The direct design optimisation histories were slightly oscillatory and the changes were relatively small due to their initial values being relatively close to the optimum design. This is due to the selection of advanced helicopter rotor aerofoil profiles as the basis vectors. As was mentioned previously the design specifications in the high angle of attack regions (eg. maximum coefficient of lift) were set carefully to ensure converged CFD solutions. This meant that the coefficient of lift values used to specify the design variables had to be reduced in some cases. The details regarding the basis aerofoils cannot be presented due the proprietary nature of the geometries. Presentation of the basis vector contribution to the final design is therefore meaningless. The performance of the final design optimisation procedure can be evaluated by comparing the optimum design variables with the design specifications, as presented in table 2, (Note the modified specification of the second constraint, ie. a reduced angle of attack for drag at maximum lift). Evaluation of the design itself can only be done by comparing its performance with the system it would be replacing.

Table 2: Design optimisation variables at optimum point.

6 %	C_D at $C_L = 0.01$	Thickness	C_D at $\alpha = 5.0°$	C_M at $\alpha = 0.0°$
	0.004	6.01	0.010	0.008
9 %	C_D at $C_L = 0.33$	Thickness	C_D at $\alpha = 6.0°$	C_M at $\alpha = 0.0°$
	0.012	9.29	0.037	-0.004
12 %	C_D at $C_L = 0.32$	Thickness	C_D at $\alpha = 9.0°$	C_M at $\alpha = 0.0°$
	0.0071	11.95	0.014	0.0006

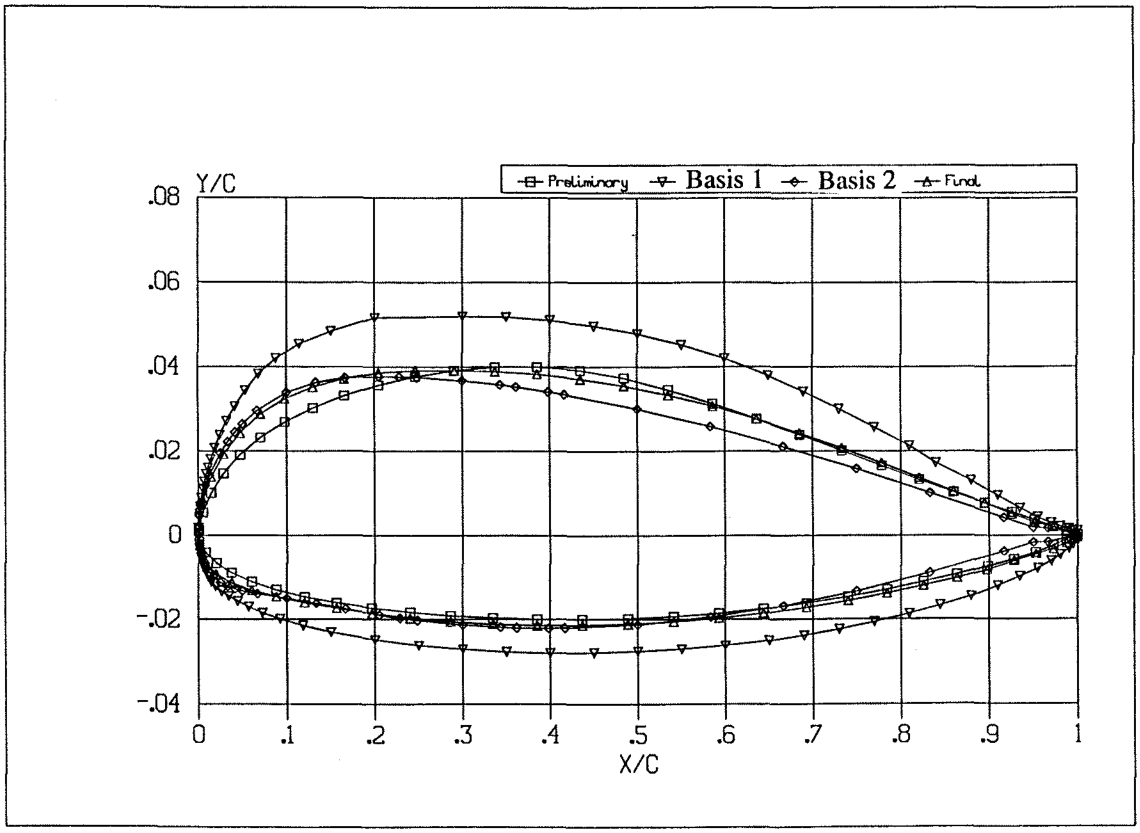

Figure 6: Schematic of all aerofoil profiles used in 6 % design.

Interesting results were obtained when comparing the inverse optimisation, direct optimisation making use of a panel code linked to a boundary layer code and the direct design using the TLNS code. The direct design using the subsonic analysis tool usually favoured the inverse design and the direct design using the transonic analysis tools generally made extensive use of the basis aerofoils. This implies that the inboard stations can be suitably designed at far less cost than the outboard stations. In the one subsonic case the direct optimisation algorithm resulted in a design very similar to the preliminary design by making use of two basis aerofoils which were markedly different to both the preliminary and final designs. Figures 6 to 8 shows the preliminary design aerofoil, the basis aerofoils and final design aerofoil that resulted from the 6%, 9% and 12% optimisation procedures respectively. These figures are specifically not scaled to highlight the subtle differences between the aerofoils

The other important result from this design is that performance improvements were realized. It is instructive to mention that all the designs were achieved within the specified constraints and that improvements in either the cost function or the optimised variable were achieved. The drag improvement of the 12% final design compared to the current rotor system was approximately 25% at the specified design point. This improvement must still be verified experimentally. Comparable improvements are expected for the 6% and 9% designs, but the current rotor system uses only 12% aerofoil sections and therefore no direct comparisons can be made. It will also be critical to experimentally assess the effect of the new aerofoil profile on the stall angle and the drag divergence Mach numbers.

The next step after the design has been successfully completed is to analyse the design for the required operation matrix, ie. Mach number, Reynolds number and angle of attack. This was completed on the three designs and is not presented here for the sake of brevity. This data is used as input for a three-dimensional rotor design and analysis procedure. The final validation of the designs would be to perform a comprehensive range of two-dimensional wind tunnel tests to verify the performance against the design specifications and to ascertain whether the predicted performance improvements are realized. These validated designs could then be incorporated into a three-dimensional rotor design.

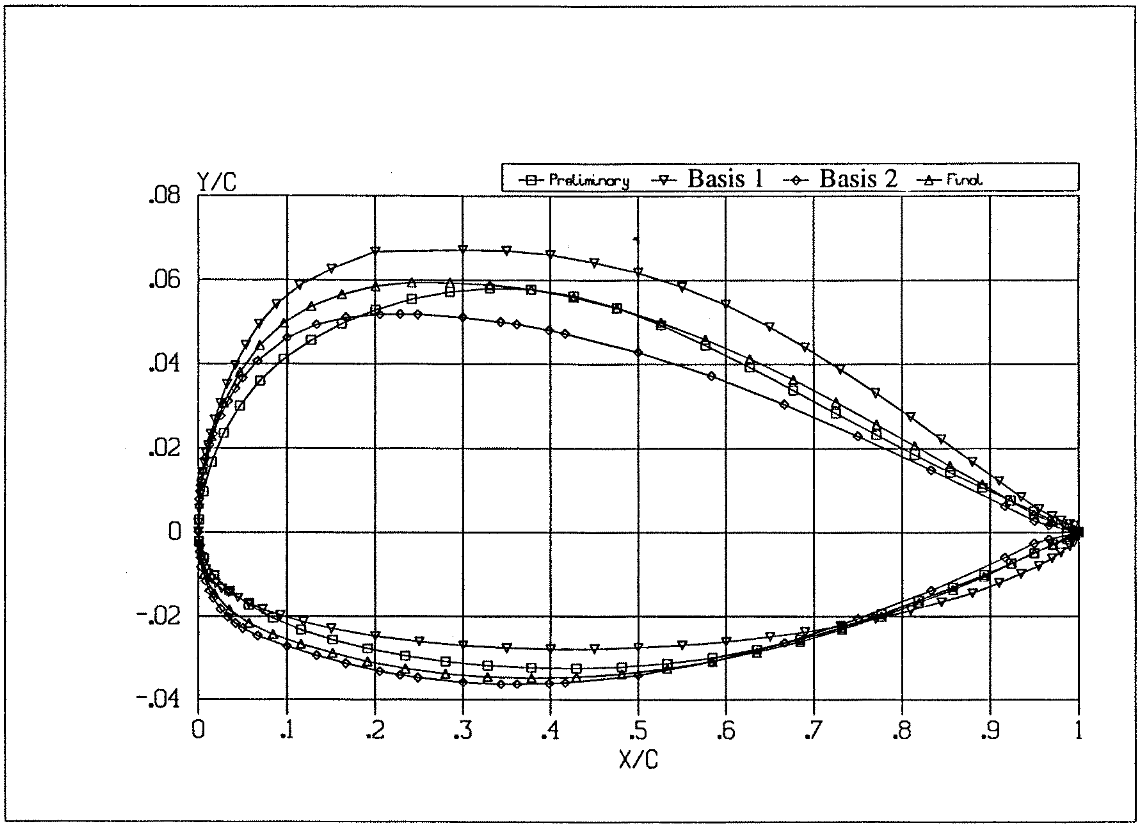

Figure 7: Schematic of all aerofoil profiles used in 9 % design.

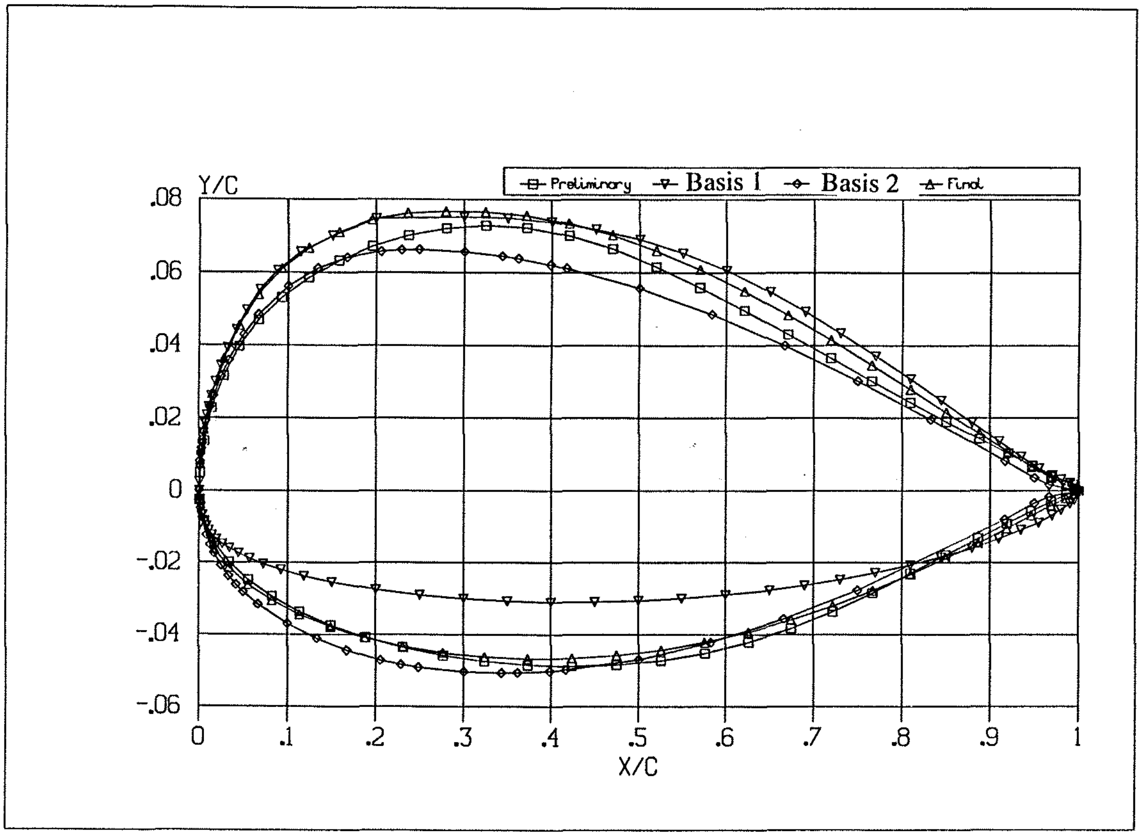

Figure 8: Schematic of all aerofoil profiles used in 12 % design.

Conclusions

An integrated inverse and direct design optimisation system was developed and used to design three helicopter rotor aerofoil sections. The aerodynamic performance of the designs were predicted to be within the design specifications for the conditions which could be numerically predicted ie. attached flows. The design approach makes use of both simple and complex techniques which can be used independently or in unison depending on the design requirements. The design optimisation resulted in a predicted 25% reduction in the drag for the 12% design, this was achieved under operating conditions typical of an inboard station and was compared to the currently used aerofoil section (similar to the NACA 0012). The next stage in this process would be to experimentally verify the predicted design performance and then use the design profiles in a three-dimensional rotor design optimisation routine. An important further development that is necessary for a more effective design optimisation procedure is the prediction of subsonic and transonic stalled flow. This will require CFD development in the turbulence modelling field and experimental validation of developments.

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