Final Report for the Solarship Optimization Work Performed During Summer 2014

University of Toronto Institute for Aerospace Studies
Computational Aerodynamics Lab

Benjamin Blake

August 2014

1 Comparison of the Region Design Variable and Free-Form Deformation Optimization Approaches for Solarship Drag Minimization

Two optimization methods were used to optimize the wing of a solarship for minimum drag. The methods used are the region design variables (RDV) approach and the free-form deformation (FFD) approach, in the hope that a preliminary comparison of the methods could be made. This chapter outlines the optimization case, and then compares the results obtained by the two methods.

1.1 Solarship Optimization Case Description

The optimization performed was a drag minimization case subject to a fixed coefficient of lift, wing volume, and wing section thickness. Formally, the case can be expressed as

$$\begin{aligned} \text{minimize} \quad & C_D \\ \text{w.r.t.} \quad & \text{Wing sectional shape variables} \\ & \text{Wing twist variables} \\ & \text{Angle of attack} && (1) \\ \text{subject to} \quad & L = \text{aircraft weight} \\ & V = V_{\text{original}} \\ & t/c \geq 0.75\,(t/c)_{\text{original}}\ . && (2) \end{aligned}$$

The operating Mach and Reynolds numbers for this case are $M_\infty = 0.2$ and $\mathrm{Re}_L = 18.13 \times 10^6$ based on the mean aerodynamic chord of 28 m. This solarship is designed for flight at an altitude of 2000 m and speed of 11.1 m/s.

Both optimization cases, the RDV and FFD methods, were run on as similar as possible grids and flow solver parameters. The initial wing geometry is given in Figure 1. There were three main differences in the cases run: (a) the geometric design variables for the FFD case were unscaled, whereas for the RDV case they were scaled by a factor of 100 (`jtstrm%geo_scale=1.d-2`), (b) the RDV method had a total number of geometric design variables of 200 on each the upper and lower wing surface, whereas the FFD approach had 100, and (c) the geometry was parametrized with $12 \times 12 \times 5$ control points per CFD mesh block for the FFD case, whereas the RDV method had a geometry parametrization of $5 \times 5 \times 5$ control points per block.

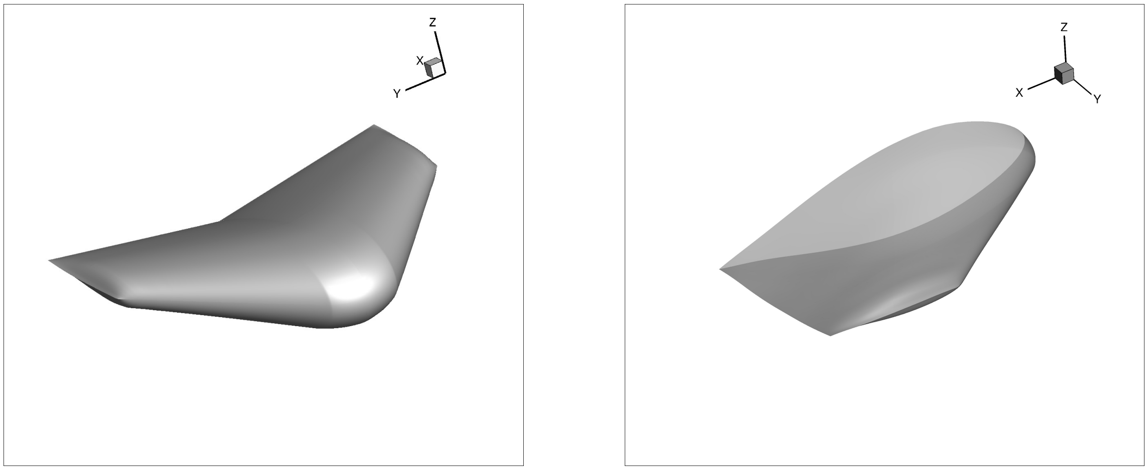


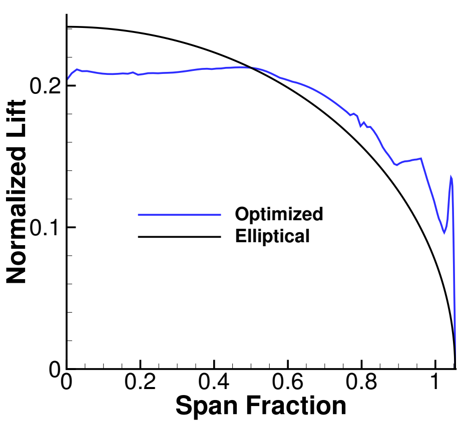
Figure 1: Initial solarship wing geometry

1.2 Comparison of RDV and FFD Results

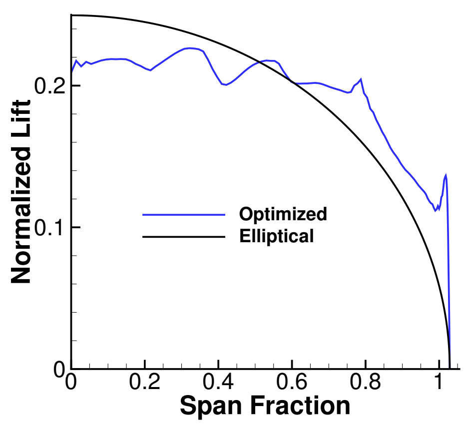
In this section all important results pertaining to the optimization cases will be given. Firstly, the wing characteristics obtained for both optimization cases are compared in Table 1. The final lift distributions are given in Figure 2, while the twist and thickness distributions are shown in Figure 3.

Table 1: Final results obtained from both optimization cases

Optimization Case	C_L	C_D	C_L/C_D	C_M	α
Initial	0.19400	0.02463	7.8765	0.02671	6.00°
FFD	0.22002	0.02469	8.9113	-0.01291	4.69°
RDV	0.22002	0.02501	8.7973	-0.01953	3.00°



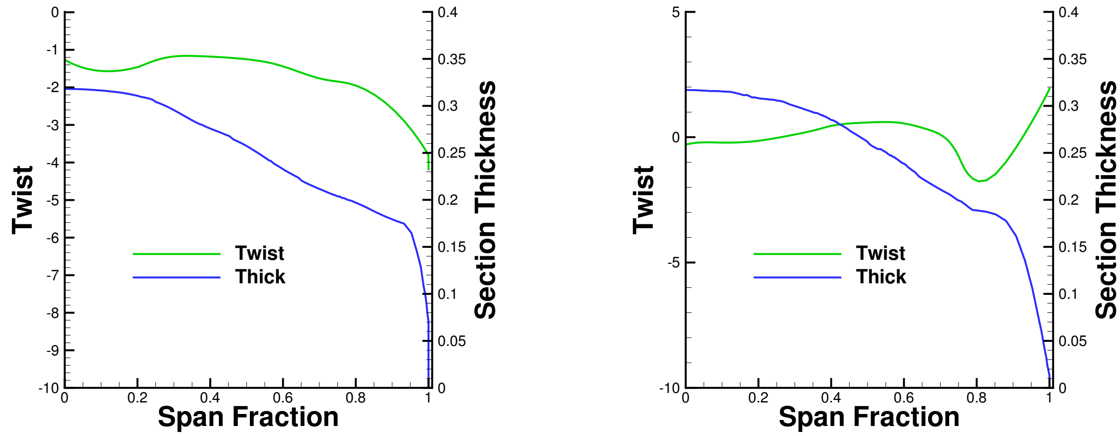
(a) FFD case



(b) RDV case

Figure 2: Comparison of lift distribution for the optimized wings from the FFD and RDV cases

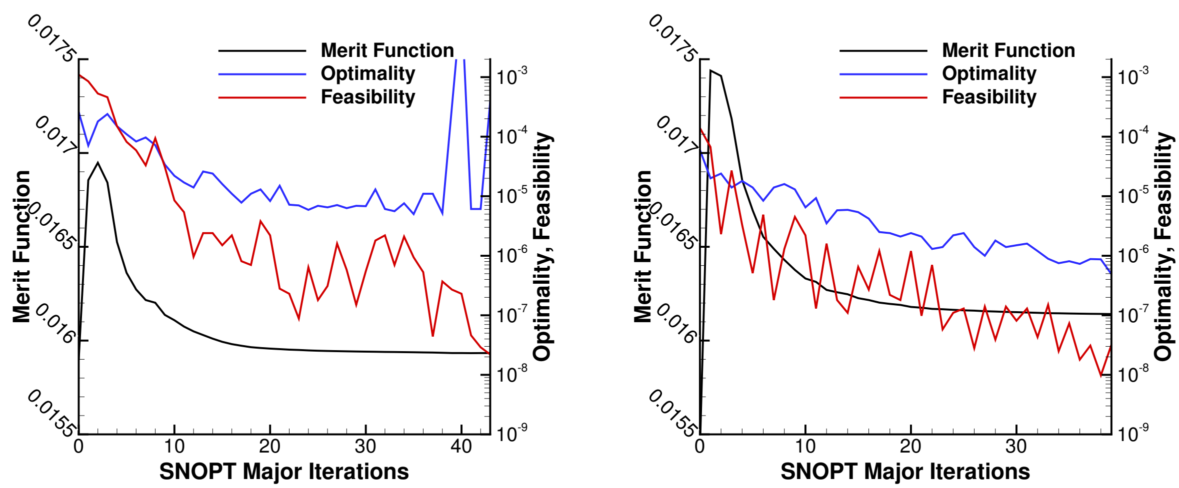
To compare the optimization efficiency the time history of the merit function, optimality, and feasibility for both methods are given in Figure 4. Finally, Figure 5 shows the optimized geometries



(a) FFD case **(b)** RDV case

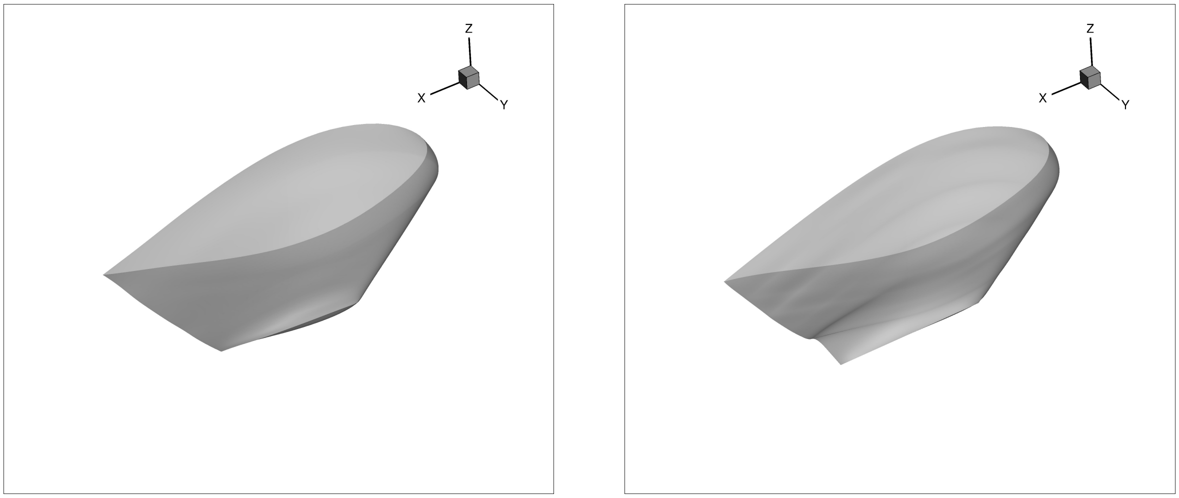
Figure 3: Comparison of the twist and section thickness distributions obtained on the optimized wings from the FFD and RDV cases

for both cases, and Figure 6 shows the areas of separation on the optimized shapes. As can be seen the region of separation appears slightly smaller for the FFD case compared to the RDV case. This could explain the slight difference in drag coefficients for the two cases.



(a) FFD case **(b)** RDV case

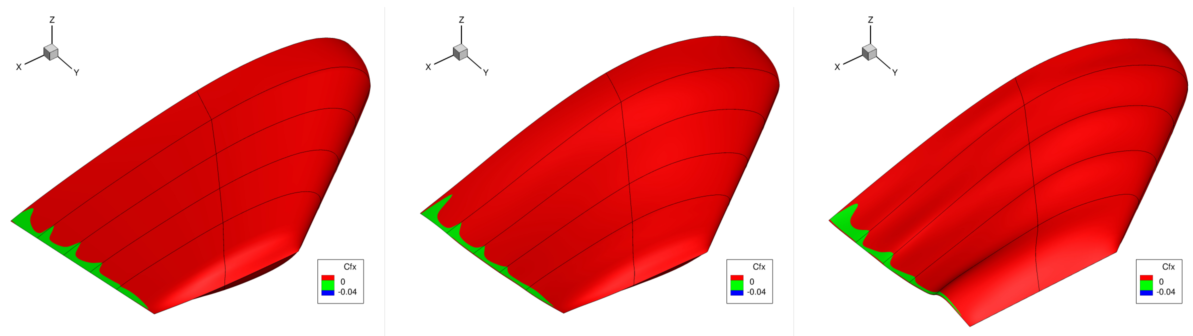
Figure 4: Comparison of the merit function, optimality, and feasibility histories for the FFD and RDV cases



(a) FFD case

(b) RDV case

Figure 5: Comparison of the final optimized shapes for the FFD and RDV cases



(a) Initial geometry

(b) FFD case

(c) RDV case

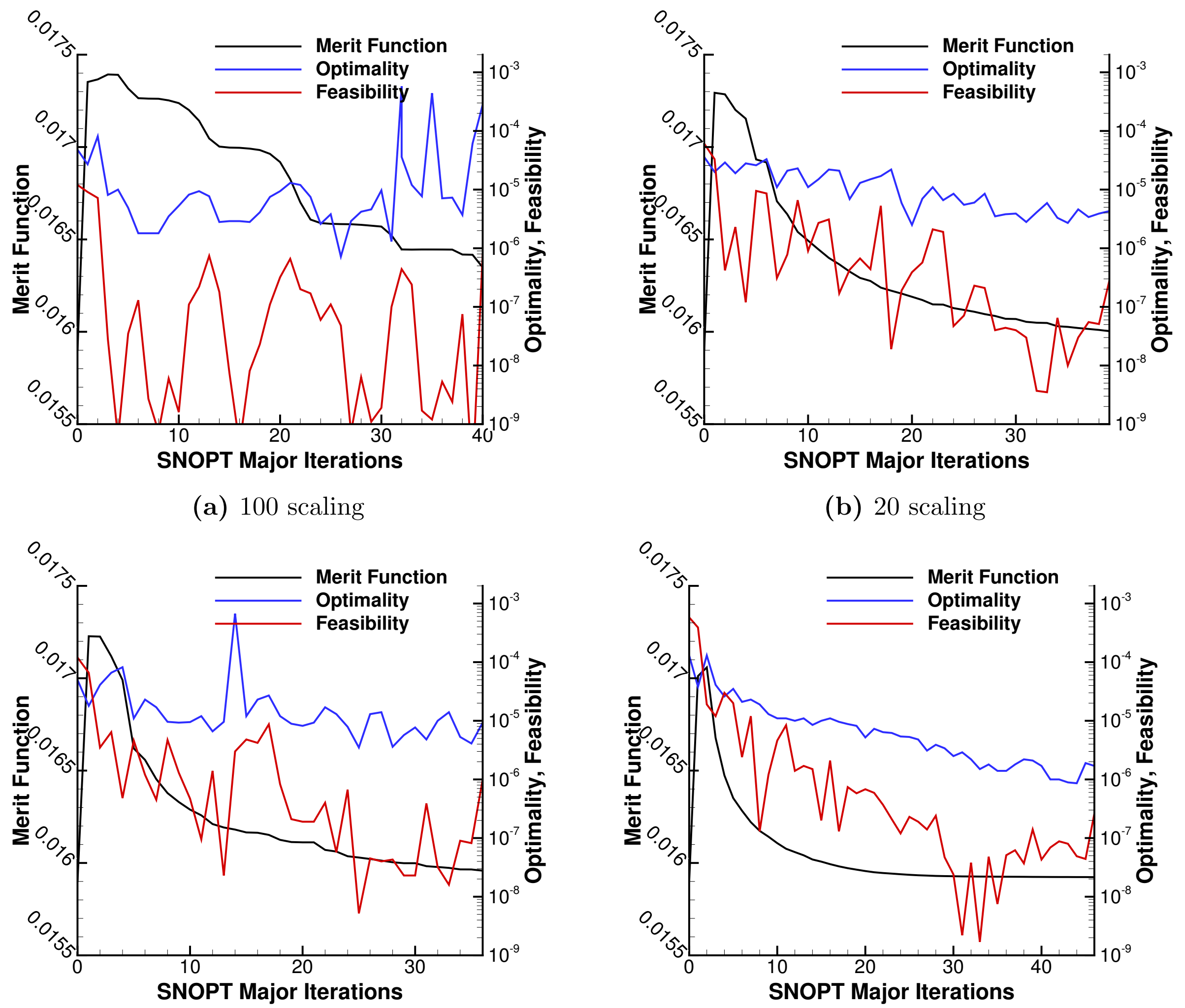
Figure 6: Comparison skin friction distributions on the initial shape and optimized shapes for the FFD and RDV cases, showing the regions of separation near the trailing edge

1.3 Effect of Design Variable Scaling on Optimization Efficiency

As was seen during the optimization the FFD case changed the angle of attack very slowly through the case compared to the RDV approach. This is because the RDV approach scales the geometric design variables by a factor of 100, decreasing the sensitivity to these design variables by a factor of 100, whereas the FFD approach had no scaling. This forces the angle of attack design variable to have a larger influence as the optimization runs in the RDV case. This also explains why at the final design the angle of attack is lower for the RDV case than the FFD case, as it is initialized to $\alpha = 6°$.

Scaling the design variables in this manner has the advantage of "evening out" the design space so that the optimizer approaches the optimum design quicker. Because a proper scaling would be very beneficial to add to the FFD method a preliminary test was performed on this solarship optimization case with various values for the geometric scaling. The scalings used are 100, 20, 10, and 2, and this is done by setting `jetstrm%geo_scale` to 1×10^{-2}, 0.5×10^{-2}, 1×10^{-1}, and 0.5×10^{-1}. The optimality history plots for all scaling cases are shown in Figure 7.

The design variables for the FFD case do have larger displacements than the RDV case, however



(a) 100 scaling

(b) 20 scaling

(c) 10 scaling

(d) 2 scaling

Figure 7: Preliminary results into the effect of the geometric scaling variable on optimization efficiency for the FFD case

they are on the same order of magnitude. This does make it interesting that the best scaling is two orders of magnitude less than for the RDV case, so there may be an internal handling of the FFD design variable positions that is affecting this scaling value.

Additionally, the scaling of the design variables can affect the initial values of the optimality, feasibility, and merit function. The initial values of these parameters with the corresponding scaling values are given in Table 2. As can be seen the feasibility is affected the most, it increases quite significantly with decreasing scaling. The initial optimality also increases with decreasing scaling, albeit much less than the feasibility, and the merit function remains constant. These effects of the geometric design variable scaling must be taken into account when setting SNOPT exit parameters.

Table 2: Initial values of feasibility, optimality, and the merit function based on the design variable scaling

Scaling factor	Feasibility	Optimality	Merit function
100	1.2×10^{-5}	4.8×10^{-5}	1.5897×10^{-2}
20	6.1×10^{-5}	3.6×10^{-5}	1.5897×10^{-2}
10	1.2×10^{-4}	5.0×10^{-5}	1.5897×10^{-2}
2	5.8×10^{-4}	1.3×10^{-4}	1.5897×10^{-2}
1	1.1×10^{-3}	2.6×10^{-4}	1.5897×10^{-2}

1.4 Conclusions

The primary conclusions on the comparison of these two methods can be made in terms of the final optimized shape. Firstly, the FFD method did obtain a slightly lower final coefficient of drag than the RDV method. It can also be seen from Figure 2, 3, and 5 that the FFD method attained a much smoother final geometry than the RDV method. This is somewhat expected simply due to the nature of the FFD method in that the control points are not directly on the wing surface, as with the RDV method. Also, twice as many control points were used for the RDV method compared to the FFD method, potentially allowing more localized shape changes.

In terms of optimization efficiency we can see for both methods the merit function plateaus somewhere between 20 and 30 SNOPT major iterations. The main difference is seen in the optimality. The optimality for the RDV method decreases in a much more predictable, controlled manner, as shown by its linear nature (on the log plot) in Figure 4 (b), whereas in Figure 4 (a) it is much more sporadic, and seems to plateau. Furthermore, the merit function seems to plateau after around the same number of major iterations, even though the RDV method has twice as many design variables.

In terms of the scaling comparisons for the FFD case it can be seen that the amount of scaling provided to the geometric design variables does affect the optimization progress significantly. Furthermore, we can see that using the same scaling value for the FFD case as the RDV case, 100, does not show good performance in terms of optimality reduction whatsoever (Figure 7 (a)). From these preliminary results it appears that a scaling of 2 produces the fastest reduction in merit function and provides the most controlled, linear decrease in the optimality. Using this value of scaling the optimality is able to decrease by approximately two orders of magnitude, whereas the unscaled case decreases by only slightly more than one order of magnitude.

These preliminary findings show that for this case the FFD approach produces a very smooth geometry with slightly lower coefficient of drag compared to the RDV approach. It does seem to come at the cost of decreased optimization efficiency with respect to the number of design variables. However, hopefully a further study into the effect of the geometric design variable scaling could lead to increases in optimization efficiency for the FFD method.