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DESIGN OF A TWIN ENGINE PROPELLER AIRCRAFT ; AERODYNAMIC INVESTIGATION ON FUSELAGE AND NACELLE EFFECTS

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SOMMARIO

Durante l'anno 2006 la Tecnam ha portato avanti la progettazione di un velivolo bimotore leggero denominato P2006. Il progetto del Prof. L. Pascale è basato sullo sviluppo di un velivolo quadriposto motorizzato con due motori Rotax leggeri da 100 hp. Il nuovo velivolo è caratterizzato da un peso massimo al decollo paragonabile con quello di velivoli monomotori e per questo denominato VELT (Very Light Twin). Nel presente lavoro vengono delineati gli elementi principali del progetto alla base della scelta della configurazione. Nel lavoro vengono poi mostrati i risultati di indagini numeriche e sperimentali svolte presso il Dipartimento di Ingegneria Aerospaziale dell'Università "Federico II". Le prove e le ricerche, oltre che alla determinazione delle caratteristiche aerodinamiche del velivolo, sono state incentrate sulla valutazione degli effetti aerodinamici della fusoliera e delle gondole sull'aerodinamica ed in particolare sulla distribuzione di carico aerodinamico lungo l'apertura, fondamentale ai fini della valutazione dei carichi certificativi.

ABSTRACT

Design of a new twin propeller aircraft named P2006 VELT (Very Light Twin) has been carried out at Tecnam aircraft industries during 2006. The new aircraft design, performed by Prof. L. Pascale, is based on the idea to built a 4-seat aircraft with two light engines (Rotax 912, usually used for ultralight aircraft) and to enter the market with a twin-engine aircraft with the same weight of a single engine aircraft (VEry Light Twin). The present paper shows all main criteria on which the design of the aircraft and the choice of the configuration have been based. At Dipartimento di Ingegneria Aerospaziale (DIAS) of University of Napoli "Federico II" a deep aircraft aerodynamic investigation has been performed both numerically and experimentally (through wind-tunnel tests). All tests and research activities have been focused on the evaluation of aircraft aerodynamics and in particular on the measurement of fuselage and nacelle aerodynamic effects. Deep investigations have concerned the evaluation of fuselage and nacelle effect on lift distribution along wing span, fundamental for the evaluation of certification loads.

1. INTRODUCTION

During the last 15 years *Tecnam Aircraft Industries* has been designing and developing more than 10 light and Ultralight(ULM) 2-seat aircraft characterized by high-wing or low-wing configurations and introducing interesting technological innovation (for light aircraft with the weight of 500-600 Kg) like the retractable gear. The market of light aircraft has been growing in the last decade all over the world and Tecnam has reached a leadership with more than 2000 aircraft sold in 15 years. The Department of Aerospace Engineering (DIAS) of University of Naples have been deeply involved in research activities concerning almost all of these aircraft[1,2]. Extensive activities have been carried out in collaboration with Tecnam on structural analysis, structural tests, aerodynamic analysis and optimisation, noise and vibration tests, wind-tunnel tests and flight tests. Almost all light aircraft produced by Tecnam have been tested in the main wind-tunnel belonging to DIAS. An example of some light aircraft that have been an important commercial success are shown in fig. 1.

Since 2006 *Tecnam* has started his intention to enter the market with a new CS 23 certified 4 seat aircraft.

In the last years, starting from the United States, the General Aviation has been revitalized, due to the necessity to decongest the classical skyway system and to use thousands of small airport in the country. With this aim the AGATE consortium was founded in 1994 to develop affordable new technologies to be applied on next generation light airplanes. In addition the fast economical growth of developing countries (like in Africa, south-America and in south-east of Asia) that do not have developed transportation systems has pushed the use and the diffusion of light aircraft in those areas. In example in some remote area of south Africa the transport through light aircraft can be the only solution, taking into account the absence of asphalt roads and the low acquisition and maintenance costs of these kind of machines.

Fig. 1: P92 Echo and P2002 JR aircraft

General aviation and light aircraft can be also extensively used for touristic transport and to perform services like aerial monitoring (police patrol or fire monitoring) with a reasonable cost respect to the classical use of helicopter. The other aspect (in particular looking at the not-developed countries market) that has been carefully considered by *Tecnam* has been the installation of engines using standard automotive fuel instead of aviation fuel. The reason is based on the lower cost and especially on the easy possibility of finding this fuel everywhere. The above remarks put clearly in evidence the growing market for light aircraft with 4 seats, with a flight speed around 250-300 Km/h, with capability of flight altitude up to 12000 ft, with relatively simple , light and not-expensive construction (typical of ultralight and VLA certified aircraft) and so with a reasonable cost and with low maintenance costs. It is very important (considering the possibility of use in not developed areas and the take-off and landing capabilities from not-prepared airfields) the characteristic of relatively short take-off and landing run.

2. MARKET ANALYSIS AND P2006 AIRCRAFT DESIGN ASPECTS

Design of a new twin propeller aircraft named P2006 VELT (Very Light Twin) has been carried out at *Tecnam* aircraft industries during 2006. The design of the new aircraft, performed by Prof. L. Pascale, is based on the idea to built a 4-seat aircraft with two light engines (Rotax 912, usually used for ultralight aircraft) and to enter the market with a twin-engine aircraft with the weight of a single engine one. This project starts with the consideration that Rotax 912 S is the only engine available for the aviation market that uses automotive fuel and is FAR 33 certificated. This engine has been recently designed taking all the advantages of the latest technologies developed in the automotive market over the standard G.A. engines. Those mainly are:

- Reduced frontal area and better weight to power ratio
- Lower specific fuel consumption
- Lower propeller rpm i.e. higher efficiency and lower acoustic emissions
- Stable engine head temperatures due to liquid cooling

So far this modern powerplant, given its moderately low power (73 KW or 100 hp), has been used essentially on two seats single-engine light airplanes. It now becomes evident the opportunity to design a four-seats airplane powered by two of these Rotax engines with a neglecting weight difference, higher safety due to the twin engine arrangement and quite lower costs respect the single engine competitors.

In the following table(table 1) we compare the performance of some four seat, 200 hp aircraft available on the market today. It is evident that:

- For the first time ever it is possible to compare a **twin-engine** four seat aircraft with single-engine four-seat aircraft, due to their similar weight and power specifications;

- The P2006 empty weight is the lowest among twin engine aircrafts while the payload is higher. This can be attributed to the high structural and system efficiency and because of the excellent weight-to-power ratio of the Rotax engine. The wing-mounted engines relieve the aerodynamic load on the wing with a consequently lighter structure;
- The remarkable expected propulsive efficiency of P2006 can be ascribed to the low propeller rpm and low engine nacelle drag. These aspects, together with a streamlined fuselage, result in a good aerodynamic efficiency, as also confirmed through wind-tunnel tests (see after);
- From an operating point of view, is worth to consider that the option to use automotive fuel instead of AVGAS allows P2006 operators to dramatically reduce direct costs, making also possible to fly in regional or remote areas where AVGAS is difficult to find or prohibitively expensive;
- Low fuel consumption of Rotax engines and a high aerodynamic efficiency allows P2006 to be flown over long distances and in areas where ground facilities are poor.
-

MODEL	Cessna 172R	Cessna 182T	Piper PA28-181	Cirrus	Diamond	EADS Socata	TECNAM
Specifications	Skyhawk	Skylane	Archer	SRV-G2	DA-40	TB10 Tobago	P2006T
wingspan (m)	10,97	10,97	10,80	10,84	12,00	10,04	11,20
wing area (mq)	16,20	16,20	16,00	12,50	13,47	11,90	14,76
lenght (m)	8,28	8,84	7,32	7,92	8,02	7,75	8,70
height (m)	2,72	2,84	2,20	2,59	1,98	3,02	2,90
cabin width (m)	1,00	1,07	1,06	1,24	1,14	1,08	1,20
cabin lenght (m)	3,60	3,40	2,49	2,53	n.a.	2,53	2,60
landing gear type	fixed, tricycle	fixed, tricycle	fixed, tricycle	fixed, tricycle	fixed, tricycle	fixed, tricycle	retractable, tricycle
Engine							
manufacturer	Lycoming	Lycoming	Lycoming	Continental	Lycoming	Lycoming	Rotax
model	IO-360-L2A	IO-540-AB1A5	0-360-A4M	IO-360-ES	0-360-M1A	0-360-A1AD	2x 912 S
horsepower	160 hp @ 2400 RPM	230 hp @ 2400 RPM	180 hp @ 2700 RPM	200 hp @ 2600 RPM	180 hp @ 2700 RPM	180 hp @ 2700 RPM	2x98 hp @ 2400 RPM
Propeller							
type	Fixed Pitch, 2 blade	Const. speed, 3 blade	Fixed Pitch, 2 blade	Const. speed, 2 blade	Const. speed, 2 blade	Const. speed, 2 blade	Const. speed, 2 blade
diameter (m)	1,91	2,00	n.a.	1,93	1,80	1,88	1,78
Design weight & Loading							
max. gross weight (kg)	1043	1406	1157	1360	1149	1150	1160
std. empty weight (kg)	588	860	760	929	744	730	750
useful load (kg)	455	550	397	431	405	420	410
seating capacity	4	4	4	4	4	4	4
fuel capacity (lt)	159	348	182	213	148	210	200
Wing loading (kg/mq)	64,4	86,9	72,3	108,8	85,3	96,6	78,6
Power loading (kg/hp)	6,52	6,10	6,43	6,8	6,38	6,39	5,92
Performance							
max. level speed s.l. (kts)	123	149	133	n.a.	n.a.	n.a.	150
cruise speed (kts)	122 (80%,8000 ft)	145 (80%,6000 ft)	128 (75%,7900 ft)	150 (75%)	145 (75%,6500 ft)	127 (75%,6000 ft)	145 (75% 7000 ft)
cruise speed "	116 (10000 ft)		n.a.	n.a.	134 (65%,10000ft)	109 (65%,6000 ft)	140 (65%,9000 ft)
stall speed, flaps up, pwr off (kts)	51	54	n.a	54	52	n.a.	53
stall speed, flaps down, " " "	47	49	52	n.a.	49	n.a.	48
best rate of climb (ft/m')	720	924	n.a.	900	1070	787	1350
service ceiling (ft)	13500	18100	14100	n.a.	15000	13000	16500
fuel cosump. lt/h (65%)	28	41	32	35	32	32	32
cruise range w/reserve (30') nm	580	968	487	634	n.a.	n.a.	750
takeoff, ground roll (m)	288	242	346	409	219	505	235
takeoff, total distance (50 ft) (m)	514	461	490	597	352	n.a.	460
landing ground roll (m)	168	180	280	309	146	460	180
landing distance (50 ft) (m)	395	411	427	622	314	n.a.	420
						* Single eng. R/c (s.l.), ft/m'	350
						Single eng.ceiling, ft	7500

Table 1: 4-seat light aircraft comparison

Fig.2 shows the comparison of frontal area and general characteristics of Rotax 912S engine and Lycoming IO-360 used in Cessna 172 and Piper PA-28 aircrafts. The figure shows that the weight-to-power ratio of Rotax is favourable and so the weight of 2 Rotax 912S is lower than the weight of one Lycoming. It si also possible to see that Rotax 912S engine frontal area is lower and in general allows a wing-mounted streamlined nacelle, reducing drag penalty arising from the twin-engine wing-mounted configuration. Other important consideration is that Rotax 912 max power is obtained at 2390 rpm instead of 2700 rpm relative to Lycoming.
Lower rpm allows higher propeller thrust at low flight speed improving aircraft take-off and climb performances. Fuel consumption is another big advantage of Rotax versus Lycoming.

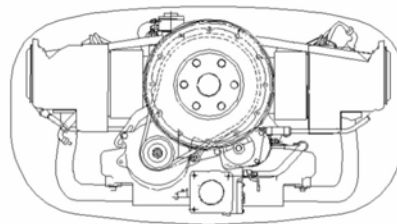|	**Rotax 912S**	**Lycoming IO-360**
Weight- dry	59 Kg	149 Kg
Max Power	100 hp @2390 rpm	200 hp @2700 rpm
Frontal Area	0.322 m^2	0.428 m^2
Max width	575 mm	867 mm
Fuel cons.	19 l/h	46 l/h
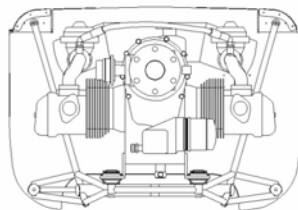
Rotax 912S   Lycoming IO-360

Fig. 2 : Comparison of Rotax 912S engine and Lycoming IO-360

The Rotax 912S will drive on P2006 aircraft a 2-blade Hoffmann constant speed propeller with pitch feathering device and with Diameter of 1.78 m. The reduced frontal area of Rotax 912S engine, allows to have a good ratio between the area of propeller disk and the engine-nacelle frontal area behind the disk. As we know the engine frontal area behind the propeller can reduce propeller efficiency and this reduction is associated with the above mentioned ratio. The propulsive maximum thrust available by two Rotax 912S has been evaluated through Hoffmann propeller charts. Correction to take into account engine frontal area behind the propeller have been applied. Similar calculation have been performed for one 200 hp Lycoming engine.

Fig. 3 shows that at low flight speed 20% higher thrust can be obtained by Rotax912S engine. At cruise and high-speed condition not remarkable difference can be observed. The higher thrust of Rotax912S is mainly due to the fact that the same engine power is distributed on much larger propeller disk area(area of two disks of 1.78 m diameter). Other small effect arises from lower rpm of Rotax 912S (2390 instead of 2700) at maximum power conditions.

Fig. 4 shows weight and certification characteristics of several light single and twin-engine aircraft. Through an accurate analysis of this figure the following considerations can be outlined:
-    The Maximum take-off weight (MTOW) of P2006 is comparable to single-engine aircraft;
-    Looking at flight performances P2006 can not compete with classical twin-engine aircraft, usually powered by much powerful engine.

Conclusion is that P2006 is a twin-engine aircraft that can compete in a favourable way (similar performances but lower direct and operative costs) to single-engine aircraft.

It can also be observed that P2006 aircraft fills a market area in which are not present other aircrafts.

The weight difference with other twin-engine aircraft is evident. The light twin engine will be favourable compared with a single engine four seat aircraft powered by a 180 or 200 hp engine.

The introduction of a light twin-engine is actual not a novelty. In fact, after the war in Czech Republic was designed and built a light twin-engine aircraft named AERO 45. The 4-seat aircraft was powered by two Walter 105 hp engine each and was characterized by a MTOW of 1600 Kg. The wing loading was 88 Kg/m^2 and maximum flight speed was 270 Km/h. The aircraft had a fairly good success and more than 800 aircrafts were built.

All design aspects previously outlined and others specified in the next paragraph, has leaded to the P2006 configuration, shown in the aircraft 3-view of fig. 5, together with its main geometrical and mass data.
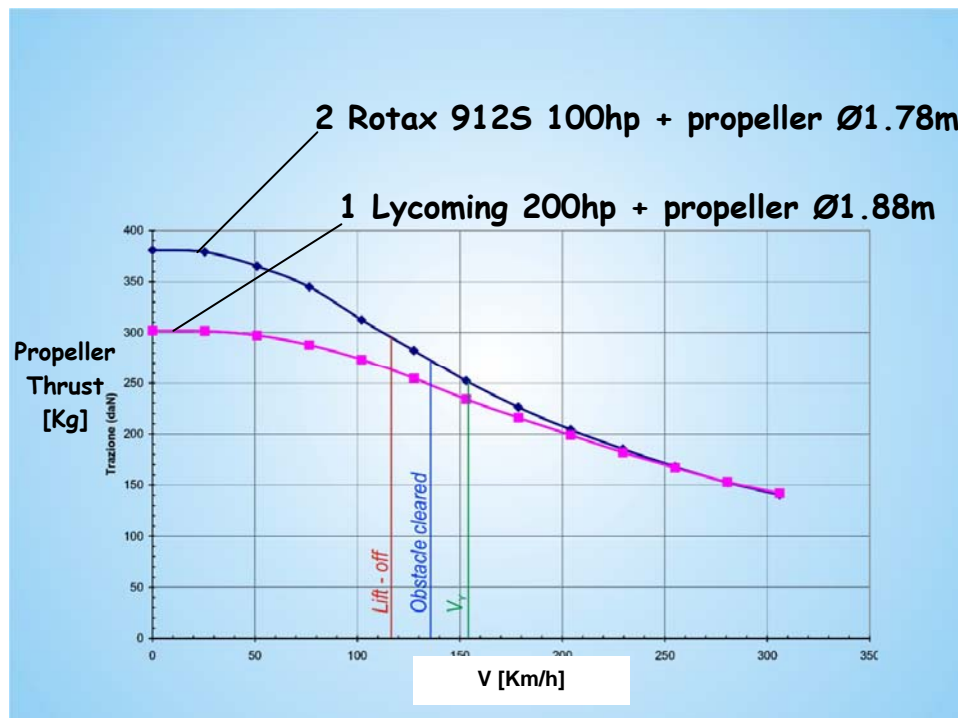
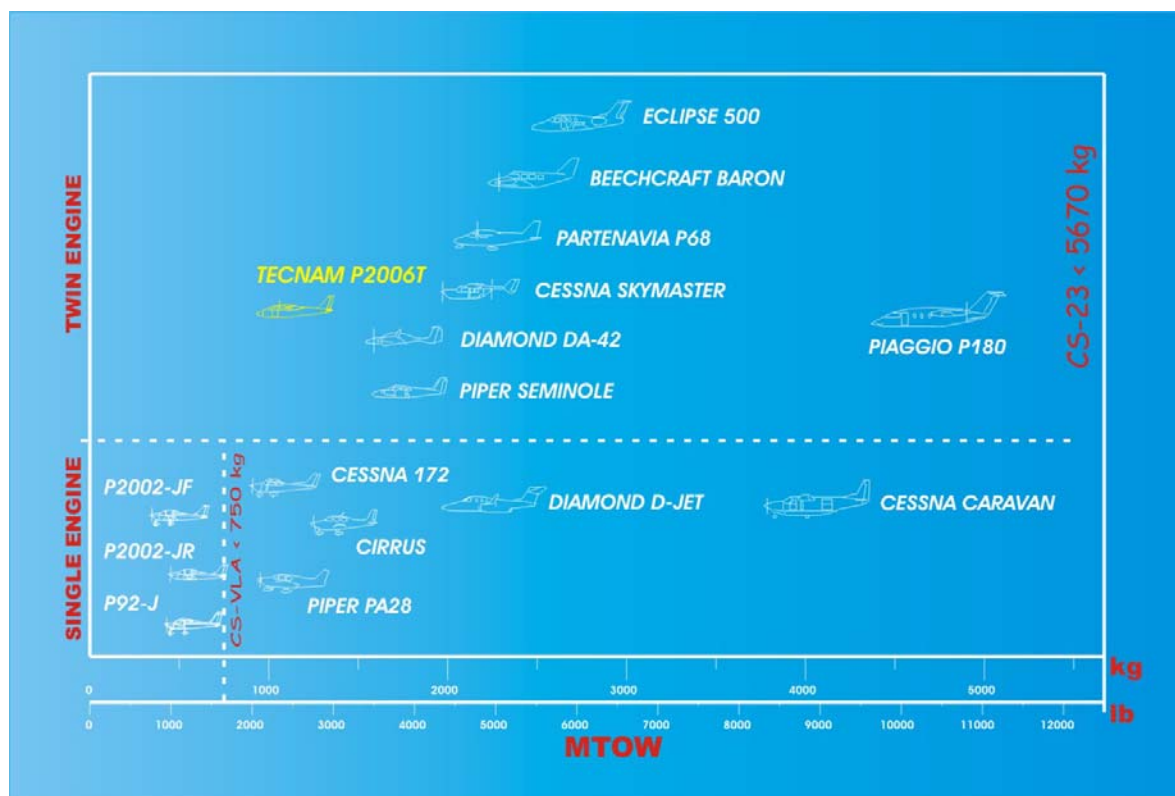*Fig.3 : Calculated propeller thrust for Rotax912S and Lycoming engine*

Fig.4 : Table of Max Take-off Weight (MTOW) and certification base of several light aircraft

P2006 CHARACTERISTICS

Wing span	11.2 m	Cabin width	1.20 m
Mean geometric chord	1.32 m	Maximum Take-off weight	1160 Kg
Wing Area S	14.76 m^2	Power installed	2 x 100 hp Rotax 912S
Aspect ratio	8.47		
Length	8.30 m		

Fig. 5 : P2006 aircraft

3. STUDY AND DEVELOPMENT OF THE CONFIGURATION

3.1 P2006 configuration

In the present paragraph all results about the performed study and development of the configuration will be presented. The design of the aircraft has been accomplished starting from the following design specification (see also par. 2):

➢ Easy cabin access and cabin comfort for passengers
➢ Spacious luggage compartment of more than 300 litres, which is easily accessible from external door
➢ Reduced take-off run (<1500 ft) and possibility to take-off from not prepared runways
➢ Cruise flight speed of about 140 Kt at flight altitude of 7000-8000 ft.
➢ Range higher than 500 nm (see also the evaluated PayLoad-Range Diagram in the next pages)
➢ Installation of an AFCS (Automatic Flight Control System)

The study and the development of the configuration are well described by the pictures of fig. 6.

The easy cabin access has leaded to the necessity of high-wing configuration. Other considerations that has to be taken carefully into account are aircraft CG position and certification problem arising from propeller longitudinal position. In fact both FAR 23 and CS23 state that two lines at ± 5° from propeller disk do not have to intersect pilot position or pilot flight command. This leads to the fact that the two propellers have to be located well

behind or well in front of pilot position. The low-wing configuration (A in fig. 6) and the high-wing (B in fig. 6) with the wing located to optimise aircraft CG travel show a very long nacelle due to the above mentioned certification problem. In addition the low-wing configuration show a not streamlined nacelle due to the necessity to ensure a good propeller clearance from the ground.
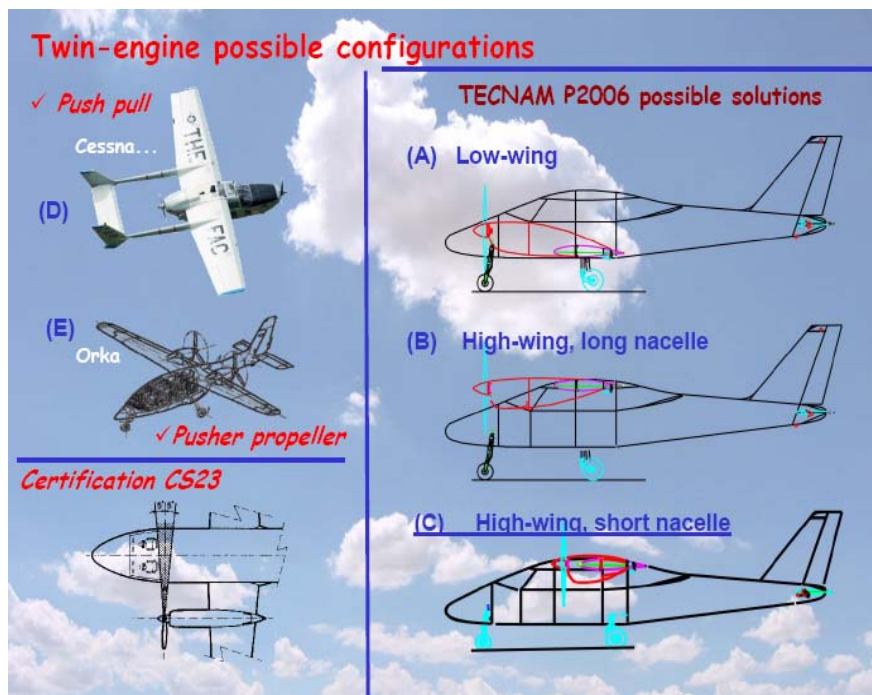

Fig. 6 : P2006 aircraft possible configurations

Both configuration A and B, with absence of CG travel problems, are therefore characterized by a big nacelle with poor aerodynamic and negative effect on aircraft parasite area. In addition that solution leads to high torsional loads on the wing due to engine inertia forces.

It is worth to notice that the low-wing configuration (that does not guarantee the easy cabin access) is also penalized by a higher landing gear (tip propeller ground clearance) with a consequent increase of aircraft empty weight. From the consideration (see design specification) to guarantee possible take-off from not prepared and grass runways the low-wing configuration is penalized due to possible ingestion for the engine and high possibility for the propeller to not work in optimal conditions.

The configuration C(see fig. 6) with high-wing, but with a cabin placed forward the wing+engine group is not optimal from CG considerations, showing a forward CG travel in full load (MTOW) conditions respect to light weight conditions (only 1 light pilot). That configuration is the best for the aircraft specifications considering that main design goal are to reduce parasite area (not possible with very big nacelles) and to have a very light empty weight (engine and nacelle mounted close to the wing). Another important consideration in favour of this choice is that the forward CG travel is not so critical like backward CG travel(that cause a dangerous decrease of aircraft stability), causing an increase of flight longitudinal stability and only a slight increase of stick forces.

The configuration C has therefore been chosen for P2006 aircraft.

In the left part of the same figure the push-pull (D) and the 2-pusher propeller configurations (E) are sketched. The two configuration have interesting good features but are not optimal for the considered aircraft specification. The push-pull has the good characteristic of absence of yawing moment in case of one engine inoperative and this leads to low vertical tail area. Some serious problems are associated with this configuration, like the structural difficulties and high costs of the twin-boom tail with double vertical tail, difficulties for the rear engine cooling, very high parasite area due to the not streamlined fuselage.

The twin-pusher propeller (configuration E) has also some problems due to engine cooling, necessity to interrupt the flap on the wing (loosing also some area available for the flap), acoustical problems due to the propeller working behind the wing wake. The above considerations make the two (D, E) configurations not convenient.

The main advantages and disadvantages of the chosen configuration (C) (see also fig. 7 with the side-view of P2006 and occupants accommodation) are:

Advantages
- easy cabin access
- nacelle with low aerodynamic drag, structural simplicity and low weight
- high span efficiency factor (Oswald factor "e") avoiding complex fairing at wing-fuselage junction typical of low-wing configurations [3]
- good flight visibility
- low effect of engines on lateral and longitudinal stability (propeller disk located close to CG position)
- propeller not exposed to dirtiness during take-off from grass runways
  Disadvantages
- high CG travel in forward direction
- fuel and engine service less easy
- necessity to have fuselage pods (sponson)
- higher weight of main landing gear support structure
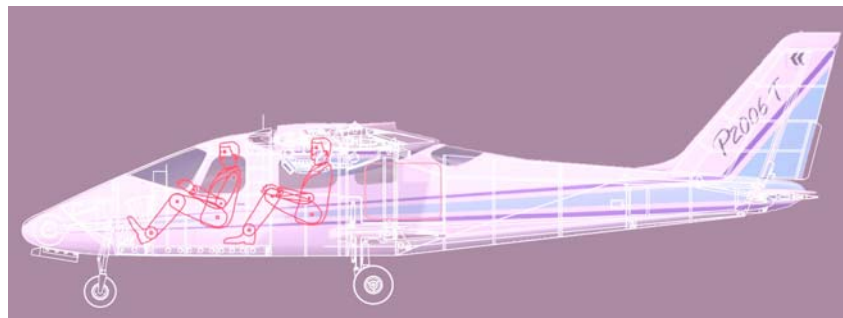
Fig. 7 : Side-view of P2006 chosen configuration

3.2 Wing Planform Design

The wing has been designed taking into account the necessity to have good flight performances and low wing structural weight. The aircraft overall performances can be well represented by a general performance parameter introduced by Oswald in NACA TR 408 [3] of 1932 :

$$\Lambda = \frac{\lambda_S \cdot \lambda_T^{4/3}}{\lambda_P^{1/3}} \tag{1}$$

The general parameter is composed by three parameters:

$$\lambda_S = \frac{W}{\left(e \cdot b^2\right)} \qquad \text{effective span loading} \tag{2}$$

$$\lambda_T = \frac{W}{\left(\eta \cdot P\right)} \qquad \text{thrust-power loading} \tag{3}$$

$$\lambda_P = \frac{W}{f} \qquad \text{parasite area loading} \tag{4}$$

where W is the aircraft weight, b is the wingspan, e is the Oswald factor, η is the propeller efficiency and P is the max installed shaft horsepower, f is the equivalent parasite area ($f = CD_o \cdot S$).

These ratios are linked respectively to:
- the energy necessary to develop wing lift (necessary to win the induced drag and associated effects)
- the energy available to develop aircraft engine thrust
- the energy necessary to win parasite drag.

The general parameter Λ combines all main aircraft characteristics and is a good indication of aircraft performances and quality. It is easy to see that the way to increase general aircraft performances is to lower Λ (and so to lower the first two parameters and to increase the third one).

To this aim the wing span has been chosen in order to contain induced drag and to have small value for λ_S.

The wing span has been set to a value of 11.2 m. The wing planform (see fig. 8) has been chosen with the following considerations:

- the mean aerodynamic chord is shifted toward aircraft nose (good for the chosen configuration due to unfavourable CG forward travel mentioned above)
- the internal part of the wing (the flapped part) is rectangular in order to simplify flap construction (flap will be lighter and with lower cost)
- the wing planform (with the external tapered part) leads to a fairly good value of the Oswald span efficiency factor "e" and leads to a safe stall path (as confirmed by wind-tunnel tests).

Concerning induced drag the critical condition will be climb with one engine inoperative (OEI climb). If flight tests will indicate unsatisfactory performances, the aircraft will be modified using improved tip shapes like winglet without making big changes in the wing main structure. The wing airfoils have been chosen in order to reduce parasite drag. A NACA 63A415 (15% thick) modified airfoil has been used in the wing rectangular part together with a slotted flap with low hinge position (see fig. 8). The tip airfoil is a similar airfoil but with 12% thickness.
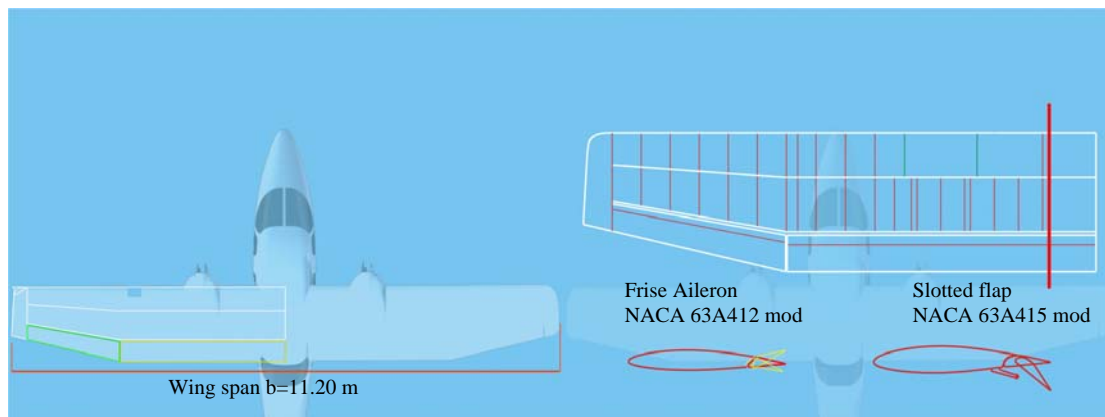
Fig. 8 : wing design

3.3 Fuselage, nacelle and tail group design

The fuselage (see 3D CAD images in fig. 9) has been designed in order to have low parasite drag. The fuselage shape is characterized by a favourable low value of fuselage wetted area over fuselage volume. Nacelle are very small and well streamlined (see fig. 9), due to contained dimensions of Rotax engine.

Fig. 9 : fuselage and nacelle 3D-CAD drawings

As for other Tecnam aircraft a all-mouvable stabilator has been chosen. This choice leads to advantages for aircraft longitudinal control(higher tail efficiency) and for stick-free stability (absence of stability reduction compared to the stick fixed case). In addition the stabilator is a simple structural solution and characterized by a lower cost. The vertical tail has been designed for minimum control speed (V_{MC}) in OEI conditions. A value slightly higher of minimum control speed respect to stall speed (V_{MC} not higher than V_S or 1.1 V_S) has been

chosen to guarantee good and safe take-off characteristics. The V_{MC} chosen value is considerably lower than the certification limit (V_{MC} not higher than 1.2 V_S).

3.4 Aircraft weight characteristics

The general performance parameter does not include any information on aircraft empty weight. Although, as known, the empty weight is one of the most important characteristics to ensure aircraft commercial success. Using standard alluminum alloy construction technique (typical of all light and ultralight Tecnam aircraft) P2006 structural weight is close to the ones of other 4-seat aircraft. As can be seen from fig. 10 P2006 lays very close to the characteristic line (representing We/Wto ratio) of single-engine aircrafts. All other twin-engine models have values of this ratio close to 0.68.
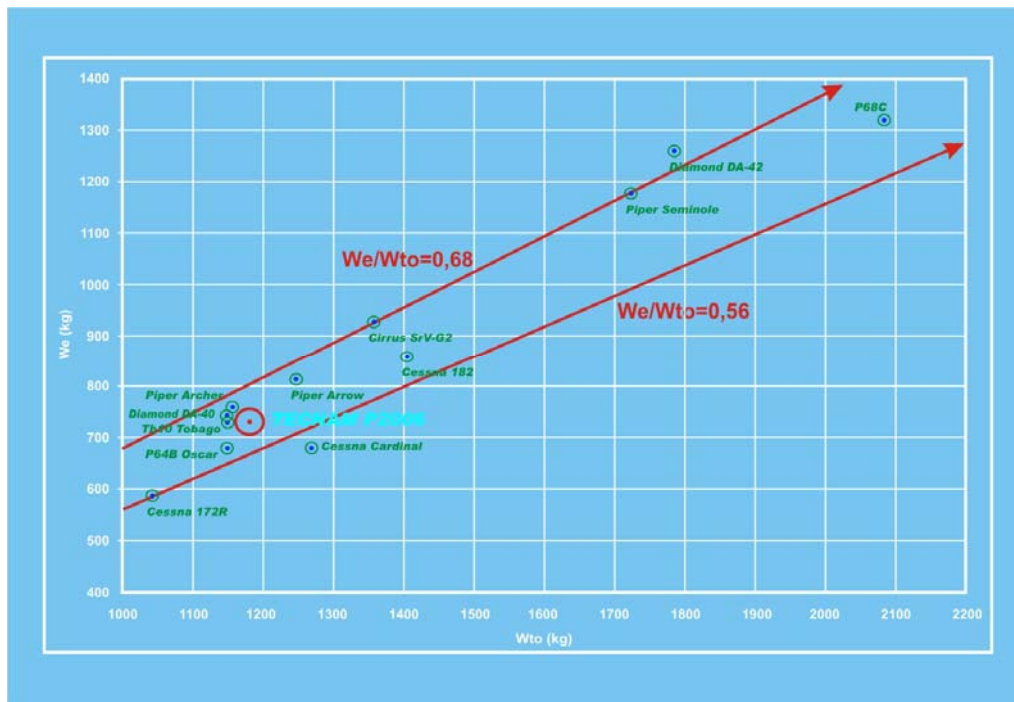
Fig. 10: Empty weight (We) and Maximum Take-off weight (Wto) of several light aircraft

4. AIRCRAFT AERODYNAMICS AND PERFORMANCES

Deep numerical and experimental investigation has been performed on P2006 aircraft at Department of Aerospace Engineering of University of Naples "Federico II". An intensive wind-tunnel test campaign has been carried out during the summer of year 2006 [4]. Department of Aerospace Engineering has been deeply involved in design and testing of Tecnam ultralight aircraft [5]. Expertise on careful analysis and testing techniques has been matured by researchers at Department of Aerospace Engineering[6]. The wind-tunnel belonging to the Department has been used intensively during the last years for the testing and design of light aircraft [7, 8, 9].

Wind-tunnel tests of a 1:6.5 scaled model have been performed on wing-body and complete configuration through 3-component longitudinal balance measurement. Reynolds number during tests was 0.6 million.

Many tests have been performed with and without the two nacelles in order to evaluate their effect on aircraft aerodynamics. Fig. 11 shows some picture with some particular of the aircraft wind-tunnel model. In the figure flow visualization through tufts showing flow separation on nacelle lower surface(that reproduces the original nacelle with engine cooling exhaust) is presented. But as it will be shown in the next figures, the loss of lift is not only in the nacelle area.

In fig. 12 the effect of nacelle on wing-body lift curve is shown. The lift slope is slightly modified by the two nacelle. Lift slope of about 0.080 [1/°] has been measured. The effect of nacelle is a lift coefficient reduction around 0.05 in all the angle of attack range. The same figure shows a tufts visualization of wing stall path. As can be clearly seen from the picture the flow separation is higher at the two sides of the nacelle. The wing external part (aileron) is charaterized by attached flow condition. As already said, the wing planform leads to good stall path with full aileron control at stall conditions.

The effect of nacelle on wing-body moment coefficient is shown in fig. 13. Moment coefficient has been measured respect to cruise aircraft CG position (about 25% of m.a.c. and 20% of m.a.c. below the wing chord as vertical position). The wing-body aerodynamic centre position shows that the fuselage (with large part in front of wing) cause an aerodynamic centre (a.c.) forward shift of about 9-10% of mean aerodynamic chord respect to the wing, supposed to be around 24-25%. This is a measure of fuselage instability and is in good accord with numerical preliminary evaluations. The effect of nacelle on aircraft stability is also measured. In the same figure the moment curve relative to the wing-body+nacelle configuration shows an a.c. further shift of about 3% (compared to the wing-body a.c. position). The loss of stability associated to nacelle is therefore reduced to a reasonable value due to the streamlined and small nacelle shape. In fig. 13 the effect of nacelle on wing-body drag is shown in fig. 13. Relevant parasite drag arises from nacelle shape and from nacelle lower surface separation. Effect on Oswald span efficiency factor (measured to be around 0.74 for wing-body and 0.66 for wing-body+nacelle) has been also measured.

Fig. 14 shows aerodynamic measurement on complete aircraft. From fig. 14a the neutral point position in cruise conditions is around 38% of the m.a.c. A classical behavior due to pendular stability (CG is placed below the chord) leads to a non-linear curve and to an increased static margin at higher angles of attack.

The drag polar at several stabilator deflection (see fig. 14b) leads to the measurement of trimmed drag polar. The measured trimmed drag polar of the complete aircraft+nacelle is characterized by a $CD_o =0.035$ and an Oswald efficiency factor of about 0.70. In order to have an estimation of aircraft drag polar to use for performance calculation, the CD_o value has to be corrected for Reynolds number effects (the cruise Re number is about 7 million respect to 0.6 million in wind-tunnel tests). The assumed trimmed flight polar is: CD_o=0.0254   e=0.70 The equivalent parasite area is f=0.361 m^2. This measured parasite drag characteristics lead to promising flight performances. In fact this value of parasite area is very far to preliminary assumption made during the design phase. The aircraft performances estimation is resumed in table 2. The aircraft should be characterized by good cruise, climb and ground performances.

Fig. 11: P2006 wind-tunnel model
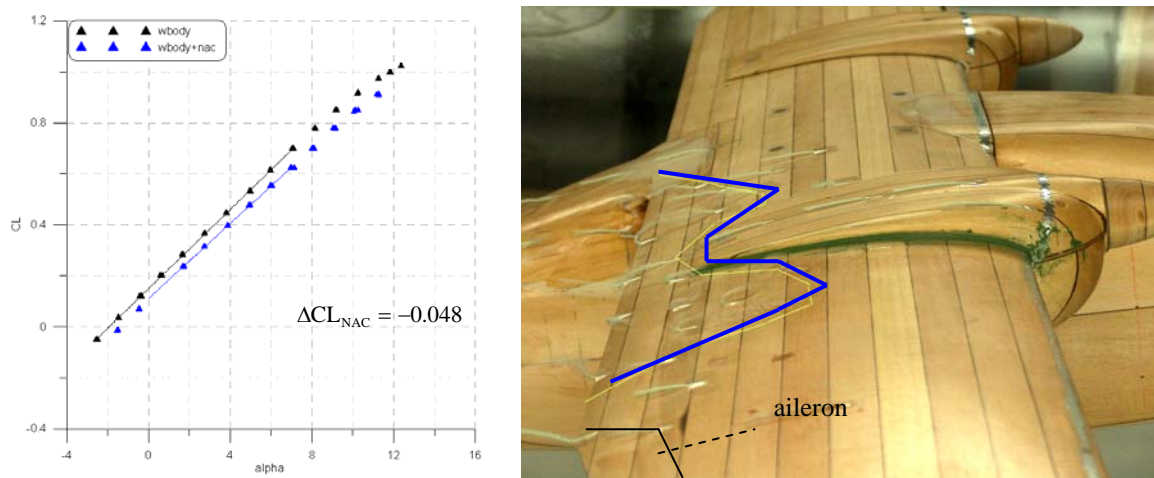

$$\Delta CL_{NAC} = -0.048$$

aileron

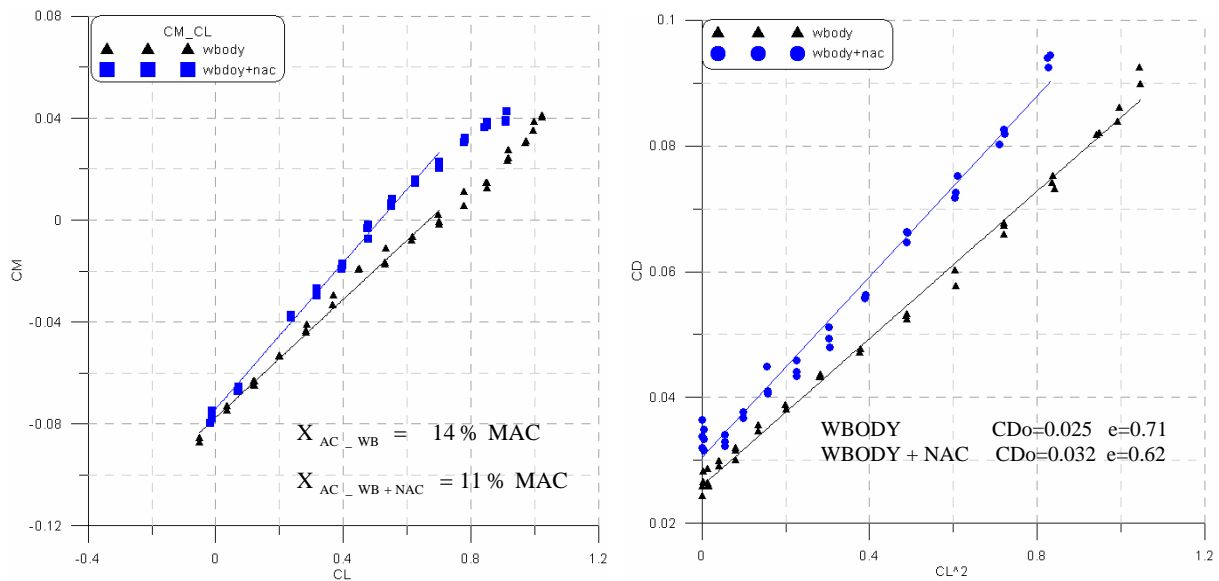*Fig. 12: Wind-tunnel tests: effect of nacelle on aircraft lift(left), wing stall path (right)*

Fig. 13: Effect of nacelle on aircraft longitudinal moment and on wing-body drag polar (wind-tunnel tests)
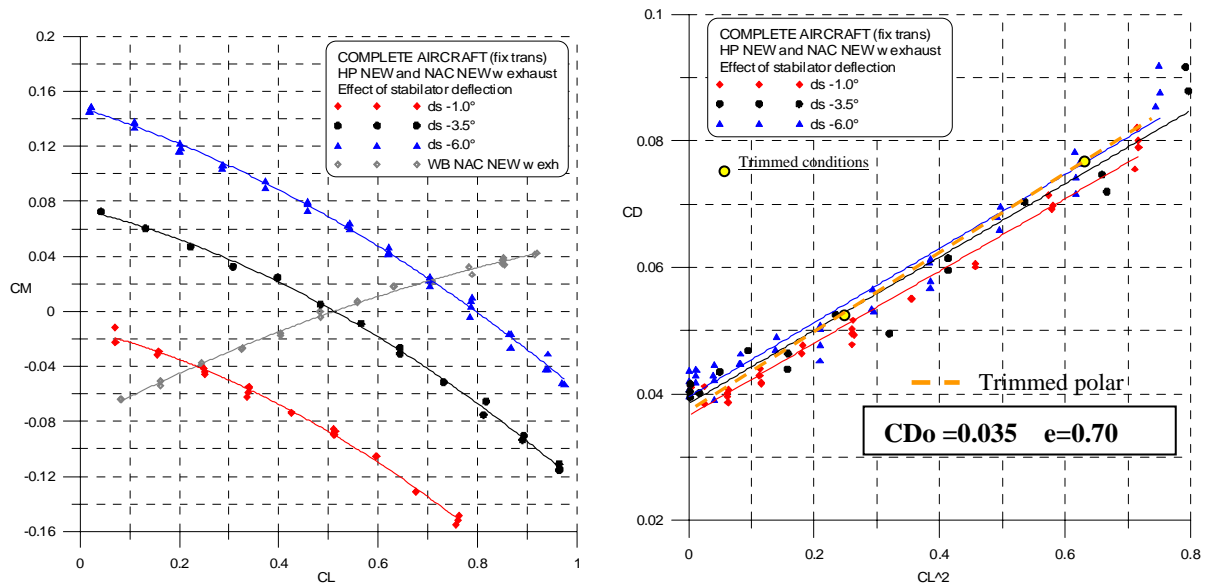

Fig. 13: Complete aircraft at several stabilator deflections. Stability and drag polar (wind-tunnel tests)

Cruise speed @ 75% and 7000 ft	140 Kts (260 Km/h)	Take-Off ground Run	235 m
Max level speed 7000 ft	150 Kts (278 Km/h)	Take-off distance (FAR obstacle)	450 m
Max Rate of Climb @ S/L	1300 ft/min	Range (65% cruise MAP)	1500 Km
Fastest climb speed Vy	83 Kts		

Table 2: P2006 estimated performances

P2006 is characterized by a value of general performance parameter Λ of 0.035. The value shows good performances, considering that other twin-engine aircraft are characterized by higher value of this parameter. In example Diamond DA42 has a value of $\Lambda=0.041$ (18% higher) and Piper Seminole has $\Lambda=0.037$.

4.1 Measurement of fuselage and nacelle effect on wing-span load

In addition the wood model has been equipped with several pressure holes on 4 sections in order to measure fuselage and nacelle effect on wing span loading. As already shown the balance measurement showed a lift coefficient global reduction of 0.05 caused by the two nacelles. Goal of the investigation was to understand the localization of lift loss and to measure effects along wing span. These measurements are useful for wing span loading estimation to be used for certification flight load assessment.

In fig. 14 the localization of the four measurement station is shown. At each station 20 pressure point (obtained through 20 tubes placed in the wood model) were measured along wing chord. The measurements were made closing 3 stations and measuring pressures in the open one.

In fig. 15 the measured span load (c*Cl) lift distribution of wing-body and wing-body+nacelle configurations are shown. In fig 16 and 17 pressure measurement at an angle of attack of 4° are shown for the wing-body and wing-body+nacelle configurations. From fig. 15 and fig. 16 it can be seen that the fuselage leads to a lower lift coefficient on the wing close to wing-fuselage junction. Figure 16 clearly show that the reason of this loss of lift is a lower pressure coefficient (more suction) on wing lower surface close to the fuselage. Pressure on wing upper surface does not seem to be modified in a relevant way. Figure 15 shows that the nacelle leads to a reduced lift not only in the nacelle area, but also at both left and right sides of nacelle on the wing. From fig. 17 it can be seen that the nacelle leads to higher suction on upper wing surface at both sides of nacelle (station 2 and 3).
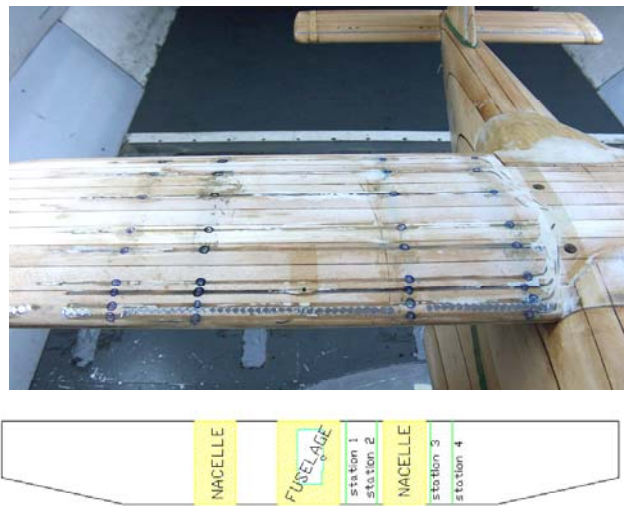

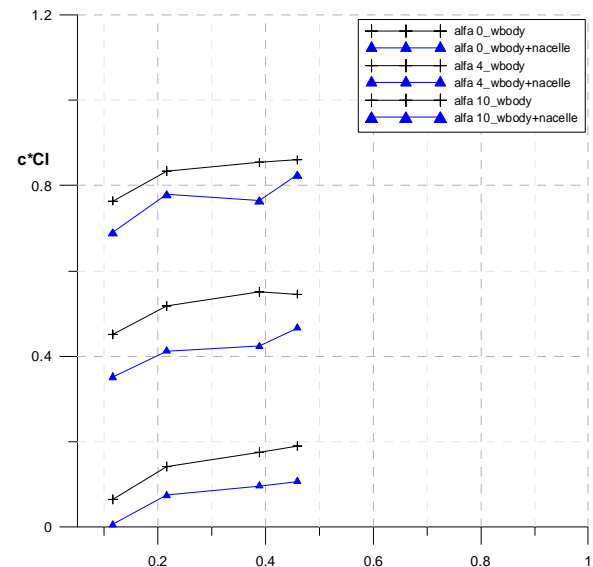
Fig. 14 : pressure holes on the model at 4 stations

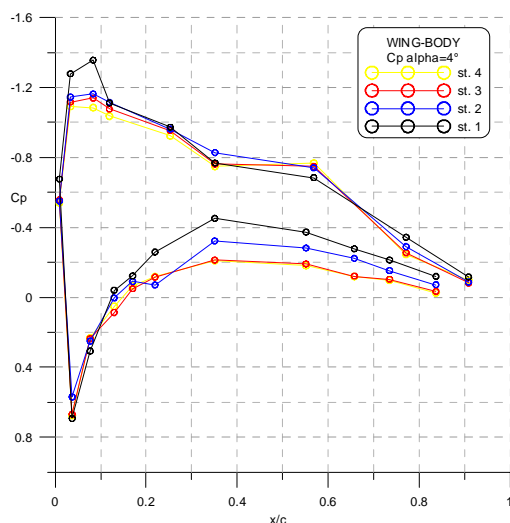Fig. 15 : span load measurement on wing-body with and without nacelle
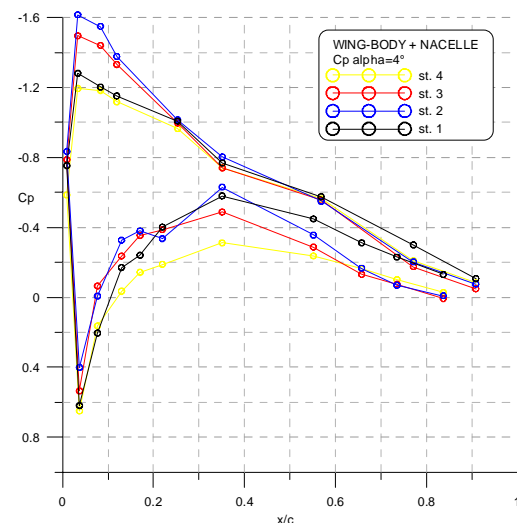

Fig. 16 :Pressure measurement for wing-body, α=4°

Fig. 17 :Pressure meas. for wing-body+nacelle, α=4°

Some aerodynamic calculations have been performed on wing-body and wing-body+nacelle configurations using a 3D standard panel method to confirm wind-tunnel test results and to extend span load estimation up to wing tip. In fig. 18 an example of calculated pressure distribution on wing-body + nacelle is shown. Fig. 19 show pressure distribution on wing-body configuration at alpha=4°. The picture clearly show that a negative pressure area is present at wing-fuselage junction. This confirm the suction which is responsible of wing lift loss at junction (see also figg. 15-16).
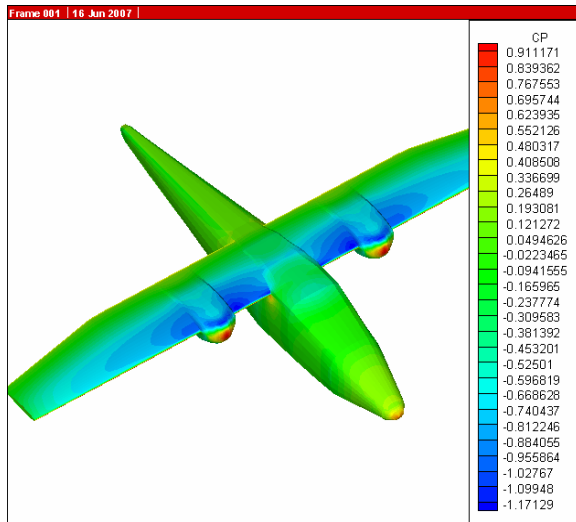
Fig. 18: 3D panel method calc. on wing-body+nacelle   Fig. 19: Calculation on wing-body at alpha=4°
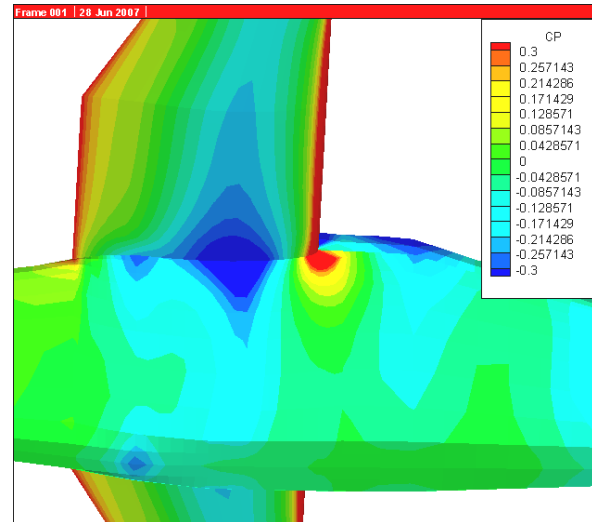
The lift span load (c*Cl) can be calculated at several angles of attack for both wing-body and wing-body+nacelle configuration and is represented in fig.20. The lift in the nacelle area does not take into account the flow separation (the nacelle is modelled as "filled" and so the code "sees" attached flow conditions) and higher values of wing chord (nacelle chord) are considered. Fig. 21 shows a comparison of numerical calculations and wind-tunnel measurements at alpha=4°. A good agreement can be observed.
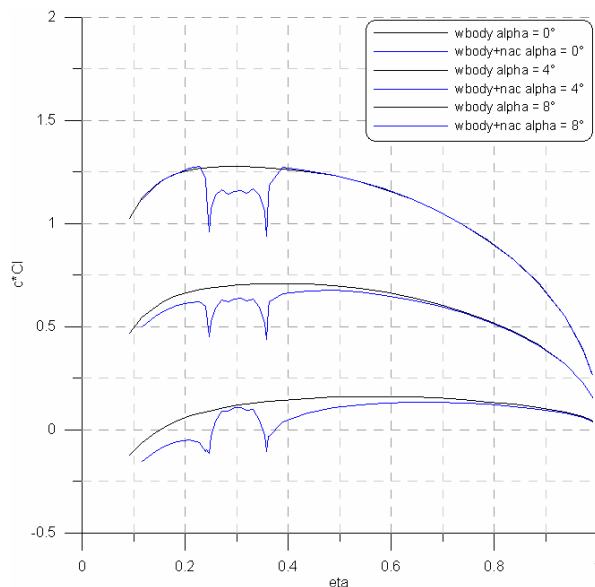

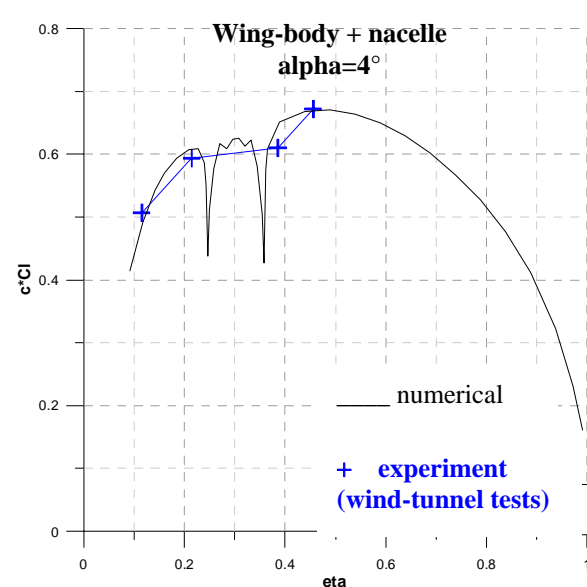Fig. 20: 3D panel method calc. on wing-body+nacelle   Fig. 21: Calculation on wing-body+nac, alpha=4°

The numerical/experimental span load curve can be used to evaluate (for difference between wing lift measured from the integration of wing span load and wing-body+nac lift measured from strain gauge balance) fuselage lift contribution. The fuselage lift is also increased by the presence of landing gear pods that acts like two small wings. In fig. 22 the wing and fuselage span load estimation (through a careful analysis of wind-tunnel measurements and numerical calculations) is presented. The figure shows some possible wing span load curves.

In fig. 22 is possible to see 4 different span load curves that can be assumed for flight load evaluation. All curves are relative to a lift coefficient of CL=0.55, that is the lift coefficient in the D point of the manoeuvre diagram for P2006 aircraft. The yellow curve is relative to the isolated wing and can be evaluated through panel method calculations performed on the wing or through lifting line theory (multhopp or schrenk). The black curve is relative to wing-body and sees the fuselage influence. The lift due to the fuselage (from (y/b/2)=0 to about 0.10) as already said has been estimated for difference between experimental/numerical curve (like that one of fig. 21) and wind-tunnel balance measurement on the configuration which includes the fuselage.

Other two curves can be drawn for the wing-body+nacelle configuration. The first curve (blue one) is obtained from the wing-body one (black) subtracting the area proportional to the nacelle negative lift contribution (fig. 12) estimated through wind-tunnel tests. The fuselage shows higher lift due to the necessity to change angle of attack in order to have always a global lift coefficient of 0.55. The last curve (red one) is the more realistic and is obtained considering the effective pressure distribution on the wing-body+nacelle configuration (see fig. 21) and assuming the same level for the fuselage lift.

The four span load distributions (all with the same global lift load) are used to evaluate structural bending moment at wing connection. Structural moment is evaluated through aerodynamic loads and also taking into account wing structure, systems and engine mass inertia forces (at manoeuvre point D the load factor n is 3.8). The resulting bending moment diagram is shown in fig. 23. It can be seen that, taking the realistic span load curve a lower (up to 10% reduction for the wing-body+nacelle case) bending moment (around 26000 Nm) is obtained at wing root respect to the simplified approach of considering standard schrenk distribution for the wing and so neglecting fuselage and nacelle influence.
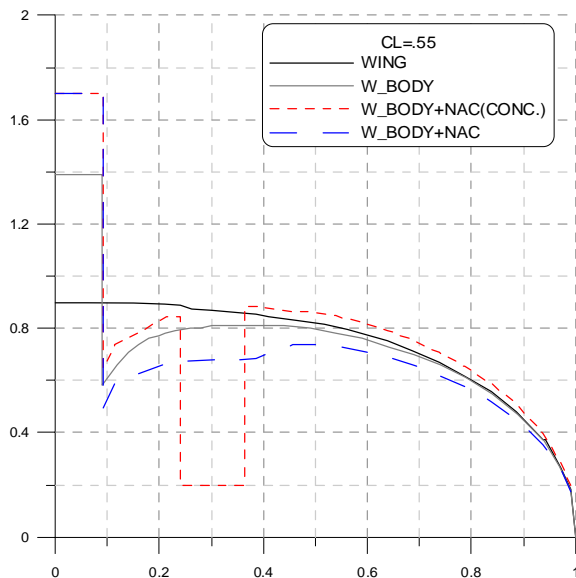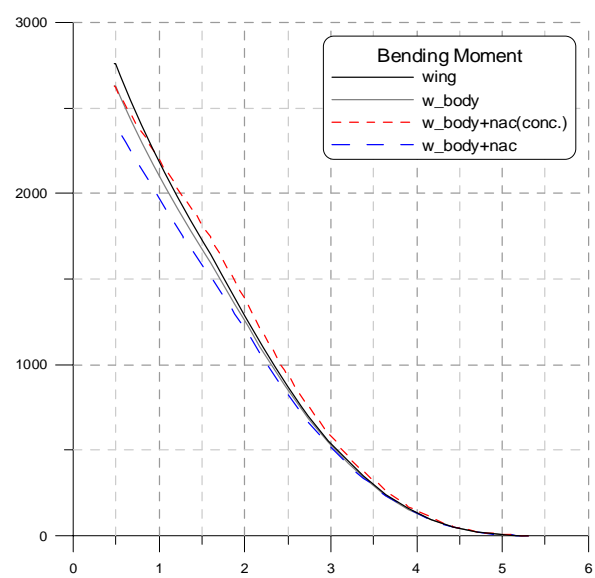

Fig. 22: Possible span load distributions at point D

Fig. 23: Bending moment curves at point D

5. CONCLUSIONS

Design activities concerning P2006 aircraft have been presented. The paper highlights all main aspects that have leaded to the chosen configuration. Comparison with other 4-seats aircraft has been illustrated. Results of a deep wind-tunnel test campaign performed at Department of Aerospace Engineering have been shown. All evaluated performances based on wind-tunnel tests show good potentiality for the aircraft that Particular importance has been devoted to the evaluation (also performed through numerical methodologies) of fuselage and nacelle aerodynamic influence. A deep analysis of wing span load has been performed and presented.

6. AKNOWLEDGEMENTS

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