

Flap Optimization for Take-off and Landing

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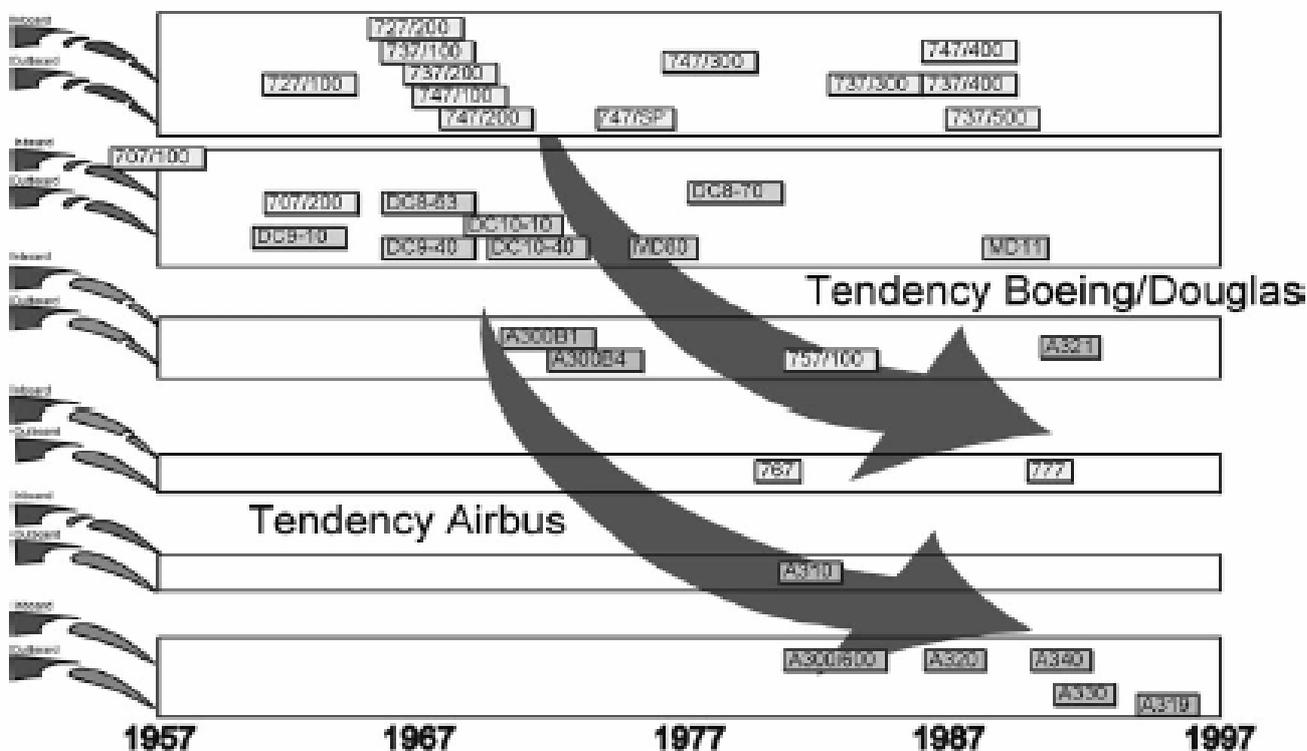
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Abstract. The present work develops a methodology for the selection of the optimal deflection and geometry of the trailing edge flap for a specific application. The optimized design of a slotted flap is the result of a process that includes the knowledge of the effects of the flap on the airplane lift and drag, and preliminary verification of the performance of the aircraft during the takeoff and landing phases. After the optimal deflection for takeoff and for landing was calculated, a CFD code was employed to modify the original airfoil and flap configuration in order to improve aerodynamic efficiency. This procedure was applied to a regional transport airplane and preliminary results were obtained. The best flap configuration was obtained for takeoff and landing. A considerable time and effort were dedicated in the process of correctly using these tools.

Keywords. Flap, optimization, take-off, landing

1. Introduction

The evolution of Boeing, Douglas and Airbus high-lift wing trailing edge concepts from B707 until today is showed in Fig. 1, (Reckzeh, 2002). The upper cross-section in each pair is the inboard configuration, while the lower one is the outboard configuration.



The effort is visible to reach a design fulfilling the aerodynamic requirements with minimum system complexity. While B727, B737 and B747 designs contained triple slotted flaps, double slotted flaps are applied on B757. B767 and B777 have a combination of double slotted and single slotted flaps. The Airbus wings contain double slotted flaps on A300 and A310 while the later designs A300-600, the A320-family (with the exception of the stretched A321) and A330/A340 work with full span single slotted flaps.

High lift leading edge devices have been the subject of research and development since as far back as 1917 (Heap and Crowther, 2003). Handley Page achieved a lift increase of 25% with a span wise slot cut parallel to the leading edge. An improvement in the shape of the slot in a different airfoil produced an increase in lift of 50% (Heap and Crowther, 2003).

Several flow control technologies have been reviewed that delay separation of the boundary layer from the airfoil surface. An increase in CL_{max} of 210% has been cited for the moving surface boundary layer control, (Reckzeh, 2002). Progressions in the understanding of aerodynamic theory, from Handley Page to Smith to Van Dam, have been assisted by more powerful computers and increased computing power has enabled 3 dimensional CFD analyses to reduce design time.

The development of concepts for realization of a feasible system is currently ongoing in the German national funded program ProHMS. In this program the development of a multidisciplinary solution (aerodynamics, systems, structures) is currently undertaken for a future aircraft design as possible replacement of the A300/A310, (Reckzeh, 2002).

In the development of previous Airbus high-lift wings the major work was based on wind tunnel experiments. Theoretical methods suited for the use under the tight time constraints of the design process were only available for 2D-section design in the past. The assessment and optimization of the 3D-wing was then performed on experimental basis.

Several methods were established in the last years including an advanced 3D panel-method, and a 2D Navier-Stokes method. Also successful applications of automated optimization tools coupled with a 2D-Navier-Stokes code were made, (Reckzeh, 2002).

Besides the CFD methods, wind tunnel experiments are of critical importance to assess the performance characteristics of the theoretically designed high-lift wings as well as the final configuration selection.

Evaluating the possibilities of those methods it is clear that they will gain a great importance already in near future.

2. High-Lift Devices

Wing trailing-edge devices evolved from plain flaps to Fowler flaps with single, double, and even triple slots.

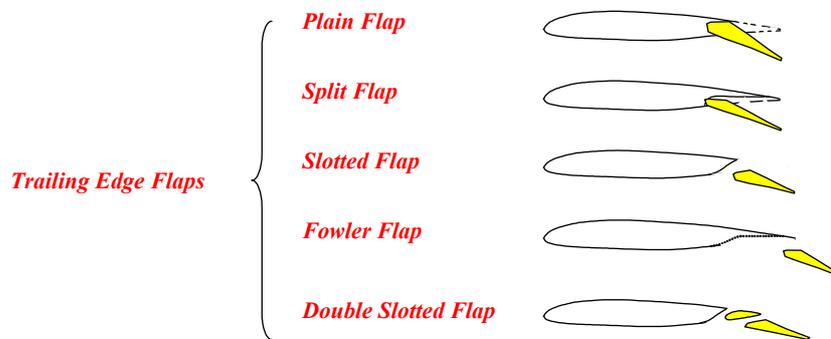


Figure 2. Trailing-edge flaps examples, (McCormick, 1994).

The additional wing lift contributed by high-lift devices is basically obtained through:

- increased airfoil camber;
- boundary layer control resulting from improved pressure distributions, reenergizing or removing low energy boundary layers;
- an increment of the effective wing area in the case of flaps extending the chord when deflected.

Not all existing configurations combine these actions simultaneously. Trailing-edge flaps increase the camber and improve the flow at the trailing-edge, but tend to promote leading-edge stall on thin sections and may cause a reduction in the stalling angle of attack. Leading-edge high-lift devices postpone or eliminate leading edge stall, but they have little effect on the airfoil camber as a whole, although locally the camber is increased. Figure 2 shows that these differences result in large variations, in the range of operational angles of incidence, at low speeds.

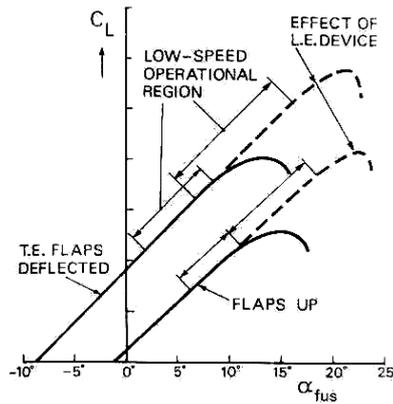


Figure 3. Lift curves with and without high-lift devices, (Torenbeek, 1982).

Most flap systems are offered with a choice of several discrete deflection angles. Deflections of up to about 25 degrees are used on take-off, while higher values are used during the approach and landing. For each item of performance there is an optimum flap angle which constitutes a tradeoff between high lift and low drag. Though the operational flexibility of the aircraft is improved by increasing the freedom of choice, the cost and time involved with the certification tests and data handling may become prohibitive, (Torenbeek, 1982).

3. Prediction of the airplane drag polar at low-speed in the take-off or landing configuration

The drag of aircraft with flaps down, undercarriage extended and one engine failure can be obtained from the drag polar in the clean configuration as follows, (Torenbeek, 1982).

$$C_D = C_{D_0} + \frac{C_L^2}{\pi A e} + \Delta_f C_{D_p} + \Delta_f C_{D_v} + \Delta_{trim} C_D + C_{D_{uc}} + \Delta C_{D_{OEI}} \quad (1)$$

4. Optimization analysis of aircraft operating characteristics

Take-off field length for example:

Analysis of the take-off characteristics is the most complicated item of performance; this applies particularly to transport aircraft, where the possibility of engine failure must be considered, (Torenbeek, 1982).

In order to examine the operational flexibility and to optimize the performance, the effect of several variables must be considered. One of the most important variables is the position of the high-lift devices.

Increasing the flap deflection angle results in increased values of C_L for stalling and liftoff; V_S and V_2 will consequently decrease and the take-off run will be shortened. However, the L/D ratio and the climb gradient deteriorate, and the airborne distance increases.

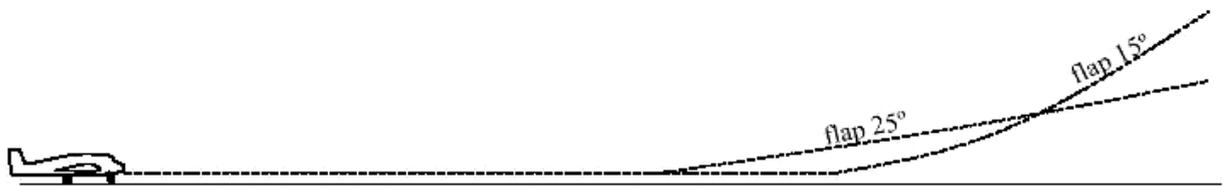


Figure 4. Influence of flap deflection in the takeoff distance, (Torenbeek, 1982).

For a given T/W ratio, an optimum flap angle can be defined, resulting in a minimum field length. The flap deflection is limited by the climb requirements with one engine failed and for low T/W the optimum flap angle is not feasible, (Torenbeek, 1982), see Fig. 5.

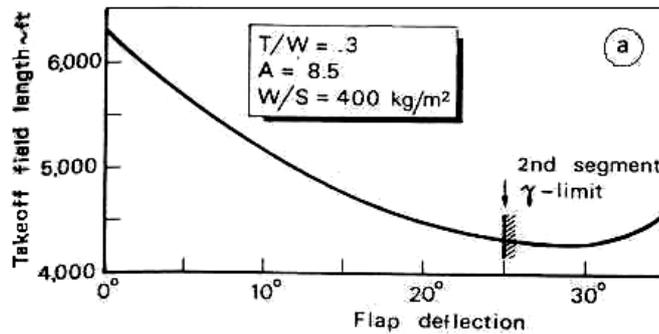


Figure 5. Effect of flap deflection on take-off performance, (Torenbeek, 1982).

4.1. Climb Performance

The airworthiness requirements for each airplane category specify the minimum permissible climb performance, with and without engine failure. A summary for turbine-powered transport aircraft is presented in Fig. 6.

PHASE OF FLIGHT	AIRPLANE CONFIGURATION					MINIMUM CLIMB GRADIENT (%)			
	flap setting	u.c.	engine thrust (power)	speed	altitude	Ne = 2	Ne = 3	Ne = 4	
TAKEOFF CLIMB POTENTIAL ("first segment")	takeoff	↓	one engine out	takeoff	V _{LOF}	0 → h _{uu1})	0	0.3	0.5
TAKEOFF FLIGHT PATH	"second segment"	↑		takeoff	V ₂	h _{uu} → 400ft	2.4	2.7	3
	final takeoff ("third segment")	↑		max. cont.	V ≥ 1.25V _s	400 → 1500ft	1.2	1.5	1.7
APPROACH CLIMB POTENTIAL	approach	↑		takeoff	V ≤ 1.5V _s	0 1)	2.1	2.4	2.7
LANDING CLIMB POTENTIAL	landing	↓	all engines takeoff	V ≤ 1.3V _s	0 1)	3.2	3.2	3.2	
Nomenclature: V _{LOF} - liftoff speed V ₂ - takeoff safety speed V _R - rotation speed V _s - stalling speed h _{uu} - height at which u.c. retraction is completed Ne - number of engines per a/c u.c.- undercarriage position			1) out of ground effect 2) flap setting such that V _s ≤ 1.10 V _s for landing 3) more precisely: the engine power (thrust) available 8 seconds after throttle opening to takeoff rating						

Figure 6. Summary of climb requirements for turbine-powered transport category aircraft (FAR 25), (Torenbeek, 1982).

5. Single Slotted Flaps

A typical single-slotted-flap configuration is shown in Fig. 7:

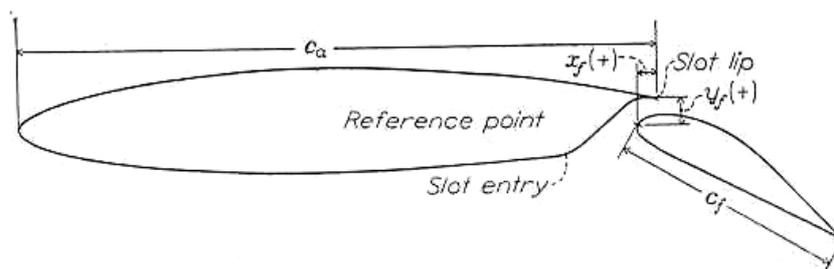


Figure 7. Sketch of typical single-slotted-flap configuration. (All dimensions are given in fractions of airfoil chord). (Cahill, 1948)

The part of the wing upper surface which extends over the flap when retracted is called the slot lip. The effective increase in chord provided by some slotted flaps is obtained by the use of an elongated slot lip. The point where the airfoil is first cut away to form the slot on the lower surface is called the slot entry. Slot entries are often made with very small radii of curvature or provided with skirts to fair over the gap in the lower surface when the flap is retracted.

Since a slotted flap increases the maximum lift by a combination of increased camber, increased chord, and boundary-layer control provided by flow through the slot, the important design parameters are flap deflection, flap size, the chord wise position of the slot lip, and the efficiency of the flow through the slot in providing boundary-layer control, (Cahill,1948).

Slotted flaps are shown to provide higher maximum lift coefficients than any of the other devices (plain flaps and split flaps). Increases in total chord are shown to provide increases in maximum lift coefficients of single slotted flaps, whether obtained by increasing the flap size or increasing the slot-lip extension. Sharp corners or skirt extensions at the slot entry are shown to reduce the maximum lift coefficients of thick airfoils with slotted flaps although the entry condition seems to have little effect on the maximum lift coefficients of thin airfoils with slotted flaps. Bending down the slot lip to direct the air flow down over the flap has been shown to have an advantageous effect on maximum lift coefficient. Data that are available seem to indicate that flap noses should have shapes similar to those of good airfoil sections. The best positions of single slotted flaps are not so well defined. Maximum lift coefficients of both single and double slotted flaps are very sensitive to flap position, however, and optimum configurations cannot be predicted with any degree of accuracy, (Cahill,1948).

Drag of airfoils with both single and double slotted flaps are lower than those of airfoils with plain or split flaps because the separation of the flow over the flap at relatively low deflections is prevented by the boundary-layer-control action of the slots. At a given lift coefficient, the drag of airfoils with slotted flaps is lowered if either the flap size or the slot lip extension is increased, (Cahill,1948).

6. Methodology / Tools

The methodology for the design of the ideal flap can be divided in three very different phases:

- Determination of the curves C_L vs. α and C_D vs. C_L as much as for the cruise configuration as for the takeoff configuration and landing;
- Determination of the “ideal” deflections of the flap that allow the aircraft to take off and to land with the smallest field length;
- Determination of the final geometry of the profile with flaps, in a way to present the best aerodynamic characteristics, using software of CFD (Computational Fluid Dynamics).

In the first phase a program was elaborated based on the software MATLAB® 6.1 and in the method of calculation of Torenbeek (1982).

In the second phase of the methodology, it was also elaborated, a program developed in the software MATLAB® 6.1 based on the calculation method described by Torenbeek (1982), with the intention of obtaining the takeoff distance for twin engine aircraft for such conditions as single engine failure. The command “fmincon” of MATLAB was used to minimize the function (takeoff distance) and to obtain the ideal value of flap deflection.

The third and last phase of the development of the design of the optimized flaps consists of the use of the MSES code (Drela, 1996) of finite volumes to solve the Euler equations and momentum equations for no viscous flow, with boundary-layer correction of iterative form.

Obtaining through MSES the configuration of the profile with the flap configuration that presents the best aerodynamic characteristics, one can return to the program developed in MATLAB to obtain the three-dimensional aerodynamic characteristics of the aircraft and to determine the new drag polar of airplane.

The new “ideal” flap deflection, for takeoff and landing of the aircraft should be obtained through the feedback of the program developed in MATLAB with the new drag polar. Thus, it is noticed the importance of the iterative process among the phases of the methodology proposed to obtain the best flap design.

With this information, one can arrive at the configuration that presents the best aerodynamic characteristic and thus define and conclude the optimized design (preliminary) of the flap of the aircraft for the takeoff and landing operation. Schematic representation of the methodology for optimized design of the flap follows:

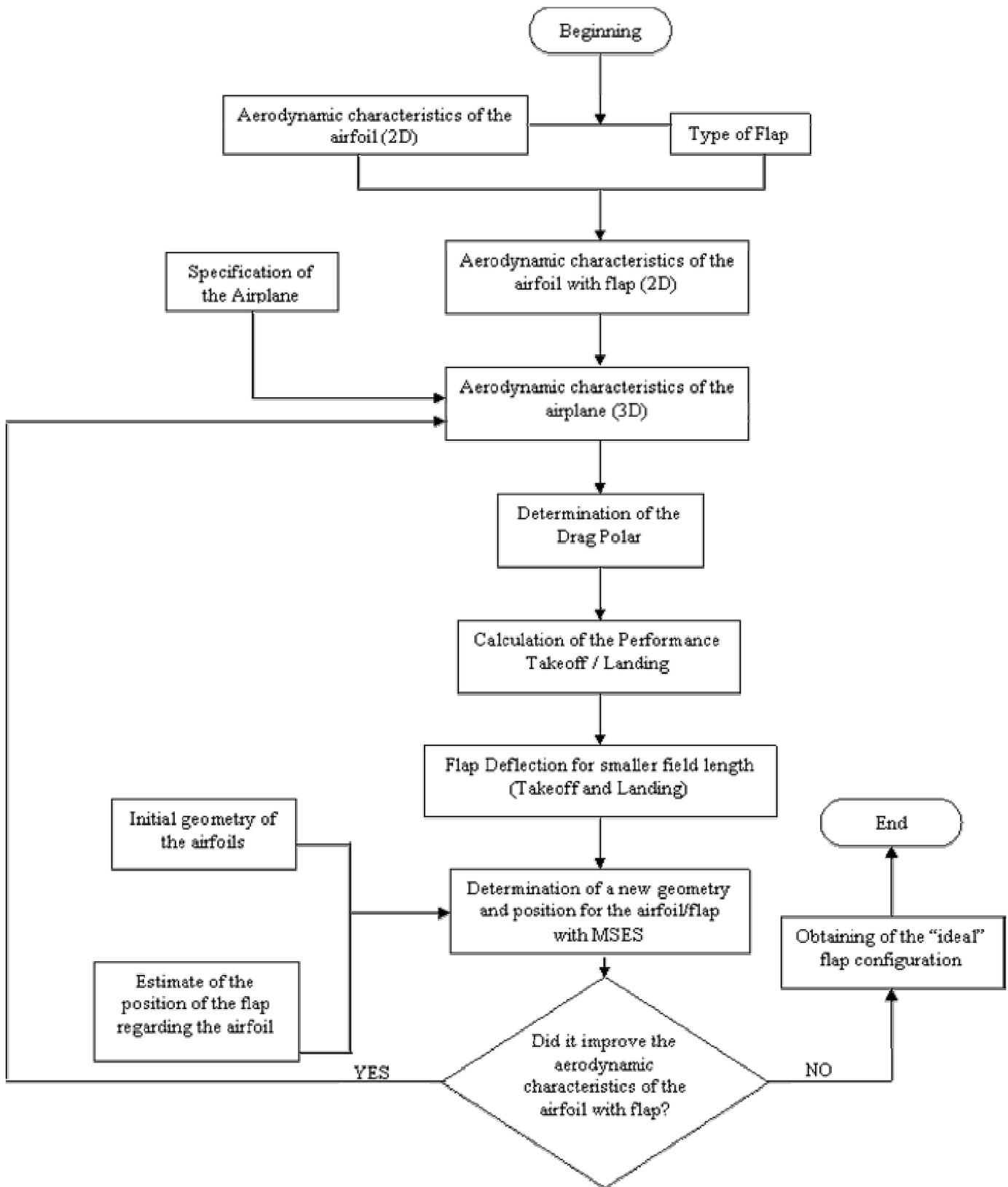


Figure 8. Schematic representation of the methodology for flap optimized design.

7. Results

Through the programs developed in MATLAB, the flap deflection that allows the aircraft to take off or land in the smallest field length is obtained, which obeys the minimums safety requirements imposed by FAR 25. In the takeoff, two cases were considered: all engines operative and one engine inoperative.

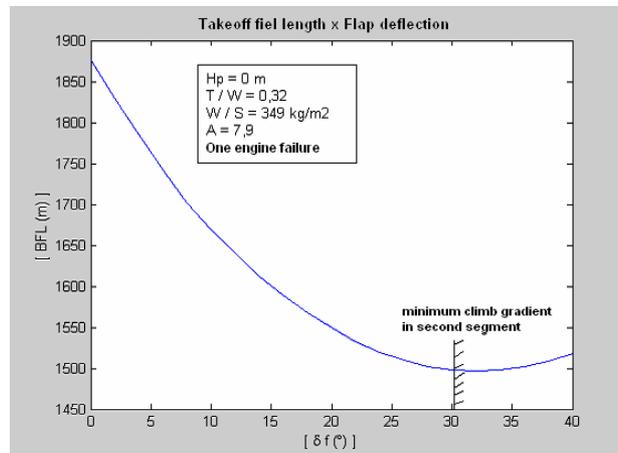


Figure 9. Effect of flap deflection on the takeoff distance with engine failure.

The figure above shows the effect of the flap deflection upon the takeoff field length. For a given T / W rate, an ideal flap deflection angle can be defined, resulting in a smaller takeoff field length. The flap deflection is limited by the climb gradient requirement with engine failure in the second segment.

The profile NLR 7301 with single slotted flap, whose experimental data are available (Tuncer and Eric, 1998), will be used to validate the results obtained by CFD.

This airfoil was projected by National Aerospace Laboratory NLR (The Netherlands), for incompressible flow in general aviation.

The airfoil equipped with 0.32c slotted flap deflected 20° , $Re = 2.51 \times 10^6$ and $Mach = 0.185$ was submitted a CFD analysis.

Values of L / D ratio, lift, drag and pitching moment coefficients were calculated for several angles of attack.

Single-slotted-flap information's:

- Basic airfoil: NLR 7301;
- Maximum thickness: $16.5\%c$;
- Airfoil chord (c): 570 mm;
- Flap chord: $32\%c$;
- Flap deflection: 20° ;
- Gap between the airfoil and flap: $2.6\%c$;
- Overlap between the airfoil and flap: $5.3\%c$;
- Transition of the laminar flow for the turbulent flow: free.

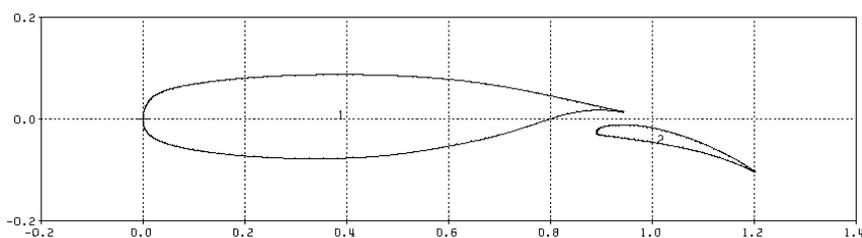


Figure 10. Airfoil NLR 7301 with flap.

Figures 11 and 12 show a comparison among the results obtained by wind tunnel experiments (Tuncer and Eric, 1998) and results obtained by computation methods (MSES) for the airfoil NLR 7301 with flap, described above. The objective of this comparison, is to validate the results obtained by the computation program MSES.

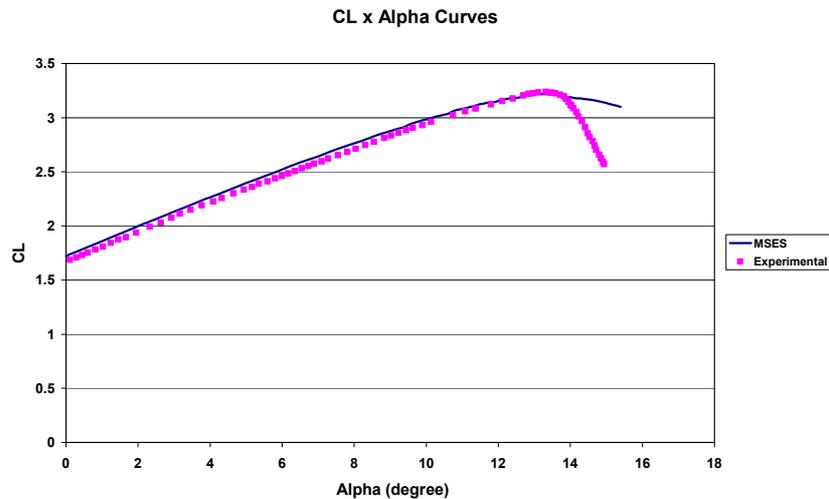


Figure 11. Comparison among the lift coefficients for several angles of attack obtained experimentally and by MSES.

In the MSES results, the leading-edge stall (abrupt stall due to the bubble caused by a high suction peak in the leading-edge) and the effect of a possible interference between the wakes of the airfoil boundary-layer on the flap boundary-layer are not considered. In spite of MSES showing the formation of an air bubble in the upper surface, this doesn't represent the leading-edge stall, but a softer trailing-edge stall. Already the results of wind tunnel tests show the occurrence of the leading-edge stall, common in that airfoil type. Therefore, the difference of lift-curve slop among the two curves after the stall is perfectly coherent and acceptable. The values of $C_{L,max}$ obtained between one method and the other, presented a difference of 0.6%.

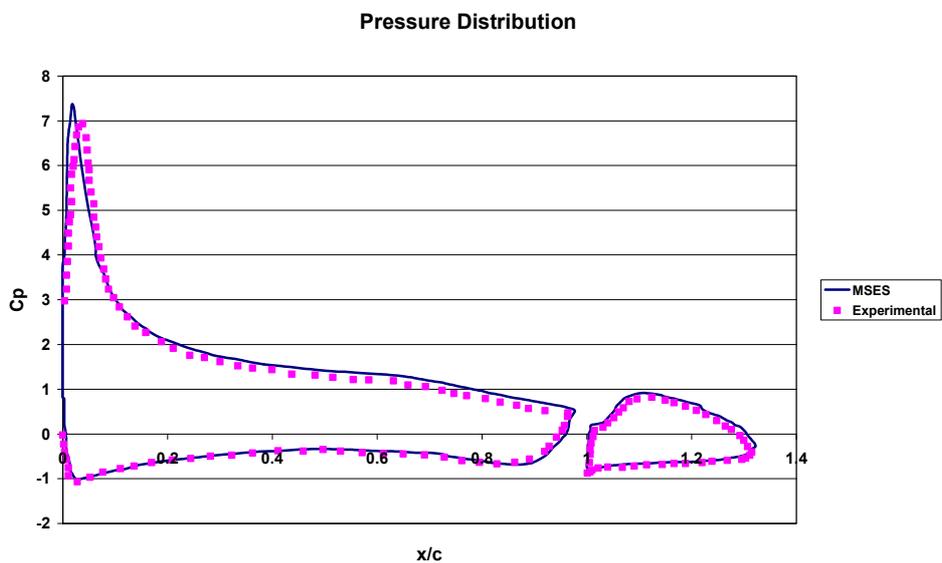


Figure 12. Comparison among the pressure distribution along the chord obtained experimentally and by MSES, $\alpha = 6^\circ$.

The values obtained between one method and the other for $C_{p,min}$ (suction peak), presented a difference of 4,5%. It is important to emphasize as well that the method of computation calculation and the experimental method are subject to errors (measurement errors). However, this difference among the methods is sufficiently small to be accepted in the preliminary phase of the project, as a way to validate the use of MSES to obtain the aerodynamic characteristics of airfoils with flaps. The authors like to emphasize that experimental data for greater angles of attack, near the stall condition, were not found. Thus, the preliminary results to be shown hereafter must be looked upon with caution.

Adopted the airfoil above as being “standard” (original airfoil), all of the airfoils modified with flap had their C_{Lmax} compared with C_{Lmax} of the “standard” airfoil. The modifications were regarding the relative position of the airfoil / flap, Reynolds number, slot lip, slot entry and size of the flap. The modifications were accomplished one per time in relation to the original through the AIRSET program (Mark, 1996). For the MPOLAR program, when varying the angle of attack from 0° to 15° , it was possible to obtain the $C_L \times \alpha$ curve and to determine C_{Lmax} for each airfoil with flap. Figure 13 and the Table 1, presented below, show the results obtained from MSES:

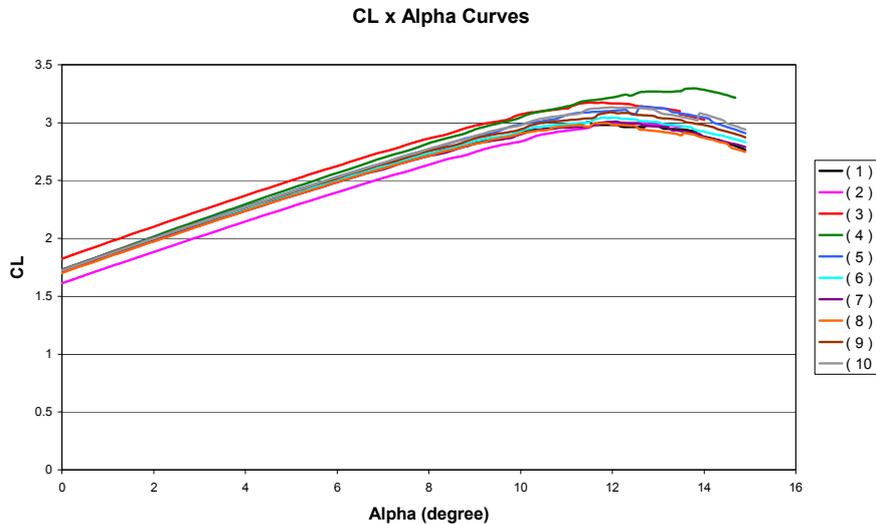


Figure 13. $C_L \times \alpha$ curves of the original airfoil and of their several modifications.

See table below to identify the indicated cases in the legend of Fig. 13.

Table 1. C_{Lmax} comparative table for the several versions of the airfoil with flap.

FLAP	MACH	Re	Δx	Δy	Size	L/Dmáx	CLmáx	Legend	
Original	0.2	2.10 ⁶	-----	-----	-----	117.7993	3.0036	(1)	
	0.2	8.10 ⁶	-----	-----	-----	-----	-----		
	0.2	14.10 ⁶	-----	-----	-----	-----	-----		
Modified Size	0.2	2.10 ⁶	0,6% -2,3%	0% 0,7%	10% smaller	117.589	3.0016	(2)	
	0.2	2.10 ⁶	-0,8% 2,5%	-0,03% -0,87%	10% larger	120.5795	3.174	(3)	
Relative Position between modified Airfoil/Flap	0.2	2.10 ⁶	5% -5%	0 0	-----	124.7847	3.296	(4)	
	0.2	2.10 ⁶	1% -1%	0 0	-----	120.6227	3.1374	(5)	
	0.2	2.10 ⁶	0 0	1% -1%	-----	119.46	3.0422	(6)	
	0.2	2.10 ⁶	-1% 1%	1% 1%	-----	117.7757	3.0091	(7)	
	0.2	2.10 ⁶	-1% 1%	-1% 1%	-----	115.9689	2.995	(8)	
	0.2	2.10 ⁶	1% 1%	1% 1%	-----	120.8533	3.0898	(9)	
	0.2	2.10 ⁶	1% 1%	-1% -1%	-----	120.0062	3.1327	(10)	
	Shorted Slot Lip	0.2	2.10 ⁶	-----	-----	-----	-----	-----	
	Stretched Slot Entry	0.2	2.10 ⁶	-----	-----	-----	-----	-----	

	Leading-edge
	Trailing-edge
	The greatest value of L/Dmax ratio and CLmax

It can be observed by the results obtained above, that the airfoil / flap configuration that supplies the largest value of C_{Lmax} and the largest L / D ratio happens when the flap is shifted back (5% c). This can be explained by the increase of the chord, in relation to the original airfoil with flap. It can be said therefore, that this airfoil / flap configuration is the best (“best” airfoil with flap configuration) for the takeoff condition ($\delta_f = 20^\circ$), because it presents the largest L / D ratio.

8. Conclusions

After presenting the methodology for flap designing optimized for transport aircrafts, it can be concluded that the proposed objective was reached.

The results obtained through the programs done in MATLAB to determine the aerodynamic characteristics and the optimized performance of the regional transport aircraft are coherent with the theoretical behaviors found in the literatures (K.C. Rudolph, 1996; Torenbeek, 1982; McCormick, 1994 and Anderson, 1984). However the effects in the aerodynamic characteristics of the airfoil with flap geometry / position altered were similar to those observed in experimental tests (Cahill, 1948).

Regarding the use of MSES as a tool to determine the cl_{max} of the airfoil with flap, it is observed that there are mathematical limitations, such as mistakes of the mesh frame, mistakes in the approach the differential equations, in algebraic equations, etc..., hindering their use for certain conditions and in many of them, generating doubtful results.

It is also concluded that a “intelligent” flap mechanism (double slotted flaps) should be used to provide a larger Fowler movement of the flap for low angles of deflection. This area increase, in the context of low flap angle, results in a better L / D ratio for takeoff.

The flap optimization is based on determining the best flap deflection to allow the aircraft to takeoff with the shortest field length possible, while respecting the minimum climb gradients. However, there are airports that have long fields and which require that the airplane depart as fast as possible from the aerial limits of the airport, to allow other aircraft to approach (airports with great air traffic). In that case, this type of flap deflection optimization should not be used, because the airplane will liftoff faster and the airport airspace departure distance will be larger. (it falls to the operator company to define what to optimize during the takeoff and landing)

The aeronautical companies should use methods and procedures of flap optimization, because knowing the best flap deflection in a certain phase of operation, makes it possible to limit the number of deflections in operation, decreasing the necessary certifications to each flap deflection and consequently time and the resulting costs.

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