A POWERED LIFT DESIGN FOR SUBSONIC CIVIL TRANSPORT AIRCRAFT

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Abstract

It has been suggested that the basic configuration of subsonic civil transport aircraft is nearing its full evolutionary potential and a departure in the form of a new configuration or technology is needed. In this paper a jet-flap type powered lift design is being evaluated and then compared to blended wing-body and other advanced technology designs.

Nomenclature

AR	aspect ratio
C_D	drag coefficient
C_{DL}	drag due to lift coefficient
C_{DOFF}	drag coefficient without blowing
C_{DON}	drag coefficient with blowing
C_{DoOFF}	zero lift drag coefficient without blowing
C_{DoON}	zero lift drag coefficient with blowing
c_j	jet momentum coefficient
C_L	lift coefficient
C_{LOFF}	lift coefficient without blowing
C_{LON}	lift coefficient with blowing
D	drag
e	Oswald factor
J	jet momentum
k_1	jet flap type factor
L	lift
m_D	mass flow rate of the jet engines dedicated to the jet flap operation
m_j	jet mass flow rate
MWE	manufacturer's empty weight
OWE	operational empty weight
sfc	specific fuel consumption
sfc_B	baseline specific fuel consumption
sfc_D	specific fuel consumption of the jet engines dedicated to the jet flap operation
S_W	wing area
T_{DP}	thrust produced by the jet engines dedicated to the jet flap operation
T_{DR}	thrust required from the jet engines dedicated to the jet flap operation
TOW	take-off weight
V_j	jet flow velocity
V_∞	freestream velocity
W_{DA}	additional jet engine weight
ΔC_D	change in drag coefficient due to blowing
ΔC_L	change in lift coefficient due to blowing
θ	jet deflection angle
ρ	density of air

1 Introduction

Since the late fifties subsonic civil transport aircraft technology has advanced substantially. This advance has been evolutionary and, consequently, the basic aircraft configuration has remained essentially unchanged. It has been suggested [1] that the conventional aircraft configuration is nearing its full evolutionary potential and a departure in the form of a new configuration or technology, or a combination of both, is needed. As a result a number of alternative concepts have been put forward, such as the blended wing-body, non-planar wings, laminar flow control, propfan and powered lift.

Powered lift is an augmentation of the wing lift obtained by various degrees of integration of the wing and the propulsion plant. Wing lift is augmented in three ways: vectored thrust - direct lift, boundary-layer control and supercirculation. Among the powered lift concepts that have been developed are the externally blown flap, the augmentor wing, the circulation control airfoil and the jet flap. The externally blown flap has been used in STOL aircraft, and more advanced concepts like the jet flap have been flight-tested in experimental aircraft. Most of them have been developed for use in the take-off and landing phases, but there in no reason why, suitably adapted, they could not provide additional lift in cruising conditions. This is something that has been originally suggested by Davidson [2] and, more recently, by Capone [3].

With the jet flap, a portion of the engine exhaust jet, or bleed air, emerges through ducts, in the form of a thin sheet, near the trailing edge of the wing at a downward angle to the mainstream flow. The jet flap provides higher lift by combining boundary-layer control and supercirculation [2]. The lift coefficient of a jet-flapped wing depends on the jet momentum coefficient and the jet deflection angle, and can reach values ten times those of conventional wings [2,3,4,5].

However, the exceptional lift characteristics of the jet flap would not be of much use in cruising conditions if they were to be accompanied by a drag increase of the same order. In Davidson's paper [2] a drag component due to the jet is added to the drag of the wing. Furthermore, a jet-to-mainstream velocity-density product ratio is established as a criterion of the drag due to the jet. According to this ratio the jet drag may be positive or negative. It is possible, therefore, to have a thrust gain. This thrust gain has been reported elsewhere [3,6] as a very high thrust recovery.

A different approach for the drag due to the jet flap is followed by Malavard, Poisson-Quinton and Jousserandot [4]. The jet drag is defined as being made of a pressure term due to the change of the airfoil drag in the presence of the jet flap, an induced drag term due to the additional lift produced by the jet flap and a term representing the thrust of the jet. Again, an apparent drag reduction or thrust gain has been observed.

The jet flap was initially conceived as an integrated lift/propulsion concept. The lift/propulsion integration offered by the jet flap has been demonstrated in the Hunting H 126 research aircraft [7]. Due to the nose-down moment exhibited only part of the propulsion plant flow was used. Some of the remaining, in the form of thrust, served to balance this moment. Therefore, even partially, the jet flap provided thrust in addition to lift. The Hunting H 126 has demonstrated in actual flight conditions the potential of the jet flap, having achieved a maximum usable lift coefficient of around six [8].

Jet-flapped wings exhibit very high lift at high values of jet momentum coefficient and jet deflection angle, and lower drag, which leads to very high L/D ratios, at low values of jet momentum coefficient and jet deflection angle. Thus, jet-flapped wings offer superior performance over the whole spectrum of flight.

In this paper a jet-flap type powered lift design for ultra-high capacity, long-range subsonic civil transport aircraft is being evaluated and then compared to a very-advanced projected-technology conventional configuration, a pure flying wing and a blended wing-body design.

2 Methodology

The usual approach to civil transport aircraft technology assessment is to estimate the effect of technology on Direct Operating Costs (DOC). Here a simpler approach will be adopted choosing fuel costs as the criterion of assessment.

To begin with, payload, range and speed of the ultra-high capacity, long –range jet-flap type powered lift design have to be specified. A payload of 72 600 kg based on a typical three-class 800 passenger aircraft is assumed. Range and speed are set at 13 000 km and 490 kt (M 0.85 at 35 000 ft) respectively. Next, the lift-to-drag (L/D) ratio, the specific fuel consumption (sfc) and the structural weight increase are evaluated and then, using the Breguet equation, the fuel consumption per passenger per distance traveled is calculated. For the evaluation of the structural weight increase and for comparison purposes a baseline design is included. This Baseline Aircraft represents a 1993 level of technology. The Baseline Aircraft L/D ratio and sfc are 19.5 and 0.55 kg/h kg respectively. The structural weight of the Baseline Aircraft in terms of MWE/(TOW-MWE) is the datum by which the other designs are compared.

3 Design Evaluation

3.1 Configuration

In order to evaluate the L/D ratio, the sfc and the structural weight increase the configuration of the design has to be defined.

The configuration is similar to that of a conventional subsonic civil transport aircraft as far as the fuselage, the tail and the undercarriage are concerned. The main difference lies with the wing and the engines.

The proposed design incorporates a number of jet engines buried in the wings, exhausting through fishtail ducts, from high aspect ratio two-dimensional nozzles located at a small control flap. These engines are positioned chordwise between the two wing spars. Their intakes are situated in the upper surface of the wing (Fig. 1), as exemplified in the Northrop Grumman B-2. Their basic purpose is to provide the jet of the jet flap, but they also provide the thrust needed in cruising conditions. In addition, there are two more engines buried in the wings, one each side, with conventional exhausts, which operate during climb, acceleration and emergencies.

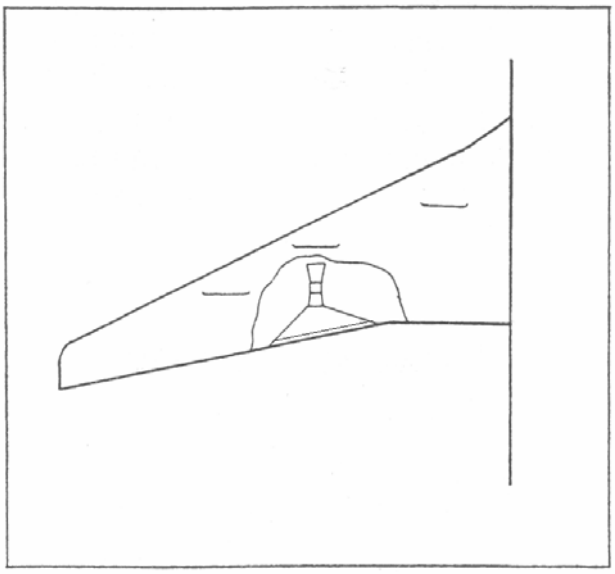

Fig. 1. Jet engines buried in the wing

3.2 L/D Ratio and Thrust Recovery

The jet flap concept is known to achieve very high lift coefficients which depend on jet momentum coefficient, jet deflection angle and jet ejection type – plain, with the use of a control flap or otherwise.

The drag coefficient of jet-flapped wings varies, resulting in L/D ratios ranging from low to very high values. For STOL applications high lift is of importance and low L/D ratio does not matter, but for the application of jet flap to cruising conditions the L/D ratio is the deciding factor.

The physics of lift and drag due to lift of jet-flapped wings are relatively well understood [2,4,9]. The lift coefficient due to the jet is given by:

$$\Delta C_L = k_1 c_j^{1/2} \sin \theta \qquad (1)$$

and the drag due to lift coefficient

$$C_{DL} = C_L^2 / (e\pi AR + 2 c_j) \qquad (2)$$

The uncertainty lies with the zero lift drag and more specifically how this is affected by the flow field in the presence of the jet. The difference between zero lift drag of the wing with and without blowing is related to a number of parameters but mainly to the entrainment drag caused by jet mixing.

As noted in most references the drag of the wing with blowing is smaller than the drag of the wing without blowing [2,3,5]. A possible exception are the experimental results by Dimmock [10] reported in the paper by Maskell and Spence [9] which show a dependence of the zero lift drag coefficient on the jet momentum coefficient.

Another, indirect, proof of drag reduction with blowing is by means of the thrust recovery. Thrust recovery is defined to be the fraction of the total jet thrust that is actually recovered as a horizontal force on the jet-flapped wing. Thrust recovery is also a function of jet mixing, but is a matter of flow separation as well. Therefore, it is related to drag but experimentally it is difficult to separate thrust and drag of a jet-flapped wing. Another complication in this respect is that thrust recovery is defined in different ways [3,4,11] and, most probably, some definitions mix thrust with drag terms. This must be the case of ref. 5 where a drag coefficient reduction of around 1.2 is shown. Ref. 3 gives a drag coefficient reduction of up to 0.025 but, then, attributes this reduction to a reduction in drag due to lift. All these differences can also be attributed on configuration and jet flap arrangement. Nevertheless, regardless of definition, thrust recovery of nearly or even higher than 100 %, as shown in refs 4 and 11, is a proof of drag reduction.

All the references which present experimental results indicating a drag reduction attribute this to zero lift drag. There is one exception [3] which accounts part of this reduction to drag due to lift. As this drag-due-to-lift reduction takes place at constant jet momentum coefficient, jet deflection angle and Mach number it is difficult to explain its origins. Perhaps, it is a function of the angle of attack but, then, the situation becomes even more complicated.

Consequently, it will be assumed that the observed drag reduction is a reduction of zero lift drag and, using the scarce data available, an evaluation of a typical L/D ratio of a jet-flapped wing will be attempted.

Using equations 1 and 2, the drag polar and the D/L ratio for zero angle of attack, α, are given by:

$$C_{DON} = C_{DoON} + C_{LON}^2 / (e\,\pi\,AR + 2\,c_j) \qquad (3)$$

$$C_{LON} = \Delta C_L = k_1\,c_\mu^{1/2} \sin\theta \qquad (4)$$

$$C_{DON} = C_{DoON} + k_1^2\,c_j\,\sin^2\theta / (e\,\pi\,AR + 2\,c_j) \qquad (5)$$

$$D_{ON}/L_{ON} = C_{DON} / C_{LON} = C_{DoON} / k_1\,c_j^{1/2} \sin\theta + k_1\,c_j^{1/2} \sin\theta / (e\,\pi\,AR + 2\,c_j) \qquad (6)$$

Reading off values for C_L and C_D from the drag polar of ref. 3 (fig. 8) for jet deflection angle δ=30 ˚ , Mach number M=0.7, jet momentum coefficient c_j=0.125, Oswald factor e=0.93 and aspect ratio AR=3 and using eqn. 3 the zero lift drag with blowing C_{DoON} is found which has a value of around 0.0011. Then, using fig. 12 of ref. 3 of the drag difference with and without blowing ΔC_D and fig. 7 of the lift difference with and without blowing ΔC_L, the lift C_{LOFF} and the drag C_{DOFF} coefficients without blowing are found. Substituting the C_{DOFF} and C_{LOFF} values into the polar of the wing without blowing

$$C_{DOFF} = C_{DoOFF} + C_{LOFF}^2 / e\,\pi\,AR \qquad (7)$$

the zero lift coefficient without blowing C_{DoOFF} is found which has a value of about 0.0141. The difference between C_{DoON} and C_{DoOFF} is near to – 0.013 and the zero lift drag with blowing C_{DoON} is less than 10 % of the zero lift drag without blowing C_{DoOFF}.

The same order of magnitude of zero lift drag difference with and without blowing can be deduced from ref. 5. Examining the three cases - c_j=0.52, 1.03 and 1.53 – presented, the zero lift drag difference with and without blowing were deduced to be -0.031, -0.016 and -0.014 respectively. The jet flap arrangement of ref. 5 is quite different of that of ref. 3 but lift and drag of jet-flapped wings depend mainly on jet momentum coefficient and jet deflection angle and much less on jet flap type.

Taking into account the above, in the attempt to evaluate a typical L/D ratio of a jet-flapped wing design, a zero lift drag with blowing coefficient C_{DoON} at 10 % of the value of the wing without blowing will be assumed. A typical value of 0.018 for the zero lift drag coefficient without blowing results in a zero lift coefficient with blowing of 0.0018.

The other parameters of the jet flap should be chosen in such a way as to maximize the L/D ratio. Eqn 6 indicates that the smaller is the jet deflection angle θ the higher is the L/D ratio. It is not clear how small this angle can be but certainly it should be bigger than the wing trailing edge semi-angle. The same applies to the jet ejection type factor k_1 and, to a lesser extent, to the jet momentum coefficient c_j.

All these are subject to constraints. One constraint is that the lift coefficient C_L should be small enough to be possible for the jet flap to act as a high lift device at higher values of jet momentum coefficient and jet deflection angle. In this way the jet flap is used as a low drag – high L/D ratio concept in cruising conditions and as a high lift device during take-off and landing.

Another constraint is that C_L should not be too small because it would lead to a large wing area and all the subsequent disadvantages.

Considering the constraints in relation to eqn 6 values of 6.5, 0.125 and 10° for the jet flap type factor k_1, jet momentum coefficient c_j and jet deflection angle θ respectively have been selected. Substituting these into eqn 6 a L/D ratio of 55 is found corresponding to a lift coefficient C_L of 0.4.

3.3 Specific Fuel Consumption (sfc)

In a jet-flap type aircraft design sfc depends on thrust recovery and losses due to the ducting. As mentioned before, in the configuration definition, thrust is provided by two conventional jet engines under and a number of dedicated jet flap engines buried in the wings, exhausting through fishtail ducts, from high aspect ratio two-dimensional nozzles located at a small control flap.

Thrust recovery and duct losses apply only to the dedicated engines. The jet momentum coefficient c_j of 0.125 and the jet deflection angle θ of 10°, corresponding to the L/D ratio of 55, can assure an almost 100 % thrust recovery [11]. Hence, the only effect on sfc is duct losses and to investigate their importance the thrust produced by these engines has to be calculated.

Using the C_L value of 0.4, corresponding to the L/D ratio of 55, and assuming a speed of M 0.83 at 30 000 ft, a take-off wing loading of 5960 N/m^2 is found. This take-off wing loading in conjuction to the take-off weight of 291 000 kg obtained after a few iterations (a similar jet flap design of ref. 12 has a take-off weight of 309 000 kg), results in a wing area of 479 m^2. The jet momentum coefficient c_j is given by:

$$c_j = J / ½ \rho V_\infty^2 S_W \qquad (7)$$

where

$$J = m_j V_j \qquad (8)$$

It should be underlined that the jet velocity V_j refers to the exit of the fishtail duct and not the engine exit. Substituting the jet momentum coefficient c_j of 0.125, the wing area S_W of 479 m^2 and the speed of M 0.83 at 35 000 ft in eqn. 7 results in a jet momentum J of 867 845 N.

Very little has been published on diffusers with substantial streamwise variation in the cross-sectional aspect ratio, characteristic of fishtail diffusers. Yaras [13], one of the few references on the subject, presents experimental results which indicate a pressure recovery comparable to straight conical diffusers. If this is the case, using typical values for intake and exhaust losses [14] a specific thrust due to duct losses of 16 m/s is assumed. This is a very rough approximation for a jet engine with a by-pass ratio of 12. To proceed with the calculation of the jet velocity V_j the drag at the speed of M 0.83 at 30 000 ft must be found first.

With a L/D ratio of 55 and a corresponding lift C_L of 0.4 the drag coefficient is 0.4 / 55 = 0.00727 giving a drag D of 52 075 N. The thrust produced by the dedicated jet engines T_{DP} must equal the drag. Ignoring pressure terms, the mass flow rate of the dedicated engines is given by:

$$T_{DP} = D = m_D (V_j - V_\infty) \qquad (9)$$

$$m_D = D / (V_j - V_\infty) \qquad (10)$$

but

$$m_j = m_D = J / V_j \quad (11)$$

thus

$$J / V_j = D / (V_j - V_\infty) \quad (12)$$

$$V_j = V_\infty J / (J - D) \quad (13)$$

Substituting into eqn 13 the values for V_∞ (M 0.83 at 30 000 ft), J and D a jet velocity V_j of 267.5 m/s is obtained and, hence, from eqn 9 the mass flow rate of the dedicated jet engines m_D is found to be 3 355 kg/s. The thrust required of the dedicated jet engines taking into account the duct losses representing 16 m/s of specific thrust is:

$$T_{DR} = m_D (V_j + 16 - V_\infty) \quad (14)$$

$$= 107\ 360 \text{ N}$$

Assuming that the trust needed by large subsonic transport aircraft is made of the thrust necessary to overcome the drag plus a 50 % for acceleration, climb and emergencies [15] the thrust split between the dedicated and the two conventional jet engines is 2 to 1. With a baseline sfc at 0.55 kg/h kg the sfc of the dedicated engines, which is the sfc of the aircraft, since the other two jet engines do not operate during cruising conditions, is given by:

$$sfc = sfc_D = sfc_B\ T_{DR} / T_{DP} \quad (15)$$

$$= 1.13 \text{ kg/h kg}$$

3.4 Structural Weight Increase

It is even more difficult at the conceptual stage to access issues relating to structural weight. Increased weight can be accounted on the greater number and thrust of engines and the fishtail ducts. On the other hand there is a weight reduction because as the jet flap acts as a high-lift device, flaps are made redundant.

To find the number of the jet engines dedicated to the jet flap operation the geometry of the wing has to be defined. For a wing area S_W of 479 m^2 and an aspect ratio AR of 10 a wing span b of 69.2 m and a mean chord c_m of 6.92 m are found. The dedicated jet engines, as already mentioned, are positioned between the two wing spars, and the fishtail ducts are located between the rear spar and the small control flap at the trailing edge. Assuming that the rear spar of the wing box is located at 65 % of the chord a chordwise mean distance of 35 % of the chord – around 2.4 m – is left for the fishtail ducts. If the fishtail ducts have a semi-angle of 60° [16], the whole semi-span of the wing can be covered by four fishtail ducts.

Therefore, the number of the dedicated jet engines is four on each side. As the total required dedicated jet engine thrust has been calculated to be 107 360 N, the average required dedicated jet engine thrust is around 13 420 N. With a lapse rate of 0.28 at M 0.83 and 30 000 ft [17] the engine sea level static thrust is 47 930 N (10 750 lbf). Jet engines of this size with a bypass ratio of 12, that has been assumed, do not exist. With a typical engine weight of 900 kg [15] for an engine of the same thrust, the additional weight is the percentage of engine thrust lost due to the ducts.

$$W_{DA} = 900\ (T_{DR} - T_{DP}) / 13\ 420$$

$$= 3\ 710 \text{ kg}$$

Duct weight is a matter of duct dimensions and materials. Work on fishtail duct weight was not available at the time of writing. Using general information on intake and duct weight [18], the length of the fishtail ducts, typical values for capture area and maximum pressure and a factor of 2 to include heat resistant material and insulation, a weight of 240 kg per intake and fishtail duct was obtained.

Flap weight estimation was based on the Torenbeek method [14,19]. Again with typical values, derived from statistics of existing aircraft, the weight of the flaps that would have been used is around 4 300 kg. With the same method the small control flap of the jet flap arrangement has a weight of 360 kg.

The weight of the jet engine pylons that would have been used was estimated, on the basis of total thrust at sea level, at 1430 kg.

Adding the weight of the dedicated jet engines attributed to losses, the weight of the eight fishtail ducts and the weight of the small control flap results in a total of 5 990 kg . Subtracting the weight of the flaps and the pylons that would have been used gives an increase in structural weight of only 260 kg. There are some other items, such as the castellated beams needed to accommodate the exhaust and the supporting structure of the dedicated jet engines, which are not in any way quantifiable at the conceptual design phase and in any case their contribution is minimal. On the whole it is rather clear that the order of magnitude is right and weight remains unchanged. The structural weight of the proposed design as a function MWE / (TOW-MWE) ratio of the baseline aircraft is essentially the same.

4 Comparison and Discussion

Substituting the evaluated L/D ratio, sfc and weights and the specified speed and range into the Breguet equation, suitably adapted, the fuel consumption is calculated.

The results are presented in Table 1 together with three other advanced designs. These are the Liebeck, Page and Rawdon Blended Wing-Body (BWB) [20], a projected current technology and a pure flying wing. The Baseline Aircraft, the Projected Technology and the Pure Flying Wing designs are, with minor corrections and modifications, those of refs 12 and 21.

The Baseline Aircraft has been chosen to represent the technology level of the year 1993 because new large long-range four-engine subsonic civil transport aircraft have not been put into operation since. The Liebeck, Page and Rawdon BWB [20] is a benchmark concept combining some flying wing qualities and very advanced technology. The Projected Technology to the year 2005 concept (ref.12, 1996), although the year 2005 has arrived, gives an indication of what was forecast in the late 80's and early 90's for the next 15 years in all areas of aerodynamics, structures and propulsion. The Pure Flying Wing is an example of the best configuration in relation to structural weight. Otherwise it is at the year 1993 technology level. The Jet Flap design is an example of a concept with superior aerodynamics. Otherwise it is at the year 1993 technology level.

The technology level is represented by the L/D ratio, the sfc and the MWE / (TOW-MWE) ratio. The designs have been specified for a typical three-class seating capacity of 800 passengers and a 13 000 km range cruising at M 0.85 and 35 000 ft. An exception is the Pure Flying Wing with 1 600 passengers, because the 800 passenger capacity is too small for achieving the structural benefits of the flying wing, flying higher at 39 000 ft at a slower speed of M 0.75 where it is more efficient [22].

The results of the comparison in respect to the amount of fuel consumed per seat-km indicate that the Projected Technology design is the best design. The Jet Flap comes second with the BWB and the Pure Flying Wing following. The point is that very few if any of the advances envisaged 15 years ago, and embodied in the Projected Technology design, have materialized. To some extent, the same applies to the BWB as it encompasses advanced technology in aerodynamics and propulsion. The Pure Flying Wing offers the worst performance which, ignoring the higher flying height, is wholly based on reduced structural weight due to configuration. In addition, its enormous wing span renders it a poor choice among the four designs regardless of fuel consumption.

The Jet Flap design, in contrast to the Projected Technology and the BWB, is based on only one technology: the jet flap concept. This fact, in effect, makes it the best design. Its fuel consumption at 7.2 gr of fuel per seat-km is 73 % lower compared to the Baseline Aircraft design.

The problems associated with a jet flap design are many. However, the development

	Baseline (1993)	Projected Technology (2005)	Pure Flying Wing	BWB (Liebeck, Page and Rawdon, 1996)	Jet Flap
Range (km)	13 000	13 000	13 000	13 000	13 000
Number of passengers	800	800	1 600	800	800
Cruise Mach number at altitude (ft)	0.85 35 000	0.85 35 000	0.75 39 000	0.85 35 000	0.85 35 000
Max L/D	19.5	27.0	25.2	29.3	63.5 (equivalent)
Cruise sfc (kg/h/kg)	0.550	0.435	0.678	0.439	1.13
Change in structural weight based on MWE/(TOW-MWE) (%)	---	- 40.8	- 71.5	+ 2.8	0.0
Payload x 10^{-3} (kg)	72.56	72.56	145.12	72.56	72.56
OWE x 10^{-3} (kg)	352.79	88.71	134.47	187.70	139.68
Fuel x 10^{-3} (kg)	275.89	51.65	208.27	82.86	75.05
Fuel reserves x 10^{-3} (kg)	22.40	4.01	24.40	21.94	3.70
TOW x 10^{-3} (kg)	723.64	216.93	512.26	365.06	291.00
gr of fuel consumed per seat-km	26.5	5.0	10.0	8.0	7.2

Table 1. Results

and entry into service of the Northrop Grumman B-2, an aircraft with four jet engines buried in the wings, leads to the conclusion that many of the purely engineering problems of the installation and operation of the jet engines of such configuration – materials, insulation, proximity to fuel tanks and others - have been solved. The only difference in wing-engine configuration between the Northrop Grumman B-2 and the jet flap design put forward here are the fishtail duct and the small control flap. It should also be noticed that not only the engineering problems of B-2 wing-engine configuration have been solved, but, judging from B-2's range and weights [15], this configuration has not compromised its performance. Its L/D ratio is low but it is, more or less, what it would be expected from a flying wing design.

Other main problem areas of the proposed jet-flap type design are the drag reduction in cruising conditions and the matching of jet engine characteristics, fishtail duct geometry and jet momentum coefficient requirements. The relation between the drag coefficient, and in particular the zero lift drag coefficient, and the jet momentum coefficient and deflection angle is the most crucial factor for the success of the jet flap concept in cruising conditions. As for the jet engine, most probably, a special type will have to be developed.

Some of the minor areas of concern are control and maintenance. Present-day electronic flight control systems are much more capable to handle problems such as the pitching-down moment exhibited by jet-flapped aircraft. During cruising conditions the jet deflection angles are small but at take-off and landing large jet deflection angles would necessitate some action. This could have the form of larger deflections or areas of the tail control surfaces or even the use of a canard [3]. On the whole, the fact that lift and thrust can be controlled through different engines facilitates control handling. Maintenance costs will be higher due to the more complicated wing structure, as witnessed with the B-2 [15], and the greater number of engines.

5 Concluding Remarks

An evaluation of a powered lift jet-flap type subsonic civil transport aircraft design has been attempted. The jet flap serves both to provide very high L/D ratios during cruising conditions and high lift in the take-off and landing phases. Comparison with advanced technology, blended wing-body and flying wing concepts in terms of fuel consumed per seat-km indicated that the proposed design is the most promising. However, a number of issues have to be investigated much further, the most important being the relation between drag coefficient and jet momentum coefficient and deflection angle.

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