CAD OPTIMIZATION OF GLIDER DESIGN WITH PROGRAM 'NAI 186'

Zhao, Dongbiao and Qiao, Xin, Nanjing Aeronautical Institute, China

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SUMMARY

A CAD program for glider optimization sizing at the preliminary design stage is described in this paper. This program was originally developed for optimization of light canard airplane design and had been used successfully in two designs of this type. The program has been modified to suit the mathematical models of glider at the preliminary design stage for optimization of sizing a glider. It utilizes constrained parameter optimization to minimize a performance index (e.g. gross weight of the glider) while satisfying operating constraints. The approach in the optimization uses geometric descriptors and mission parameters as independent design variables which are systematically iterated to find the optimum design. The constraints consist of geometric parameters, performances, trim conditions, static stabilities, handling qualities, and so on. All these parameters are calculated by the program. As a means of illustrating its use as a conceptual design tool, the optimization is used to perform a sensitivity study on design variable variations for a variety of design constants and constraint functions.

1. INTRODUCTION

The CAD program 'NAI 186' was originally developed for optimization of light canard airplane design, being used in the prelimary design of an ultralight 'TRAVELLER', AD-100, and later, effectively used for preliminary design optimization of the side by side two seater version AD-100T airplane. Both are canard configuration and made entirely of composite materials by NAI. AD-100 was the first of its class in China to be strictly certified by the Civil Aviation Administration of China. In 1990, 'NAI 186' was modified to suit the mathematical models of gliders at preliminary design stage, sizing a glider HU-11 for the entry of World Class Glider Design Competition, Phase I. This competition encouraged the efforts of improving the performances on general sailplane configurations taking advantages of applicable technical advances, yet with an inexpensive and practical construction. The objective of this paper is to exploit the potential in achieving good solutions. A glider is practically the power-off condition of an airplane. Only minor modification to the program was necessary to change the configuration and relevant aerodynamics from canard to conventional and some numerical model from those based on airplane statistics to those given in relevant reports in OSTIV Publications.

2. METHOD OF ANALYSIS

The general problem is formulated as follows:
Let the unaugmented performance index, f, be a function of the independent design variables, X:

$$f = f(X)$$

where X is a variable vector, and constraint function for iteration i

$$g_i = \begin{cases} 0 & \text{if } C_i \geq S_{1i} \text{ and } C_i \leq S_{ui} \\ S_{1i} - C_i & \text{if } C_i < S_{1i} \\ C_i - S_{ui} & \text{if } C_i > S_{ui} \end{cases}$$

where C_i is constraint value for iteration i

S_{li}, S_{ui} are lower and upper boundaries of constraint for iteration i

then, augmented performance index

$$F = f + \sum_{i=1}^{m} k \left(g_i / N_i \right)^2$$

where k is penalizing weight

N_i is constraint normalizing factor $\dfrac{|S_{1i}| + |S_{ui}|}{2}$ for iteration i.

The goal is to find the minimum of this index, F. While it is desirable to maximize the performance index $(L/D)_{max,}$ the optimization problem is done as a minimization problem by changing the sign.

A variable transformation is used to scale automatically the variables and apply 'side' constraints, which are inequality constraints applied directly on the design variables. This results in a reduction in the number of iterations required for convergence.

The form of transformation is as follows:

$$x_i = \frac{V_{ui} - V_{1i}}{2} \sin\left(\frac{\pi}{2} \; z_i \right) + \frac{V_{ui} + V_{1i}}{2}$$

where V_{ui} and V_{1i} are the upper and lower independent design variable boundaries.

The optimization is performed by a sequential simplex method which utilizes a continuous penalty function. This direct search algorithm has the advantage of not using gradient evaluations. The simplex optimizer iterates on the transformed variable Z, which spans the set of allowable values of the independent design variables with the range in Z of 1 to -1. This allows consistency in step size selection and limits the allowed values of the independent design variables.

3. EVALUATION OF UNAUGMENTED PERFORMANCE INDEX

The weight of the glider is estimated by simulating the design mission, calculating the weight of the components with statistical formulas and making weight iteration with the convergence criterion to ensure accuracy. However, the relations used to compute weights are from industry statistics and are only expected to be accurate to within 10 percent. The industry statistics for the airplane component weights come from Irving, Roskam and Stender(1)(8)(10) and are functions of all the independent design variables, the gross weight, and about 20 design constants input through the data base. We believe the results will be more accurate when the estimated weight can be adjusted with actual values after prototype construction.

The calculation of sailplane performance in terms of (L/D) ratio and rate-of-sink hinges on the determination of the total glider drag in equilibrium gliding flight. Parasite drag is calculated from a component buildup including compressibility and Reynolds number effects according to Roskam and Hoak(8)(9).

Induced drag is estimated using nonlinear corrections to parabolic drag polars for airfoil-section camber and by adding terms for tail induced drag and wingtail interference drag according to McLaughlin(11). Calculations of stability and control derivatives are typical of these used in preliminary design according to Roskam and Hoak(7)(8)(9) and include empirical adjustments from aerodynamic, wind-tunnel and flight data for compressibility and elasticity. An iterative, non-linear trim routine is used for determining the wing and tail loads in approach flight.

The flight quality analysis is initiated by trimming the glider in approach configuration. The nondimensional stability derivatives for approach are converted to dimensional stability derivatives. The characteristic equation for the fourth order longitudinal set of equations is assembled, then the four roots are found.

The preceding analyses are used to assign the following constraint functions for approach: performance, static stability, maneuver stability, dynamic stability, phugoid mode frequency and damping, and short period mode frequency and damping. The dimensional stability derivatives are used to estimate the following parameters which have been suggested as useful for flight qualities analyses: time to double or half amplitude, flight path stability in approach, vertical gain, etc.

The five independent design variables chosen for this study are shown in Table 1 along with the allowable ranges which act as side constraints that are directly applied. The major wing planform parameters – wing area and wing aspect ratio – are chosen to be with a certain degree of freedom and are expected to have the most impact upon the design. Tail sizing is accomplished by including tail area, tail longitudinal position, and center-of-gravity position as independent design variables, which are expected to have a relatively small impact upon the glider sizing, but a large impact on the trim conditions for the glider configuration.

Lastly, the fuselage length is kept as a function of the tail longitudinal position to match the glider size to the mission and wing planform.

To provide a basis for performing the trade-off studies, a baseline mission is chosen. Table 2 lists the design constants chosen for the baseline mission that are used along with the indicated ranges of independent design variables and constraint functions which are listed in Table 1.

According to the Technical Specification of the World Class Competition, and considering that there might be some 10% error in the results at this initial application stage, we added 10% to the constraints, i.e., we set:

- constraint for V_{stall}
65 - 3 -10% = 58 km/h

- constraint for w_{min}
0.75 - 10% = 0.6456 m/s,

- constraint for $(L/D)_{max}$
30 + 10% = 33.

The gross weight of the glider is chosen as the performance index to be minimized in the study. The results of performing the optimization using the baseline mission and constraints for the performance index - gross weight - currently available in this program are given in Table 3.

Independent Design Variables		Lower Limit	Upper Limit
Wing Area	(S_w)	10.63 (m^2)	16.20 (m^2)
Wing Aspect Ratio	(AR_w)	10.73	18.73
Fuselage Length	(L_f)	4.86 (m)	7.30 (m)
Tail Area	(S_t)	1.00 (m^2)	1.93 (m^2)
Aft-Most Center-of-Gravity	$(\overline{X}_{cg})$	0.1534 MAC	0.5534 MAC
Available Constraint Functions (mainly)			
Approach Wing Lift Coefficient		0.2	1.6
Approach Tail Lift Coefficient		-1.5	0.5
Static Margin		-1.0 MAC	-0.04 MAC
Passenger Volume		$Vol_{req} / Vol_{av} \leqslant 1$	
Trim Elevator Deflection Angle		-25°	25°
Lift-to-Drag Ratio	$((L/D)_{max})$	33	50
Stalling Speed	(V_{stall})	44.0 (km/h)	58.0 (km/h)
Min. Sinking Speed	(w_{min})	0.4 (m/s)	0.6456 (m/s)

TABLE 1. List of Defining Parameters

Number of Seats	1
Weight of per passenger (in this case, including payload)	128 (kg)
Wing Incidence Angle	2.5°
Wing Sweep Angle (¼c)	0°
Wing Dihedral Angle	3°
Wing Thickness Ratio	0.143
Wing Geometric Twist	-1°
Tail Aspect Ratio	5.184
Tail Incidence Angle	0°
Tail Sweep Angle (¼c)	0°
Tail Dihedral Angle	0°
Tail Thickness Ratio	0.12
Ratio of Rudder Area to Vertical Tail Area	0.6
Vertical Tail Area	1.2 (m^2)
Vertical Tail Aspect Ratio	2.03
Fuselage Diameter (equivalent)	0.6 (m)

TABLE 2. Key Design Constants Used for Design Optimization

Wing Area	(S_w)	13.41 (m^2)
Wing Aspect Ratio	(AR_w)	14.73
Fuselage Length	(L_f)	6.081 (m)
Aft-Most Center-of-Gravity	$(\overline{X}_{cg})$	0.3534
Tail Area	(S_t)	1.466 (m^2)
MAIN PERFORMANCES OF OPTIMIZED CONFIGURATION		
Gross Weight	(W_{gross})	308.5 (kg)
Empty Weight		180.5 (kg)
Lift-to-Drag Ratio	$((L/D)_{max})$	33.5
Stalling Speed	(V_{stall})	58 (km/h)
Min. Sinking Speed	(w_{min})	0.6454 (m/s)

TABLE 3. Results of Optimized Configuration

Figure 1 shows the graphic output from the program of the glider configuration optimized. Figure 2 shows the speed polar of the optimum configuration.

4. SENSITIVITY TO PARAMETER VARIATIONS

As a means of illustrating the ease with which a trade-off study can be performed with direct optimization and to gain some insight into the impact of varying independent design variables, a parameter sensitivity study is performed for the baseline mission.

Figures 3 to 7 show the effects of changes of wing area, wing aspect ratio, fuselage length, tail area, and center-of-gravity respectively on the gross weight, $(L/D)_{max}$, W_{min}, stalling speed V_{stall}, and airplane pitching moment coefficient variation with lift coefficient $\partial c_m/\partial c_l$ while other variables are fixed at the optimum point. Wing area has the most impact upon the design of the baseline configuration, both on performance and trim conditions, as shown in Figure 3. Figure 4 shows that the wing aspect ratio has a large effect on the performance, especially on the $(L/D)_{max}$ and w_{min}. Fuselage length has a large impact only on the gross weight (see Figure 5). Tail area and center-of-gravity have small effects on the performance and significant impacts on the trimming condition, as shown in Figure 6 and Figure 7.

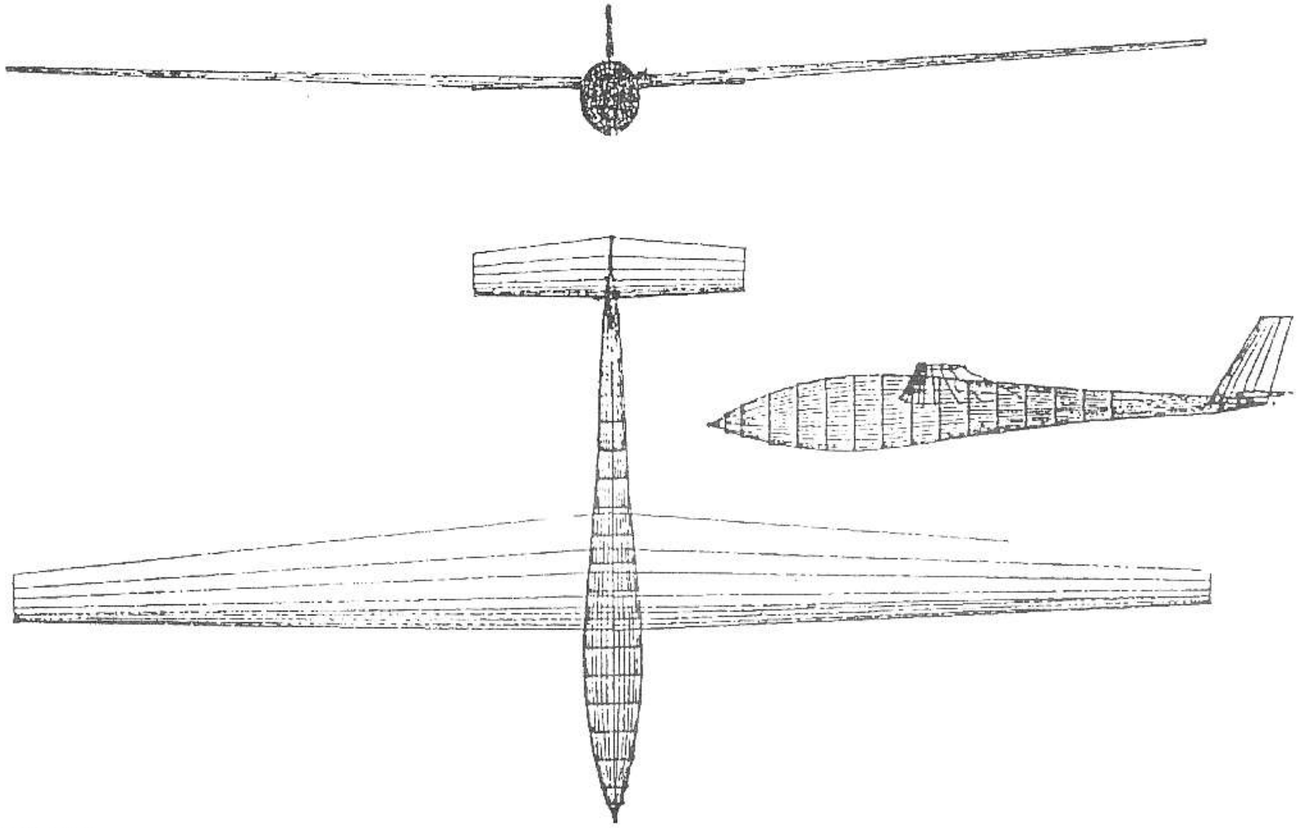

FIGURE 1.

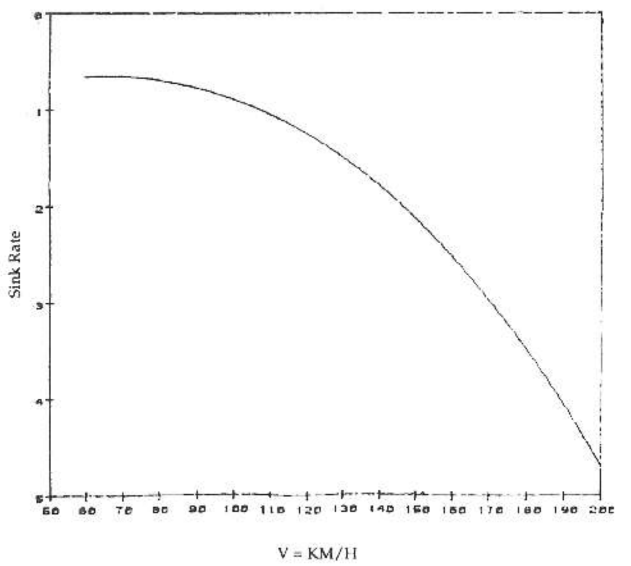

FIGURE 2. Calculated Speed Polar for Sailplane (Optimized)

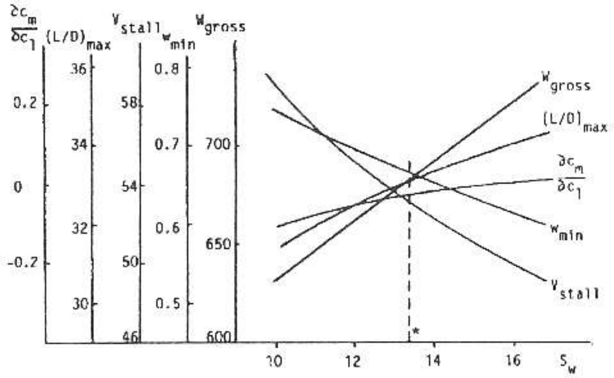

FIGURE 3. Performances with the effect of wing area.

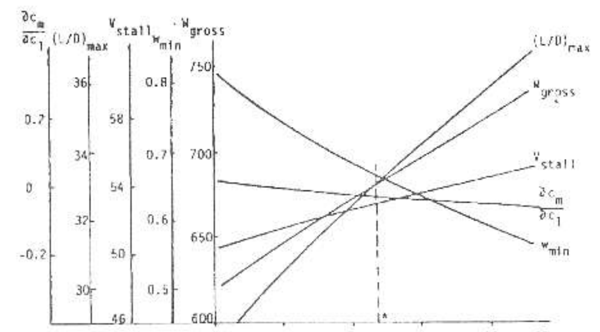

FIGURE 4. Performances with the effect of wing aspect ratio.

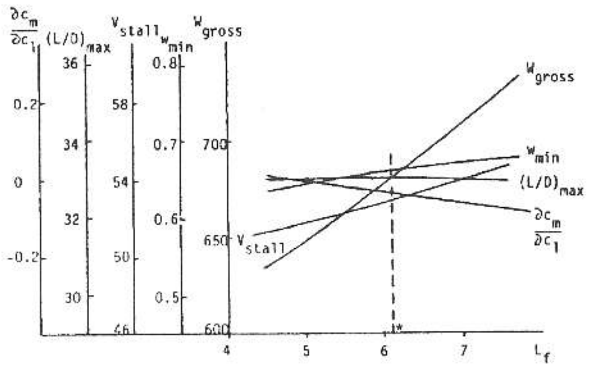

FIGURE 5. Performances with the effect of fuselage length.

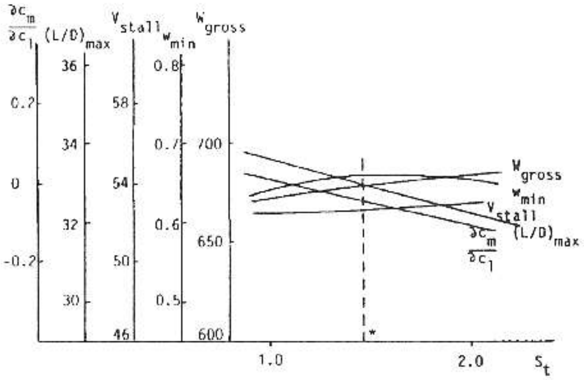

FIGURE 6. Performances with the effect of horizontal tail area.

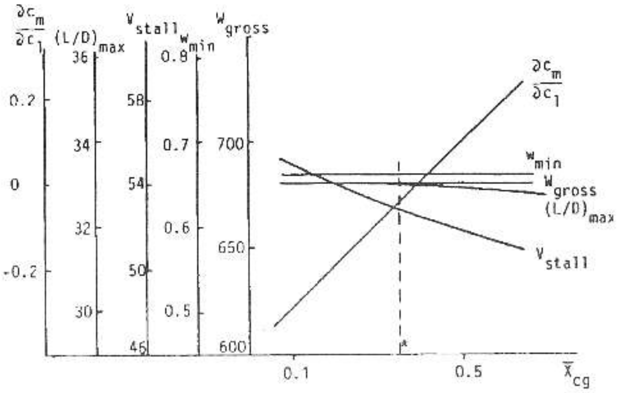

FIGURE 7. Performances with the effect of aft-most center-of-gravity.

5. CONCLUDING REMARKS

A constrained parameter optimization technique for the preliminary design of an optimal configuration of glider has been performed. A result of this study has shown that gross weight can be a robust, rich performance index, being used as a figure-of-merit for numerical optimizations. This index has the advantage of being useful as an indication of conceptual design for the glider.

The prime advantages the program has over other optimizations for airplane (glider) design are that it:
1) includes airplane geometric parameters as independent design variables;
2) has a moderately extensive set of industry statistics for weight;
3) contains a fair representation of the drag aerodynamics;
4) generates stability and control derivatives for flight-quality analyses;
5) includes a model for the interference effects between wing and tail;
6) iterates non-linear force and moment equations to satisfy longitudinal trim requirements;
7) contains a set of equations of motion for both performance and flight quality analyses.

As a means of illustrating its use as a conceptual design tool, direct optimization is used to perform a sensitivity study on parameter variations for a variety of design constants and constraint functions. The optimal design in terms of aircraft geometry is shown to be sensitive to the design. Seeing the sensitivities about the parameters for the baseline configuration, the designer can make some initial decisions about potential changes at the preliminary design stage.

6. REFERENCES

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DESIGN AND WIND TUNNEL TESTS OF AN AIRFOIL FOR THE HORIZONTAL TAILPLANE OF A STANDARD CLASS GLIDER

In the above paper, by L.M.M. Boermans and F. Bennis, published in Volume 16, No. 2, the table of ordinates was incomplete. The complete table for this paper is as follows:

TABLE 1. Cordinates of DU86-137/25

100.000	0.000	44.559	6.790	.047	-.301	50.084	-6.582
99.871	.014	41.606	6 846	.294	-.696	53.040	-6.426
99492	.056	38.678	6.864	.764	-1.091	55.980	-6.228
98.880	.124	35.786	6.844	1.435	-1.502	58.894	-5.984
98.043	.219	32.941	6.788	2.290	-1.925	61.773	-5.691
96.988	.341	30.155	6.697	3.318	-2.352	64.612	5.347
95.722	.488	27.439	6.571	4.516	-2.770	67.410	-4.950
94.254	.661	24.803	6.411	5.882	-3.181	70.167	-4.506
92.592	.860	22.256	6.217	7.410	-3.583	72.880	-4.019
90.745	1.084	19.809	5,992	9.093	-3.972	75.554	-3.500
88.721	1.332	17.471	5.735	10.924	-4.348	78.191	-2.970
86.531	1.605	15.249	5.448	12.894	-4.708	80.775	-2.457
84.183	1.902	13.152	5.132	14.994	-5.048	83.286	-1.981
81.686	2.223	11.186	4.791	17.216	-5.364	85.696	-1.553
79.037	2.571	9.359	4.425	19.552	-5.655	87.982	-1.179
76.229	2.984	7.677	4.039	21.944	-5.918	90.121	-.862
73.352	3.541	6.146	3.636	24.533	-6.151	92.092	-.604
70.546	4.177	4.774	3.218	27.157	-6.351	93.875	-.398
67.796	4.723	3.565	2.788	29.857	6.517	95.455	-.242
65.012	5.168	2.524	2.349	32.625	-6.646	96.821	-.128
62.179	5.555	1.656	1.904	35.450	-6.736	97.963	-.058
59.305	5.881	.964	1.457	38.323	-6.788	98.855	-.030
56.394	6.154	.453	1.015	41.232	-6.799	99.488	-.017
53.454	6.379	.138	.578	44.169	-6.768	99.870	-.004
50.494	6.558	.007	.131	47.124	-6.695	100.000	0.000
47.526	6.695						