate structural weight.

Multidisciplinary optimization allows designers and researchers to incorporate relevant disciplines simultaneously. The best of the concurrent problem is better to the design found by optimizing each discipline in sequence, since it can make use of the exchanges between the disciplines. Including all disciplines simultaneously for MDO significantly increases the overall complexity of the optimization problem. Recently MDO researchers have looked into different optimization methods in non-gradient based approaches in the past decade. The objective of this research is to optimize a wing of a subsonic fixed UAV. Thus, for this multidisciplinary problem, genetic

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algorithm is chosen for optimization purposes. Since there are no high fidelity software's involved, GA is an adequate choice for this optimization problem.

The use of genetic algorithm for optimization in aeronautics has been widely used in the last twenty years. From the work [12], in 1994 to the work of [13], in 2013, genetic algorithms are widely used in the field of aerospace. The advantage of using GA is that it uses a relatively small number of iterations to converge to the optimal solution and its simple in its application. For our simulation, we will select 70 generations of population size of 70 each. The mutation, selection will be crossover mutation. So the maximum number of iterations in our simulation is 4900 simulations.

Research Approach

The research is conducted with focus on MDO of the wing of a subsonic UAV. The disciplines which are part of MDO are Aerodynamics, Structures and Flight Dynamics. An effort is made to be as close to real solutions as possible e.g. drag prediction of wing includes polar drag, friction/form drag and interference drag due to fuselage. Validation of each section of code is done against an available experimental data result. Constraints are formulated e.g. Engine, type of aircraft and maximum thickness/chord ratio of airfoil. The objective of the research is to maximize the design variables to ensure that the effect of each parameter is fully captured and is reflected in the main results. Also, it is desired to ensure that all the parameters and their effects are captured correctly through comparison with experimental results. Ultimately, it is desired that the research is comprehensive enough so that the complexity of each discipline is not compromised. The objective function which is optimized is dependent on output of flight dynamics and uses weightage formula for the important parameters of flight e.g. range and endurance. Since aerodynamics and structures directly affect the abovementioned parameters, the objective function is not only a single function, but it also considers all the disciplines interconnected into the same function. The object UAV whose wing is to be optimized is a light weight UAV with a take-off weight of approximately 40 kg. The parametric drawing of this UAV is shown in Figure 1. The CAD model shows the main dimensions and parameters of the object UAV. This research focuses on optimizing the wing of this object UAV.

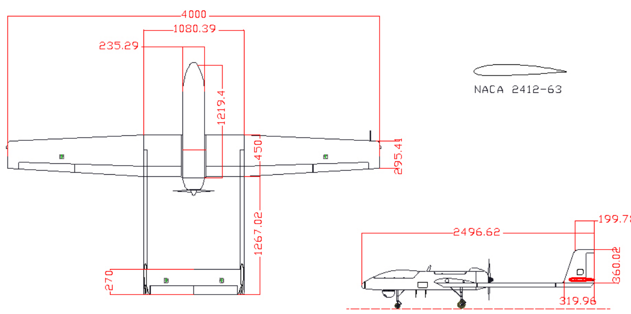

Figure 1: Parametric model of object UAV.

The object UAV is flight tested and manufactured. Figure 2 shows the manufactured, flight ready UAV on the test field. Since most of the parameters of the UAV are finalized, optimizing the wing and replacing it can upgrade the UAV without making other significant changes in the UAV.

Figure 2: Manufactured flight ready object UAV.

The result of the research is a wing design of the object UAV which gives better result for objective function and remains within the design window of constraints defined. Thus, this research upgrades the object UAV and it shows a new significant effort on research in methods of MDO for light weight UAVs.

Variables of Simulation

It is decided that the number of kinks in the wing will be one and the number of variables of this optimization are twelve. The variables are defined as the chord lengths of the root, kink and tip, the location of quarter chord point of kink and tip and the airfoil definition variables. The location of the quarter chord point of the root is fixed, thus it is not being considered as a variable. The airfoil which will be selected will belong to NACA four digit series, so the variables of airfoil are the maximum camber as percentage of the chord, the distance of the maximum camber from the leading edge in tens of percentage of the chord and the maximum thickness of the airfoil. The location of quarter chord point of kink and root will define three variables each so in total they will define six variables and the remaining three variables are the chord lengths of root, kink and tip. The airfoil will not be optimized; rather any one of the NACA 4 digit airfoil will be selected depending upon the performance required. The quarter chord point locations on the tip and the root will be defined through aspect ratio, dihedral angle and the local span of the kink and the root. These will be then translated into the respective position of the quarter chord points.

Limits and Constraints of Variables

The limits of the variables are given in Table 1. The constraints of each variable are given in Table 2.

Sr. No	Variables Definition	Variable Name	Upper Limits	Lower Limits
1.	Maximum camber of airfoil	A	3	0
2.	Distance of max. camber of airfoil	B	4	0
3.	Maximum thickness of airfoil	C	15	8
4.	Chord length of root(m)	R1	1.5	0.2

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5.	Chord length of kink(m)	R2	1.5	0.2
6.	Chord length of tip(m)	R3	1.5	0.2
7.	Maximum Span from root to tip (m)	b1	5	0.5
8.	Maximum Span from root to kink (m)	b2	5	0.2
9.	Sweep angle from root to tip (deg)	S1	60°	0°
10.	Sweep angle from root to kink (deg)	S2	60°	-60°
11.	Dihedral angle from root to tip (deg)	D1	5°	0°
12.	Dihedral angle from root to kink (deg)	D2	5°	-5°

Table 1: Variable definition and limits in optimization.

Constraint Number	Constraints Definition
Geometric Constraints	
1.	
2.	
3.	
4.	
Aerodynamic Constraints	
5.	
6.	
Structural Constraints	
7.	
Flight Dynamics Constraints	
8.	
9.	Compulsory segments of mission performed

Table 2: Constraints of optimization.

Objective Function Formulation

The objective function developed for the multidisciplinary optimization of the wing is dependent on the performance of the UAV as the performance of the UAV is the main concern for the user. The flow chart of the optimization problem is given in Figure 3.

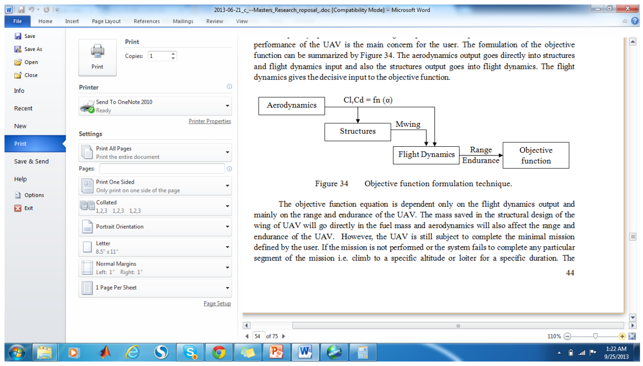

Figure 3: Objective function formulation.

Simulation Models

The models for aerodynamics, structures and flight dynamics have been separately prepared and validated through reference [14-16]. Model constructed for aerodynamic calculations is taken from [14], the flight dynamics is taken from [15] and weight estimation for wing is calculated through reference [16]. Innovation was captured in modeling of each discipline and an effort was made to make models as realistic as possible with cross validation with experimental results or high-fidelity software's results. These models are purposefully built to cater for multidisciplinary optimization problem i.e. they require minimum computational effort and one complete cycle of simulation takes roughly half a minute which is very ideal for large iterative process.

Results of Optimization

The genetic algorithm was first run for 20 generations of population size of 80 each. As shown in Figure 4, the genetic algorithm was unable to converge to the optimized solution. So the second run of 70 generations each of population size of 70 was taken. The solution was converged at about 4000 iterations. Figure 5 shows the optimized solution convergence with respect to the number of iterations and Figure 6 shows the zoomed convergence in the last two hundred iterations. As is seen in the zoomed view of the last two hundred iterations, the variation in the objective function is minimal thus the solution is accessed as optimized by genetic algorithm.

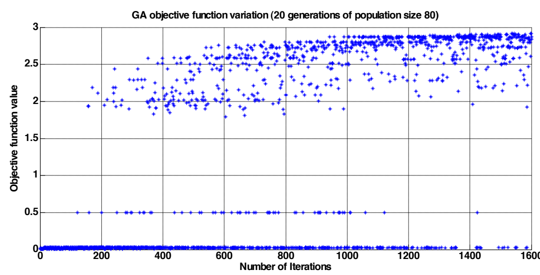

Figure 4: Genetic algorithm results (20 generations/population size = 80).

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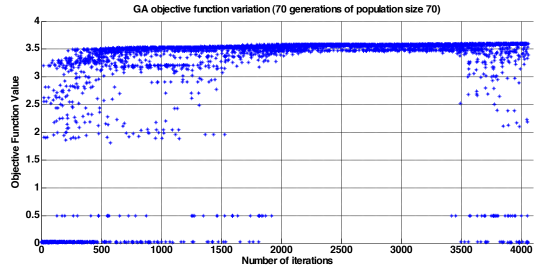

Figure 5: Genetic algorithm results (70 generations/population size=70).

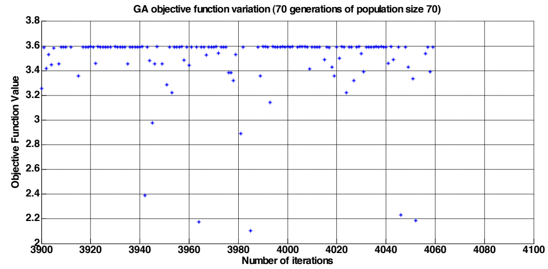

Figure 6: Zoomed view of genetic algorithm final results.

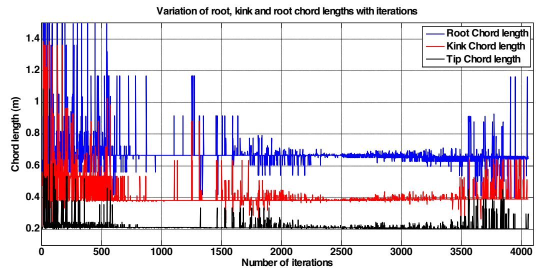

Figure 7: Variation of chord lengths in genetic algorithm.

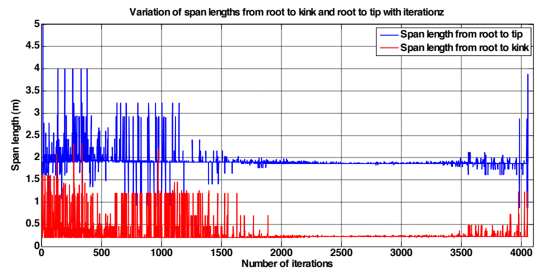

Figure 8: Variation of span lengths in genetic algorithm.

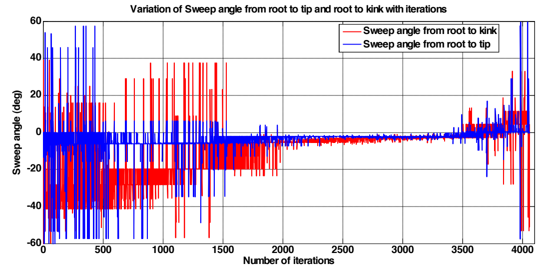

Figure 9: Variation of sweep angle in genetic algorithm.

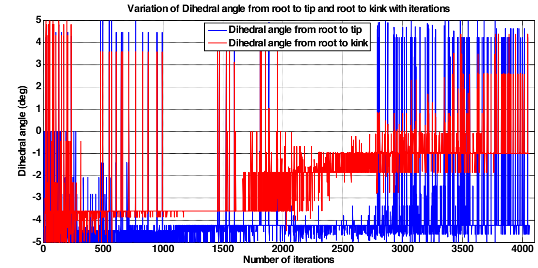

Figure 10: Variation of dihedral angle in genetic algorithm.

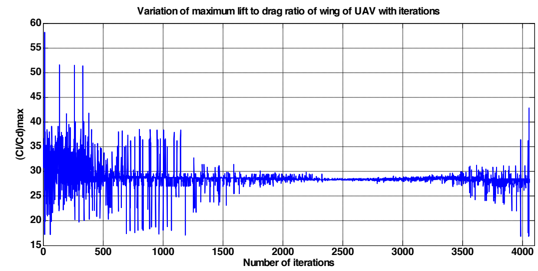

Figure 11: Variation of (Cl/Cd) max of the wing.

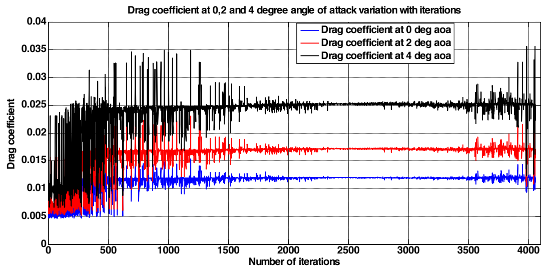

Figure 12: Variation of drag coefficient of wing at 0°, 2° and 4° angle of attack.

The variations of geometric constraints with respect to the number of iterations are shown from Figure 7 to 10. The variation in chord lengths of root, kink and tip is shown in Figure 7.

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The variation of span length from root to tip and root to kink is shown in Figure 8.

The variation of the sweep angle from root to kink and root to tip is shown in Figure 9 and the variation in dihedral angle from root to kink and root to tip is shown in Figure 10.

The aerodynamic data and its variation were also stored in the optimization process. The variations of aerodynamic data during the optimization are shown from Figure 11 to Figure 12.

The variation in maximum lift by drag ratio of the wing is shown in Figure 11. As the UAV will mostly fly at low angle of attacks, the drag coefficient at 0°, 2° and 4° and their variations are shown in Figure 12.

The variation of wing mass was also stored for optimization. As can be seen, the lesser the mass of the wing, the more fuel it can carry.

This is clearly shown in Figure 13 that the optimization result has tried to obtain the minimum mass for the wing, thus wing weight was an important factor for optimization. If the performance of the UAV is not demanded so high, this decrease in mass can also be used for other payloads or decreasing the overall takeoff weight.

Geometric Parameters	Original Configuration	Optimized Configuration	Trend in Geometric Parameter
Chord length of root (mm)	450	643	Increase
Chord length of kink (mm)	450	391	Decrease
Chord length of tip (mm)	295.41	203.5	Decrease
Span wise length to kink from root (m)	0.4226	0.1116	Decrease
Span wise length to tip from root (m)	1.8823	1.7532	Decrease
Sweep angle from root to kink (deg)	0	11.47	Increase
Sweep angle from root to tip (deg)	1.77	0.427	Decrease
Dihedral angle from root to kink (deg)	0	0.994	Increase
Dihedral angle from root to tip (deg)	0	4.25	Increase
Mass of the wing (kg)	5.5631	4.394	Decrease
Clmax of the wing	1.9036	2.0027	Increase
(Cl/Cd)max of the wing	33.35	28.49	Decrease
Total Range possible (km)	1860	2105	Increase
Total Endurance possible (hr)	15.5	17.87	Increase
Objective Function Value	3.152	3.594	Increase

Table 3: Comparison of original and optimized solution.

The optimization result for the UAV wing and the original wing are compared in Table 3. The trend of each variable is also shown. The airfoil selected for the original wing was NACA2412 whereas the optimization yielded in the selection of the NACA 3415 airfoil.

This airfoil might not produce the best optimum result, but as airfoil optimization was not the concern and also the design variables were 12 which yielded in a very big design space.

It is necessary to either constraint design variables in a more compact solution space where the chances of finding the optimal solution are maximum or first optimize the airfoil for the design UAV and then use that airfoil for further aerodynamics/structures and flight dynamics solution.

The isometric view of the original and optimized wing is shown in Figure 13. The top, front and side views of the original and optimized wing are shown in Figure 14, 15, 16 and 17 respectively. The red color denotes the original wing, whereas the blue color denotes the optimized wing.

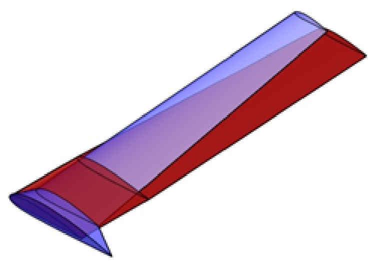

Figure 13: Comparison of original and optimized wing (Isometric View).

Figure 14: Comparison of original and optimized wing (Top View).

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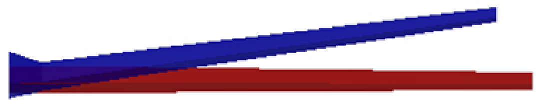

Figure 15: Comparison of original and optimized wing (Front View).

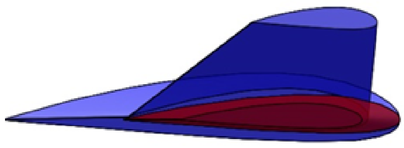

Figure 16: Comparison of original and optimized wing (Side View).

Figure 17: Comparison of original and optimized wing lift to drag ratio.

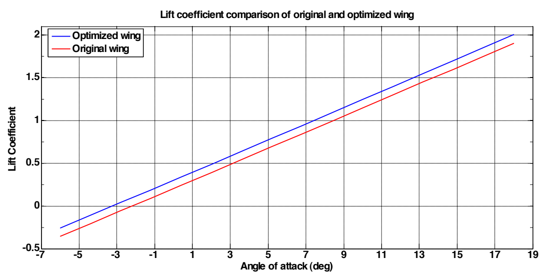

Figure 18: Comparison of original and optimized wing lift coefficient variation.

The optimized wing is better in two disciplines i.e. structures and flight dynamics compared with the original wing, but in aerodynamics its lift coefficient is better but overall L/D ratio has deteriorated. Flight dynamics helps in the selection of the optimized wing compared with the original wing and its configuraton (Figure 18).

Conclusion

A new model for UAV wing parameter estimation has been developed and incorporated into an MDO design formulation. Modeling the various interaction effects of flight dynamics together with other disciplines such as aerodynamics and structures is important. This technique can be used to optimize wing of any other light UAV by just changing the input parameters of the new UAV which include engine data, fuselage lift and drag variation and other structural component weight. The task of optimizing the wing of the given fixed wing UAV was achieved successfully and the results of the original wing matched the original wing configuration. Also, each discipline results was crossed checked and verified against experimental or analytical results. The theoretical results were found in close proximity of experimental or analytical results. An effort was made to achieve as realistic MDO results as possible.

The objective function was carefully selected so that it shows the true optimized result for the UAV rather than depending upon the output of single independent discipline. Genetic algorithm also proved to be a better choice as it yielded in better optimization in terms of the number of iterations needed for saturated results. The genetic algorithm converged before the total number of generations was complete. MATLAB inbuilt genetic algorithm function was chosen as it also has authenticity in its coding and looks at each variable independently. Choosing the inbuilt genetic algorithm function limited in assigning the importance of each independent variable, but the optimization results were satisfactory and the optimization process did not halted during the iterative process. Every wing design did its own aerodynamics, structures and flight dynamics evaluation. Each iteration took approximately half a minute and the total results were computed within 1.5 days, which is a fast result for a MDO problem which include three separate disciplines.

The results obtained from the comprehensive programming and evaluating parameters at different stages yielded in a fast, validated and comprehensive technique to solve multidisciplinary optimization problem. Genetic algorithm also yielded in quick results and found the optimized solution for such a vast design space. It can be safely said that given the design space, and the type of UAV, the multidisciplinary optimization yielded in quick and optimized solution. The optimized solution is otherwise difficult to be found without the use of some optimization technique. The objective of this research, which was to optimize the wing of a light weight UAV, is attained successfully and the results show that the original design can be changed for better performance of the overall UAV.

This technique can be used to optimize the whole UAV by incorporating the fuselage of the UAV in the design too. By doing aerodynamics and structural optimization of fuselage, that can also be incorporated in the future studies. Addition of other aircraft components such as flaps and elevators can also be incorporated. If desired, high fidelity methods like CFD for aerodynamics and CAE software's like ANSYS for structures can be incorporated in the design methodology. However, incorporating these may acquire higher accuracy but it will also increase the computational time. A computer cluster may be in need if high fidelity methods like CFD and CAE are incorporated within optimization loop which can be observed by the fact that it took almost 4000 simulations to acquire the desired results. Another method can be used by finding the solutions of 20 or more different iterations at different design level with the use of high fidelity software and then use interpolation techniques to acquire the results for optimization. However, the use of this technique also has its own objections.

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