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COMPARISON OF GLOBAL OPTIMIZED SHAPES OF FLYING CONFIGURATIONS WITH THOSE OF GLIDING BIRDS

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Abstract. The determination of global optimized (GO) shape of a flying configuration (FC) (namely, the simultaneous optimization of its camber, twist and thickness distributions and also of the similarity parameters of its planform) leads to an enlarged variational problem with free boundaries. An own optimum-optimorum (OO) theory was developed in order to solve this enlarged variational problem. According to this OO theory the GO shape of FC is searched inside of a class of elitary FCs defined by their common chosen properties. A lower limit hypersurface of the drag coefficients of elitary FCs versus the corresponding set of similarity parameters of their planforms is defined. The elitary FCs corresponding to the optimum set of similarity parameters, which is obtained by the numerical determination of the position of the minimum of this hypersurface is, at the same time, the GO FC of the set. The GO shapes of FCs, designed by the author, according to her OO theory, are compared with the shapes of gliding birds. The transversal cuts of the GO FCs look like those of gliding birds and also their behaviors, by changing of start values of optimization one by one, are similar because nature optimizes too.

1 INTRODUCTION

The determination of the GO shape of a FC (namely, which has its camber, twist and thickness distributions and also the similarity parameters of its planform simultaneously optimized, with respect to minimum drag at cruise) leads to an enlarged variational problem with free boundaries. The GO shape of FC is chosen among a class of elitary FCs, optimized for different fixed values of the similarity parameters of their planforms. The class of elitary FCs is defined by their chosen common properties, namely their surfaces are expressed in form of superpositions of homogeneous polynomes in two variables with free coefficients and with the same maximal degree, their planforms are polygones, which can be related by affine transformations and they all fulfill the same constraints.

A lower-limit hypersurface of the inviscid drag functional $C_d^{(i)}$ as function of the similarity parameters ν_i of the planform is defined, namely:

$$(C_d^{(i)})_{opt} = f(\nu_1, \nu_2, ..., \nu_n). \quad (1)$$

Each point of this hypersurface is obtained by solving a classical variational problem with given boundaries (i.e. a given set of similarity parameters). The position of the minimum of this hypersurface, which is numerically determined, gives us the best set of the similarity parameters and the FC's optimal shape, which corresponds to this set, is at the same time the global optimized FC's shape of the class.

A class of GO FCs, which look like gliding birds in transversal sections, it is: they are convex in their frontal parts and have wave forms at their rear parts, is obtained, if the Kutta condition (namely, the pressure equalization along the subsonic leading edges) and the integration conditions (the FCs have the same tangent planes along the junction lines wing-fuselage, wing-leading edge flaps) are introduced among the constraints of these enlarged variational problems like in [1].

2 DETERMINATION OF THE GLOBAL OPTIMIZED AND FULLY-INTEGRATED SHAPE OF WING – FUSELAGE CONFIGURATION

The enlarged variational problem of the determination of the inviscid GO shape of the integrated wing-fuselage FC is now considered. It shall have a minimum inviscid drag, at cruising Mach number, M_∞. This FC is treated like an equivalent integrated delta wing, fitted with two artificial ridges, which are located along the junction lines between the wing and the fuselage. The downwash w on the thin component of this integrated FC is supposed to be continuous and expressed in the form of a superposition of homogeneous polynoms in two variables, namely:

$$w = \tilde{w} = \sum_{m=1}^{N} \tilde{x}_1^{m-1} \sum_{k=0}^{m-1} \tilde{w}_{m-k-1,k} |\tilde{y}|^k \quad . \quad (2)$$

The downwashes w^* and $\overline{w}'^*$ on the wing and on the fuselage zone are expressed in form of two different superpositions of homogeneous polynoms:

$$w^* = \tilde{w}^* = \sum_{m=1}^{N} \tilde{x}_1^{m-1} \sum_{k=0}^{m-1} \tilde{w}^*_{m-k-1,k} |\tilde{y}|^k \quad , \qquad \overline{w}'^* = \overline{w}^* = \sum_{m=1}^{N} \tilde{x}_1^{m-1} \sum_{k=0}^{m-1} \overline{w}^*_{m-k-1,k} |\tilde{y}|^k \quad . \quad (3a,b)$$

$$\left(\tilde{x}_1 = \frac{x_1}{h_1} \ , \quad \tilde{x}_2 = \frac{x_2}{\ell_1} \ , \quad \tilde{x}_3 = \frac{x_3}{h_1} \ , \quad \tilde{y} = \frac{y}{\ell} \ , \quad \ell = \frac{\ell_1}{h_1} \ , \quad \nu = B\ell \ , \quad B = \sqrt{M_\infty^2 - 1} \right)$$

The coefficients $\tilde{w}_{m-k-1,k}$, $\tilde{w}^*_{m-k-1,k}$ and $\overline{w}^*_{m-k-1,k}$, together with the similarity parameters ν

and $\bar{\nu} = Bc$ of the planforms of entire FC and of the fuselage of the integrated FC, are the free parameters of optimization and ℓ_1 and h_1 are the half-span and the maximal depth of this FC. The quotient $k = \bar{\nu} / \nu$ between the similarity parameters of the planforms of the fusrlage and of the wing of this FC depends on the purpose of FC and is here considered constant.

The corresponding axial disturbance velocities u and u^* on the thin and thick-symmetrical components of the FC, obtained by the author, by using the hydrodynamic analogy of Carafoli and the principle of minimal singularities (which fulfill the jumps along the singular lines) are, as in [1], it is:

$$u = \ell \sum_{n=1}^{N} \tilde{x}_1^{n-1} \left\{ \sum_{q=1}^{E\left(\frac{n-1}{2}\right)} \tilde{C}_{n,2q} \tilde{y}^{2q} \cosh^{-1} \sqrt{\frac{1}{\tilde{y}^2}} + \sum_{q=0}^{E\left(\frac{n}{2}\right)} \frac{\tilde{A}_{n,2q} \tilde{y}^{2q}}{\sqrt{1-\tilde{y}^2}} \right\} , \tag{4}$$

$$\begin{aligned} u^* = \ell \sum_{n=1}^{N} \tilde{x}_1^{n-1} \Bigg\{ & \sum_{q=1}^{E\left(\frac{n-1}{2}\right)} \tilde{C}^*_{n,2q} \tilde{y}^{2q} \cosh^{-1} \sqrt{\frac{1}{\nu^2 \tilde{y}^2}} + \sum_{q=0}^{E\left(\frac{n-2}{2}\right)} \tilde{D}^*_{n,2q} \tilde{y}^{2q} \sqrt{1-\nu^2 \tilde{y}^2} \\ & + \sum_{q=0}^{n-1} \tilde{H}^*_{nq} \tilde{y}^q \left[\cosh^{-1} M_1 + (-1)^q \cosh^{-1} M_2 \right] \\ & + \sum_{q=0}^{n-1} \tilde{G}^*_{nq} \tilde{y}^q \left[\cosh^{-1} N_1 + (-1)^q \cosh^{-1} N_2 \right] \Bigg\} . \end{aligned} \tag{5}$$

$$\left(M_{1,2} = \sqrt{\frac{(1+\nu)(1 \mp \nu\, \tilde{y})}{2\nu(1 \mp \tilde{y})}} \ , \quad N_{1,2} = \sqrt{\frac{(1+\bar{\nu})(1 \mp \nu\, \tilde{y})}{2(\bar{\nu} \mp \nu\, \tilde{y})}} \right)$$

For a given value of ν, the optimization of the shapes of its thin and thick-symmetrical components can be separately treated. The constraints of the determination of the inviscid GO shape are: the given lift, pitching moment and the Kutta condition along the subsonic leading edges of the thin FC component (in order to cancel the induced drag at cruise and to suppress the transversal conturnement of the flow around the leading edges, in order to increase the lift) and the given relative volumes of the wing and of the fuselage zone, the cancellation of thickness along the leading edges and the new introduced integration conditions along the junction lines between the wing and fuselage zone of the thick-symmetrical FC component (in order to avoid the detachment of the flow along these lines).

The similarity parameter ν of the planform of FC is sequentially varied and the inviscid drag functional of optimal FCs, for each corresponding value of ν, is obtained by solving a classical variational problem with fixed boundaries and a lower limit-line of the inviscid drag functional of elitary FCs, as function of this similarity parameter ν, is determined (for FCs with subsonic leading edges, it is: $0 < \nu < 1$). The position of the minimum of this limit-line gives the optimal value of the similarity parameter $\nu = \nu_{opt}$ and the corresponding elitars FC is, at the same time, the global optimized FC of the class.

The inviscid GO shape of the model Fadet I, designed by the author, is presented in the (Fig. 1), as exemplification.

Fig. 1 The Global Optimized Model Fadet I at Cruising Mach Number $M_\infty = 2.2$

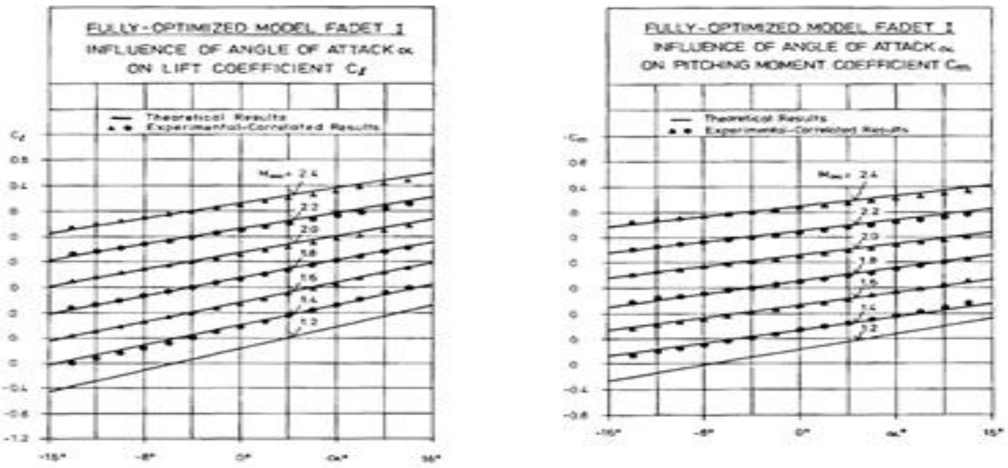
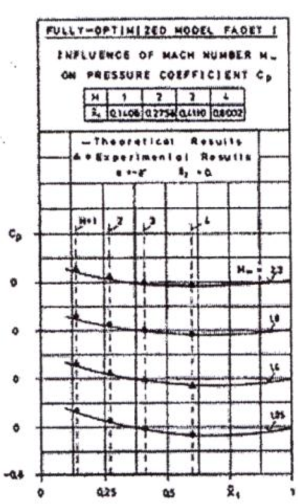
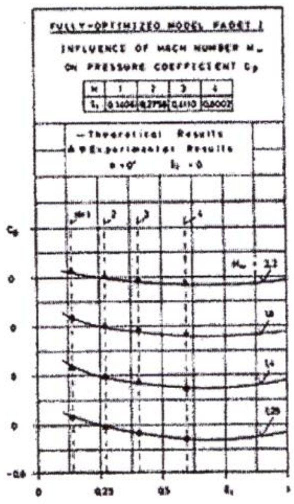


Fig. 2a,b The Lift and Pitching Moment Coefficients of the Model Fadet I

The aerodynamic performances of the Model Fadet I were measured in the trisonic wind tunnel of DLR Cologne, in the frame of some research contracts of the author, sponsored by the DFG. The measured lift and pitching moment coefficients are in very good agreements with the theoretical results as it can be seen in the (Fig. 2a,b) .





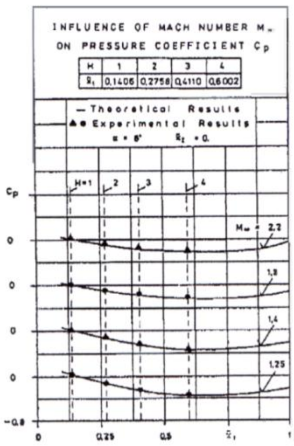


Fig 3a-c The Agreement Between the Measured and the Computed Pressure Coefficients in the Central Longitudinal Section of Model Fadet I for the angles of attack $\alpha = -8^{\circ},\ 0^{\circ},\ 8^{\circ}$

The agreement between the experimental and theoretical values of the pressure coefficients along the central longitudinal section by different angles of attack is given in the (Fig 3a-c).

3 THE CHANGE OF THE GO SHAPE OF FC, DUE TO THE MODIFICATION OF THE START VALUES OF OPTIMIZATION

Now the following start values of the global optimization, namely the chosen cruising Mach number and the given lift and pitching moment coefficients are changed one by one and the corresponding changes of the GO shapes of FCs are analyzed and compared with those of gliding birds.

Let us firstly consider two GO shapes of FCs with the same area of their planforms and with the same constraints, like the GO shapes of the fully-integrated models Fadet I and Fadet II, designed by the author and presented in the (Fig. 4a,b). These GO shapes are of minimum drag, at two different cruising Mach numbers: $M_\infty = 2.2$ and, respectively, $M_\infty = 3$. If the cruising Mach number increases, the maximal depth of the planform and the camber and twist of the GO surface of FC increase and its span decreases. The influence of the cruising Mach number over the similarity parameters of the planform is important. Therefore the multipoint global optimal design of the GO shape of FC, at two different cruising Mach numbers over the sea and land, can be successfull realized only by morphing of the shape. The use of GO FCs with movable leading edge flaps was proposed, as in [1]-[3]. The GO FC flies with the flaps in retracted position, at the higher cruising Mach number and with flaps in stretched position, at a lower Mach number. Two enlarged variational problems occur. The first one consists in the determination of the GO shape of the FC with the retracted flaps, which is of minimum drag at the higher cruising Mach number and the second one consists in the determination of the GO shapes of the stretched flaps, in order that the entire FC with stretched flaps is of minimum drag at the second, lower cruising Mach number, as in [1]- [3].

- This GO shape of FC, fitted with movable leading edge flaps, can fly with subsonic leading edges with flaps in retracted position, which has a smaller aspect ratio at higher cruising Mach number. The GO FC with stretched flaps has an augmented lift not only by the second lower cruising Mach number but also by take-off and by landing. Consequently, it needs less fuel consumption, needs shorter runways and/or can transport more passengers.

The gliding birds optimized their flight by different speeds also by morphing. They fly with smaller aspect ratio when they are gliding at higher speed and with stretched wings when they are gliding at lower speed and by take-off and by landing.

In the (Fig. 5a,b) are compared the GO shapes of two thin FCs, with respect to minimum drag for two different values of the given lift coefficients. The both FCs are flying at the same cruising Mach number, have the same pitching moment and relative thickness and the same area of their planform. The increase of the lift coefficient produces modifications of the GO shape of FC, especially in its rear part. The camber and the twist increase at its central part and decrease their values in the vicinity of leading edges. The values of the lift and pitching moment coefficients have a limited degree of freedom. The quotient pitching moment/lift must be inside of the following lower and upper limits:

$$\frac{2}{3} < \frac{C_\ell}{C_m} < \frac{N+1}{N+2} \tag{6}$$

Hereby is N the degree of the highest polynom taken into consideration in the superpositions of homogeneous polynoms of downwashes.

In the (Fig. 6a,b) are compared the GO shapes of two thin FCs, with respect to minimum drag for two different values of the given pitching moment coefficients. The both FCs are flying at the same cruising Mach number, have the same lift and relative thickness coefficients and the same area of their planform. The increase of the pitching moment coefficient produces modification, especially in the rear part of the GO shape of FC. Its camber and twist increase in the vicinity of its leading edges and they present small decrease in the central part of its GO shape. The tendency of the modifications of the GO shape of FC, by increasing pitching moment coefficient, is opposite to the tendency by increasing lift coefficient. Due to the limited degree of freedom, the quotient pitching moment/lift must be inside of the lower and upper limits given above.

Fig. 4a,b The Global Optimized and Fully-Integrated Shapes of the Models Fadet I and Fadet II

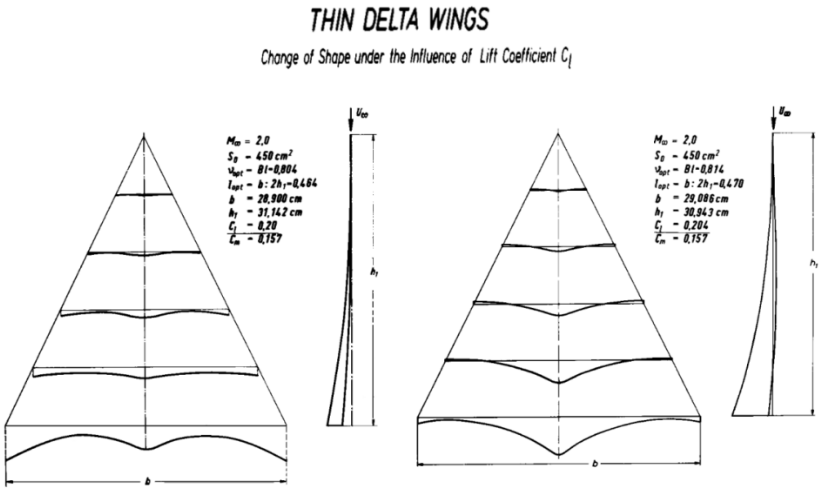


Fig. 5a,b The Modifications of the GO Shape of FC, Due to the Increased Value of the Lift Coefficient

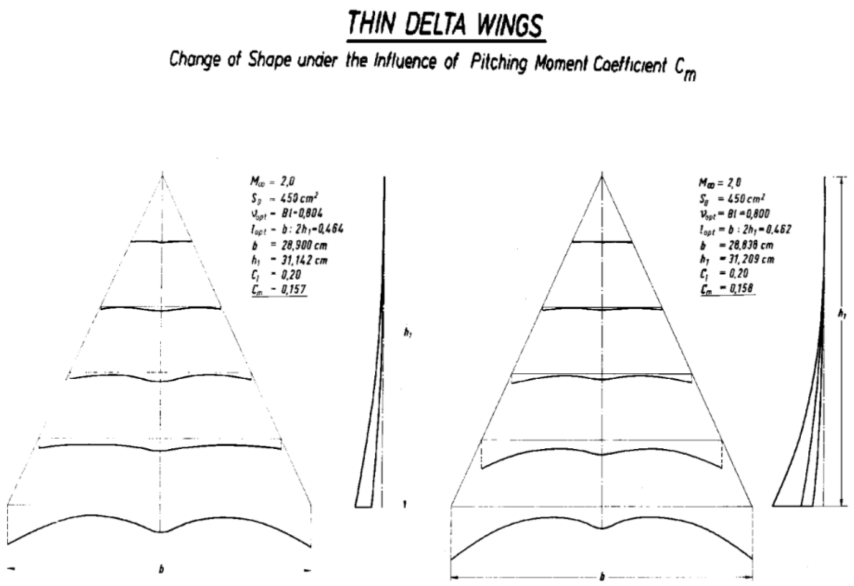


Fig. 6a,b The Modifications of the GO Shape of Thin FC, Due to the Increased Value of the Pitching Moment Coefficient

4 CONCLUSIONS

- The GO shapes of FCs models, designed by the author (Adela, Fadet I and Fadet II), are convex in the transversal sections of the frontal part and have a wave shape at the rear part, like the transversal sections of gliding birds.
- The cruising Mach number has a great influence over the optimal planform of the shape of the GO FC. If the area of the planform is constant, the optimal aspect ratio decreases when the cruising Mach number increases. It suggests the morphing of the part of GO shape of FC by using movable leading edge flaps. The morphing by using movable leading edge flaps allows the FC with retracted flaps to fly with subsonic leading edges also at higher Mach number and to be adapted at two cruising Mach numbers. The gliding birds adapt similarly their shape to the speed of their flight, by morphing. They fly at higher speed with retracted wings and at lower speed with stretched wings.
- The increase of lift produces an increase of camber and twist, especially in the central rear part of the GO shape of the FC and decrease of their values in the vicinity of the leading edges of the wing.
- The increase of pitching moment coefficient produces opposite changes of optimal camber and twist of the GO shape of FC as for the increase of lift coefficient, namely, the camber and the twist increase also especially in the rear part, but in the

vicinity of the leading edges and decrease in its central rear part.

- The gliding birds and the GO shape of the FCs have also not only the similar transversal shape but also the same behaviors by the change of start parameters of optimization.

REFERENCES

[1] Nastase A. *Computation of supersonic flow over flying configurations*. Elsevier, Oxford, UK (2008).

[2] Nastase A. Multipoint and iterative aerodynamical global shape optimization, *Proc. of EUROGEN 2011, Capua, Italy,* Paper 30, (2011).

[3] Nastase A. An extended variational method for the global optimal design of the shape of flying configurations, in supersonic flow. *Proc. of ECCOMAS Conference on CFD and Optimization, Paper 023, Antalya, Turkey* (2011).