Design of a Low-Cost Easy-to-Fly STOL Ultralight Aircraft in Composite Material

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The paper deals with the design of an aircraft, starting from a market survey, the conceptual design loop and the preliminary choice of dimensions, and leading to the detailed design of efficient high-lift systems and a low-drag fuselage shape. Technological challenges regarding the design of low-cost systems for flap/slat retraction and a simple wing folding system are highlighted. Aiming at an efficient optimization algorithm, we developed a new integration technique between CAD, aerodynamic and structural numerical calculation. Examples deriving from this new approach are presented.

Keywords: STOL, preliminary design.

Notation

AR	Wing aspect ratio.
$C_{L\max}$	Maximum Lift coefficient of the aircraft with retracted flaps.
$C_{L\max FF}$	Maximum Lift coefficient of the aircraft with full flaps.
$C_{L\max L}$	Maximum Landing Lift coefficient of the aircraft.
$C_{L\max TO}$	Maximum Take Off Lift coefficient of the aircraft.
RC, $RC_{\max}$	Maximum Rate of Climb.
S	Wing area.
S_{LG}, S_{TOG}	Landing Ground run, Take Off Ground run.
t	Time.
$t_{\min}$	Minimum time of climb to altitude z.
$V(RC_{\max})$	Speed at maximum Rate of Climb.
$V_{\max}$, $V_{\min}$	Maximum level speed, minimum level speed.
V_s, V_{sFF}	Stalling speed flaps up, stalling speed flapsdown.
W_E	Empty Weight.
W_{TO}	Maximum Take Off Weight.
P	Power.
z	Altitude.
ρ, ρ_0	Density, density at sea level.

1 Introduction

The class of Ultralight (ULM) and light aircraft in general has attracted by growing interest through Europe in recent years. Only in Italy in the last 5–6 years, at least 10 companies have started production of ULM aircraft. There is a very active market for this class, used to promote flight at all levels and for sports aircraft The maximum flight speed for ULM aircraft has been increased in recent years through the use of more powerful engines (100 hp instead of 64 or 80) and better aerodynamics. It is not surprising that a maximum level speed of about 280 km/h has been reached. Since the weight constraints are very strict, it is important to study ways to improve structural design, safety, flight qualities, aeroelastic behaviour and systems reliability, without raising costs.. Following the experience acquired in our department in designing light and ultralight aircraft, the design of a new composite ULM is being carried out at DPA. The design goals established for this new design were: 1) Short Take-Off and Landing (STOL) aircraft capable of taking off and landing from an uprepared runway within 40 m; 2) almost complete construction in composite material; 3) foldable wing, in order to make the ULM very easy to use, to put on a trailer and to hangar in a normal size garage; 4) wing with a retractable leading edge slat and slotted/fowler flaps; 5) maximum speed around 190–200 km/h at MTOW of 450 kg; 6) good flight and handling qualities, to be safely flown by inexperienced pilots; 7) low cost.

2 Market survey

All the analyzed aircraft are ULM (W_{TO} = 450 kg = 4415 N) and equipped with an 80 hp (59.6 kW) engine; most of them are made of aluminium alloy with a high wing configuration, ensuring high stability and easy piloting. None satisfies all the above-mentioned design goals. In fact, the YUMA, the Savannah and the Zenair CH 701 are successful STOL aircraft made of aluminium alloy; however, their de-

Table 1: Weights, sizes and performances at sea level of the analyzed aircraft (M. – Material: a – aluminium alloy, c – composite; W.p. – Wing position: h – high, l – low.)

Aircraft	M.	W.p.	W_E [N]	$\frac{W_E}{W_{TO}}$	$\frac{W_{TO}}{S}$ [N/m^2]	S [m^2]	AR	V_S [km/h]	V_{SFF} [km/h]	$V_{\max}$ [km/h]	RC [m/s]	S_{TOG} [m]	S_{LG} [m]	$C_{L\max}$	$C_{L\max FF}$
P92 ECHO 80	a	h	2757	0.62	334.43	13.20	6.55	71	61	210	5.5	110	100	1.40	1.90
P96 GOLF 80	a	l	2757	0.62	361.84	12.20	5.78	71	61	225	4.5	110	100	1.52	2.06

Aircraft	**M.**	**W.p.**	W_E [N]	$\frac{W_E}{W_{TO}}$	$\frac{W_{TO}}{S}$ [N/m^2]	S [m^2]	AR	V_S [km/h]	V_{SFF} [km/h]	V_{max} [km/h]	RC [m/s]	S_{TOG} [m]	S_{LG} [m]	C_{Lmax}	C_{LmaxFF}
REMOS G-3	c	h	2757	0.62	366.65	12.04	7.98	75	63	220	6.5	80	140	1.38	1.95
DF 2000	a	h	2747	0.62	367.88	12.00	8.33	66	56	215	5.5	110	100	1.79	2.48
YUMA (STOL)	a	h	2766	0.63	328.46	13.44	7.07	55	50	175	6.0	40	55	2.30	2.78
SAVANNAH (STOL)	a	h	2668	0.60	343.81	12.84	6.28	50	45	160	6.0	50	50	2.91	3.59
ZENAIR CH 701 (STOL)	a	h	2580	0.58	387.24	11.40	5.90	53	48	153	7.0	50	50	2.92	3.56
AMIGO !	a	l	2806	0.64	339.58	13.00	5.24	74	64	250	6.5	80	100	1.31	1.75
SLEPCEV STORCH Mk4 (STOL)	a	h	2649	0.60	275.91	16.00	6.76	52	46	155	4.5	50	50	2.16	2.76
SKY ARROW 450T	c	h	2825	0.64	326.76	13.51	6.96	70	61	192	5.1	120	80	1.41	1.86
Allegro 2000	a	h	2727	0.62	387.24	11.40	10.23	73	63	220	5.0	150	100	1.54	2.06
SINUS 912 Motoaliante	c	h	2786	0.63	360.07	12.26	18.28	66	63	220	6.5	88	100	1.75	1.92
AVIO J-Jabiru	c	h	2649	0.60	474.17	9.31	9.49	74	64	216	6.0	100	160	1.83	2.45
EV-97 EURO STAR Model 2001	a	l	2570	0.58	448.63	9.84	6.67	75	65	225	5.5	125	90	1.69	2.25
JET FOX 97	a, c	h	2845	0.64	301.95	14.62	6.54	70	60	175	6.0	100	120	1.30	1.77
TL 96 Star	a	l	2747	0.62	364.83	12.10	6.87	80	63	250	6.0	90	100	1.21	1.94

sign is unattractive, and they have a fixed slat on the leading edge, which reduces maximum cruising speed. The Sky Arrow 450T and the REMOS G-3, on the contrary, are high cost “non-STOL” aircraft in composite materials, advanced ULM. They can easily by put onto a trailer, due to their removable or foldable wing. The main characteristics of the analyzed aircraft are shown in Table 1. Their main performance characteristics in terms of landing run versus maximum level speed at sea level are shown in Fig. 1.

3 Design point

The methodology followed during the design process is similar to that reported in [1], but it has been expressly modi-

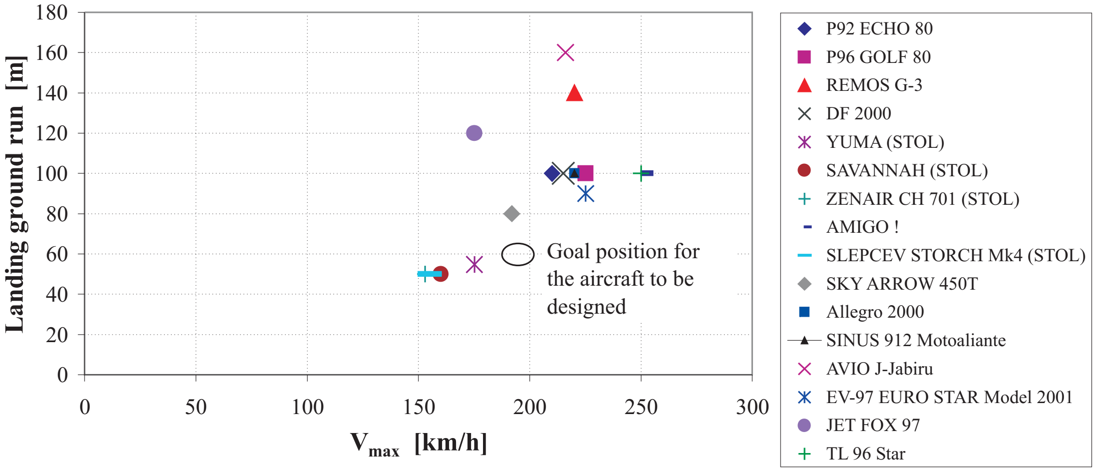

Fig. 1: Landing ground run versus maximum level speed at sea level

fied for the ULM category: in particular, new statistical relations between take off ground run S_{TOG} and Take Off Parameter for ULM TOP_{ULM} (1), landing ground run S_{LG} and landing stall speed V_{SL}, power index Ip (3) and maximum speed at sea level V_{max} have been calculated, as shown in Figs. 2, 3 and 4. TOP_{ULM} is defined as:

$$TOP_{ULM} = \frac{\left(\frac{W}{P}\right)_{TO}\left(\frac{W}{S}\right)_{TO}}{\sigma \cdot C_{L\max TO}}; \tag{1}$$

with $\left(\frac{W}{S}\right)_{TO}$ in [N/m^2] and $\left(\frac{W}{P}\right)_{TO}$ in [N/W];

$$\sigma = \frac{\rho}{\rho_0}. \tag{2}$$

Ip is defined as:

$$Ip = \sqrt[3]{\frac{\frac{W}{S}}{\left(\frac{W}{P}\right)_{cr}}} \tag{3}$$

with $\frac{W}{S}$ in [psf] and $\left(\frac{W}{P}\right)_{cr}$ in [lbs/hp];

$$P_{cr} = kz * kv * \varphi * P_{TO}. \tag{4}$$

In (4) P_{cr} and P_{TO} are respectively the power at cruising and take off, *kv* and *kz* are the speed and altitude factor (for a four-stroke engine $kv = 1$ and $kz = \sigma^{1.22}$), φ is the engine admission limit. The data scattering is probably due to limited reliability of the published data, and due to an unbiased difficulty in measuring the data: for example, slight differences in executed manouvres lead to great differences in measured data.

For this STOL aircraft, the main restrictions are maximum speed, take off and landing run, as shown in Fig. 5. Once these limitations have been reported in a graph relating power loading $(W/P)_{TO}$ and wing loading $(W/S)_{TO}$, the resulting shaded area represents all the possible design point choices. Maximum power loading is fixed ($(W/P)_{TO} = 74$ N/kW), because maximum take off weight (450 kg = 4415 N) and power (80 hp = 59.6 kW) have been fixed. In this way only maximum wing loading has been

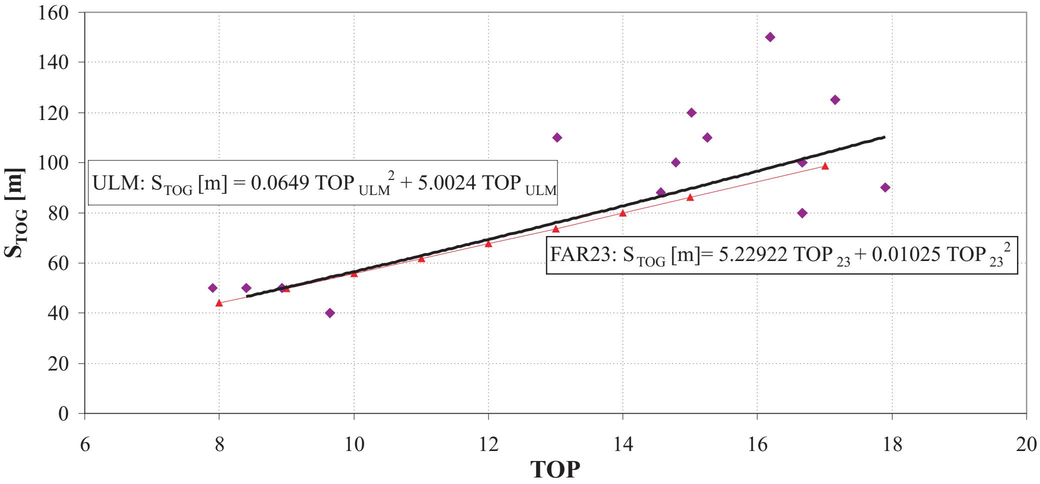

Fig. 2: Take off ground run S_{TOG} versus take off parameter TOP

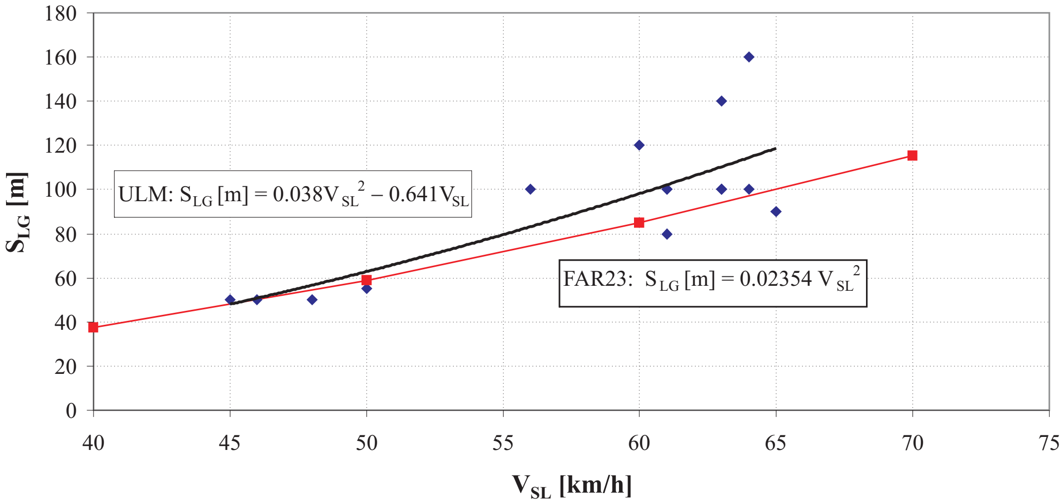

Fig. 3: Landing ground run S_{LG} versus landing stall speed at sea level V_{SL}

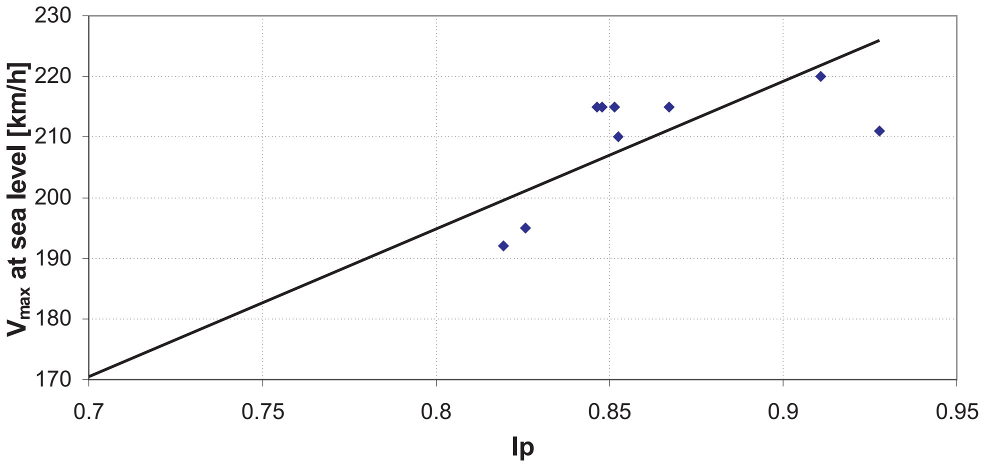

Fig. 4: Maximum speed V_{max} versus power index *Ip*

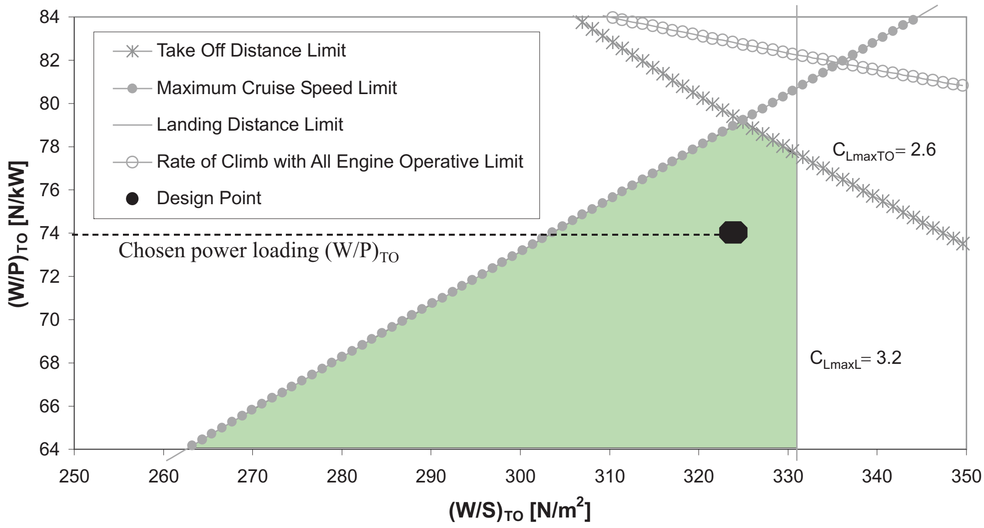

Fig. 5: Maximum power loading $(W/P)_{TO}$ versus maximum wing loading $(W/S)_{TO}$

chosen, based on the criteria for keeping the wing area as small as possible (mainly for cost reasons) and using appropriate values of maximum take off and landing lift coefficient ($(W/S)_{TO} = 324$ N/m^2, $S = 13.6$ m^2, $C_{LmaxTO} = 2.45$, $C_{LmaxL} = 3.12$).

4 Preliminary design

The conceptual loop is shown in Fig. 6. It looks simple, but, for example, converting the geometry of sections into CAD geometry is a complicated and delicate step: aircraft

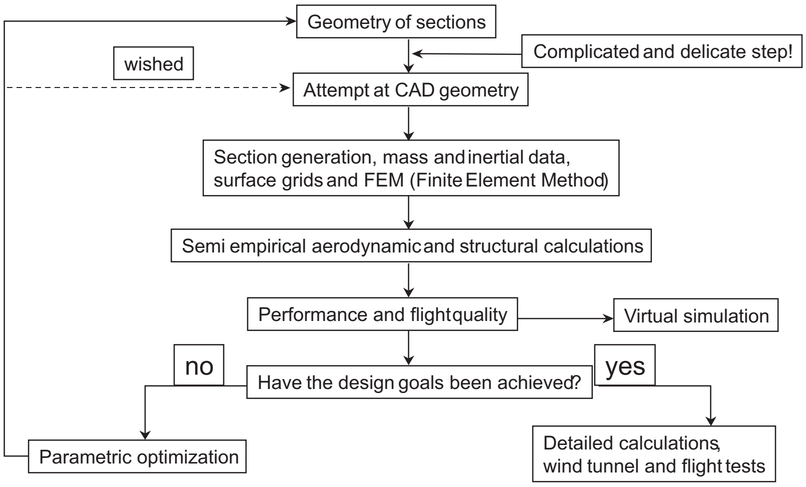

Fig. 6: Conceptual loop design

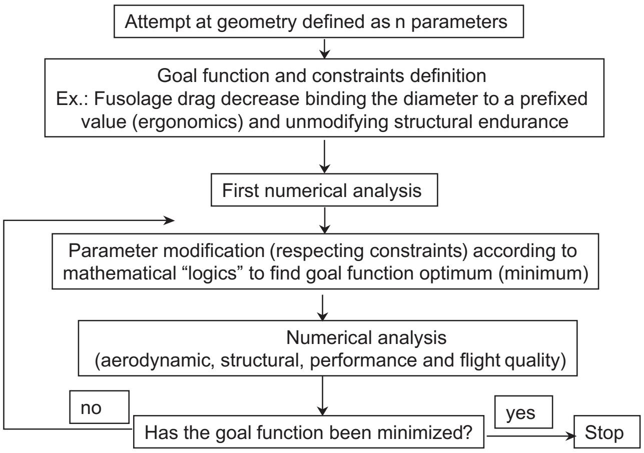

Fig. 7: Parametric optimization loop

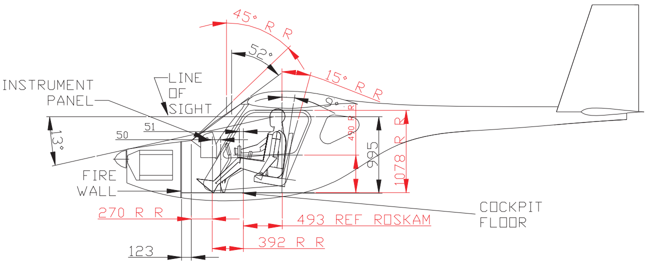

Fig. 9: Ergonomics and line of sight of the fuselage

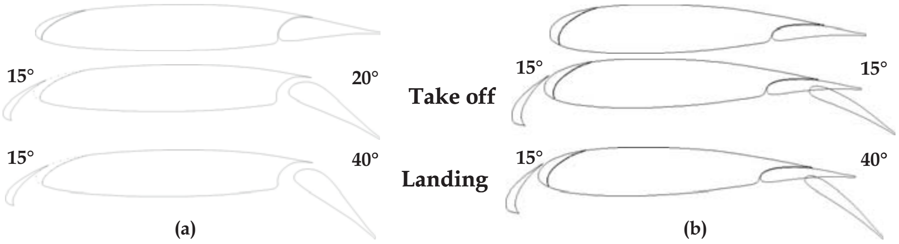

Fig. 8: Possible high lift system configurations: (a) slat – single slot; (b) slat – fowler

surfaces must be carefully defined, otherwise the aircraft geometry will be different from the desired design. The parametric optimization loop is shown in Fig. 7. First of all, the preliminary geometry was fixed, analyzing existing aircraft and applying semi-empirical methods. The wing was sized to minimize the required power at cruising speed. Some airfoils were analyzed and a new airfoil was designed (modifying NACA GAW1 airfoil) to provide a compromise between lift, drag and pitch moment coefficients. The high lift system and aileron sizing ensures the STOL characteristic and good lateral control; this has been demonstrated by J. Roskam [2], W. McCormick [3], C. D. Perkins and R. E. Hage [4] and by the authors [5]. In particular, two possible high lift system configurations are shown in Fig. 8. The horizontal and vertical tails were sized by the volume method, ensuring good stability and control also in landing. The fuselage design is very important and it was based on aerodynamic, ergonomic and line of sight studies, as shown in Fig. 9. A 3-view of the aircraft is shown in Fig. 10; Table 2 reports the main dimensions, weights and loadings.

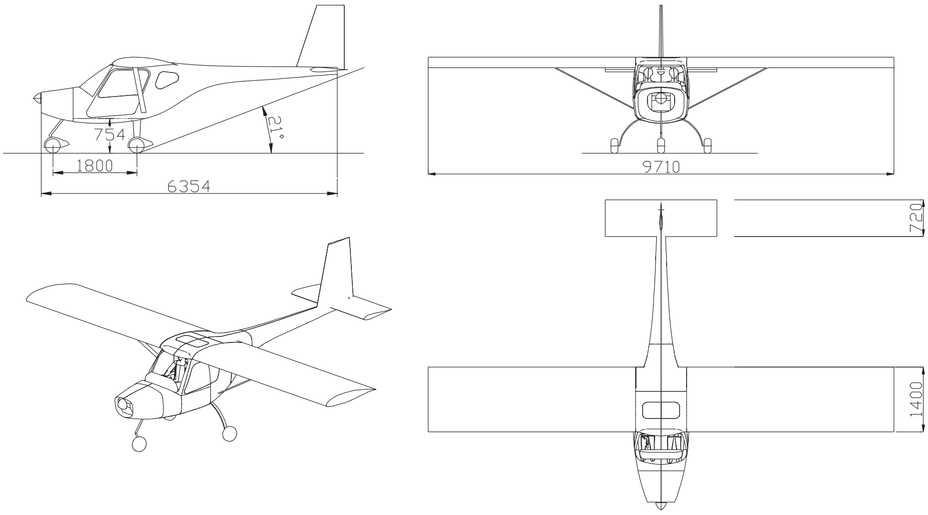

Fig. 10: 3-view of the aircraft

Table 2: Main dimensions, weights and loadings

DIMENSIONS, EXTERNAL				
WING		AIRCRAFT		
Span [m]	9.71	Length overall [m]	6.52	
Root chord [m]	1.40	Height overall [m]	1.35	
Tip chord [m]	1.40			
Aspect ratio	6.93	PROPELLER (fixed-pitch)		
Incidence [deg]	2.00	Blade number	3	
		Diameter [m]	1.66	
HORIZONTAL TAIL				
Span [m]	2.80	AREAS		
Root chord [m]	0.72	Wing [m^2]	13.60	
Tip chord [m]	0.72	Ailerons [m^2]	1.22	
Aspect ratio	3.90	Leading edge flap [m^2]: slat	2.04	
		Trailing edge flap [m^2]: single slot	2.85	
VERTICAL TAIL		Horizontal tail [m^2]	2.01	
Span [m]	1.47	Vertical tail [m^2]	1.08	
Root chord [m]	0.87			
Tip chord [m]	0.61	**WEIGHTS AND LOADINGS**		
Aspect ratio	2.00	Empty weight	280 kg	2747 N
Incidence [deg]	0.00	Max T-O and landing weight	450 kg	4415 N
Leading edge sweep angle [deg]	22.20	Max wing loading	33.09 kg/m^2	324 N/m^2
Trailing edge sweep angle [deg]	13.00	Max power loading	5.63 kg/hp	74 N/kW

5 Numerical analysis

The design was accomplished using a code named AEREO [5], which has been developed in recent years at DPA to predict all aerodynamic characteristics in linear and non-linear conditions (high angles of attack) and all flight performances as well as dynamic behavior and flight qualities of propeller driven aircraft. The figures below report some aerodynamic characteristics (Figs. 11, 12, 13 and 14) and performance characteristics (Fig. 15) of the aircraft calculated with AEREO code. Table 3 reports the main performances of the aircraft. Further optimization of the global configuration is in progress to improve the wing aero-structural behavior as well as the relative position of the wing and horizontal tail to minimize downwash and induced drag.

Table 3: Performances

PERFORMANCE (Max weight, ISA, at sea level)			
Max speed [km/h]	194	Take off run to 15 m [m]	121
Cruising speed [km/h]	165	Landing run from 15 m [m]	100
Stall speed [km/h]: flaps up	65	Landing run [m]	50
flaps down: slat – single slot	48	Theoretical ceiling [m]	7908
Max rate of climb [m/s]	6.69	Service ceiling [m]	7317
Take off run [m]	55		

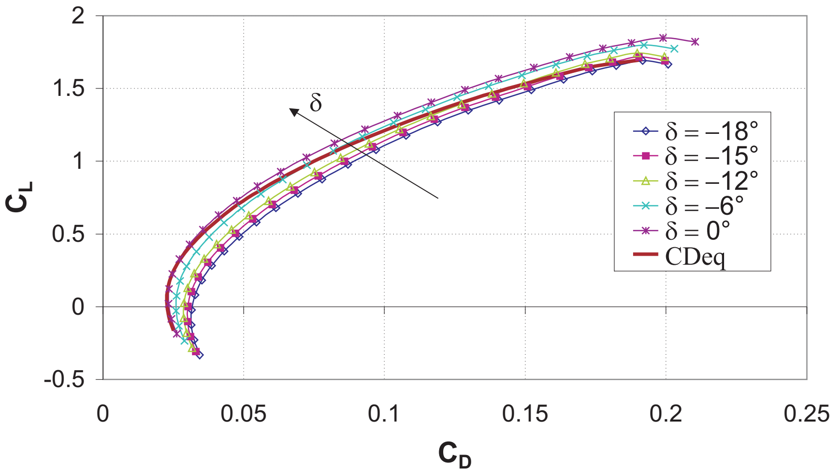

Fig. 11: Polar curves parameterized in d (horizontal all-movable tail deflection) and equilibrium polar curve

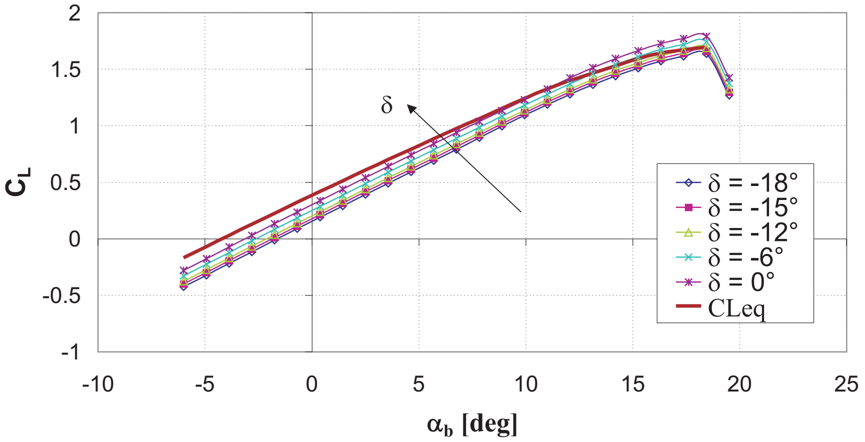

Fig. 12: Lift coefficient of the aircraft versus alpha body (incidence angle measured in regard to the thrust axis) parameterized in δ (horizontal all-movable tail deflection) and equilibrium lift coefficient

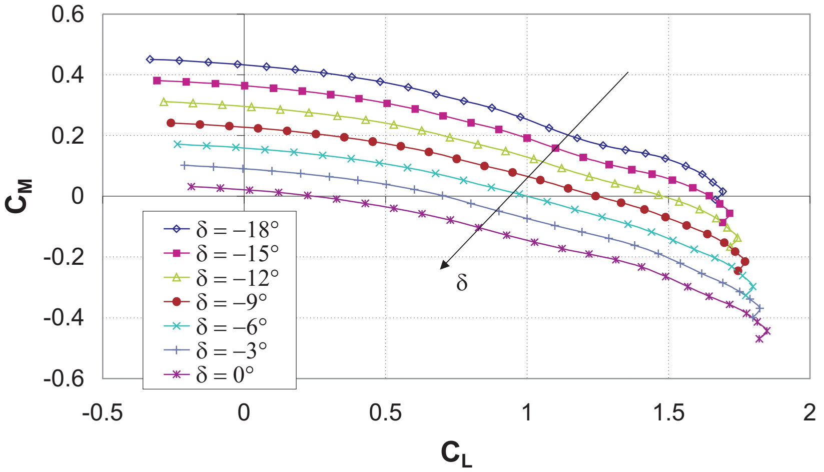

Fig. 13: Pitch moment coefficient versus lift coefficient parameterized in δ (horizontal all-movable tail deflection)

6 Conclusion

The preliminary design of a STOL ULM aircraft and numerical performance prediction has been shown. The aircraft shows acceptable performances that are consistent with the desired design goals. The predicted performances were obtained with AEREO code, which confirmed its usefulness as a fast and reliable design tool for propeller-driven aircraft. The parametric design and optimization loops have been highlighted. Detailed design and optimization of the high-lift system and three-dimensional aerodynamic analysis are in progress, while wind tunnel tests (high-lift airfoil, aircraft model) are planned in the near future.

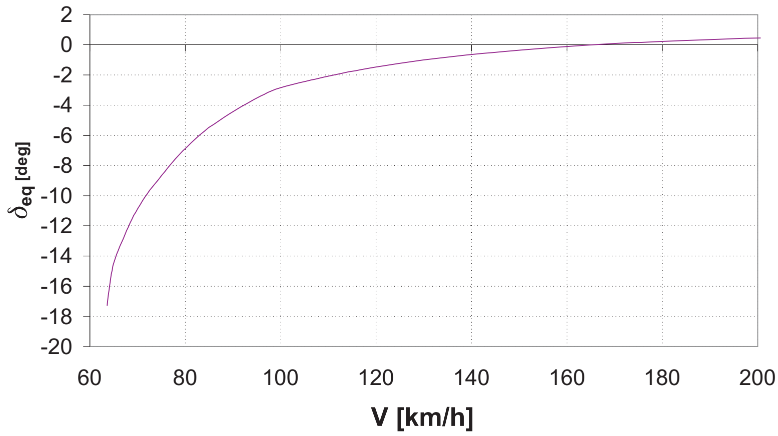

Fig. 14: Equilibrium horizontal all-movable tail deflection versus speed (center of gravity position is at 25 % of mean aerodynamic chord)

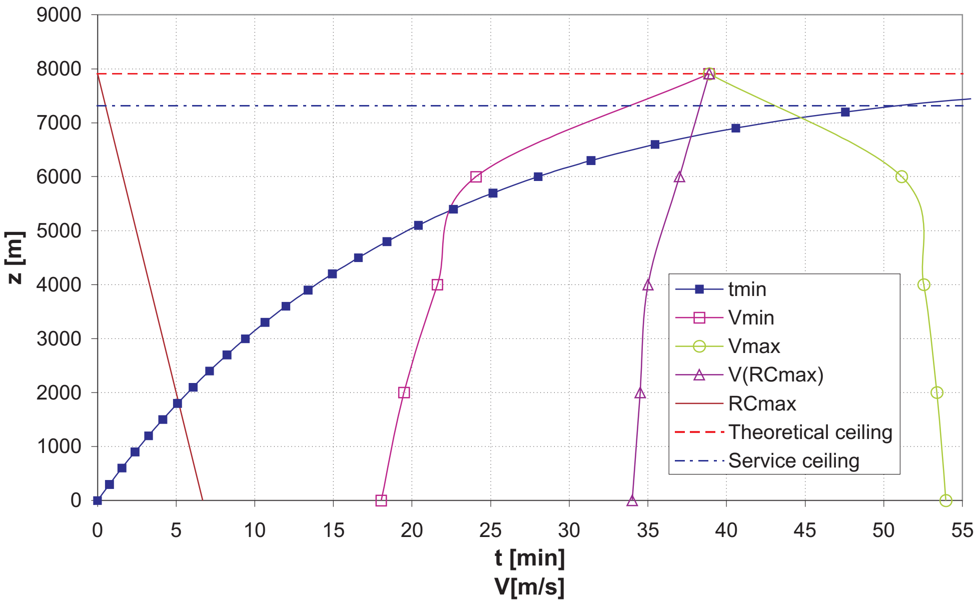

Fig. 15: Flight envelope

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