A BRIEF COMPARISON OF POWERED LIFT, FLYING WING AND CURRENT TECHNOLOGY SUBSONIC CIVIL TRANSPORT AIRCRAFT CONCEPTS

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Abstract

Since the introduction of the jet engine, subsonic civil transport aircraft technology has advanced substantially. This advance has been evolutionary, consequently the basic aircraft configuration has remained essentially unchanged. It has been suggested that the conventional aircraft configuration is nearing its full evolutionary potential and a departure, in the form of the flying wing concept, has been proposed for ultra-high-capacity aircraft.

The application of powered lift has already been considered for cruising flight conditions. In this paper a powered lift-jet flap concept is put forward as an alternative to both the flying wing and current aircraft technology. By means of a case study, three subsonic civil passenger aircraft concepts are evaluated: the flying wing, the jet flap and one based on projected developments in current technology. Then, using the Breguet equation, they are compared in terms of fuel consumed. For comparison purposes each concept does not include the technology features of the other two.

This comparison produced similar results for the jet flap and the projected current technology, showing that further investigation is needed. The flying wing not only comes behind the jet flap and the projected current technology in relation to the fuel consumed, but, due to the enormous size required for it to carry passengers, it poses a number of additional problems.

Introduction

Since the introduction of the jet engine in the late fifties, considerable improvements have been made in subsonic civil transport aircraft aerodynamics, structures, propulsion and systems, but none could be regarded as a revolution, thus the basic aircraft configuration has remained essentially unchanged.

It has been suggested that the present subsonic civil transport aircraft configuration is nearing its full evolutionary potential, and a departure in the form of the flying wing concept has been proposed[1,2]. Furthermore, flying wing designs appear among the proposals for the future Ultra-High-Capacity Aircraft (UHCA)[3,4,5,6].

The flying wing has been known for many years. Examples of flying wing design range from the Northtrop prototypes of the forties to today's B-2[7,8]. The main advantage of the flying wing is its lower structural weight due to the distribution of weight, lift and, possibly, landing loads along the span[7,9,10,11]. Aerodynamicaly, there is general agreement that the flying wing is inferior to an optimum conventional configuration[7,12,13]. A further conclusion is that the best flying wing configuration is a thick wing of low aspect ratio [8,9,13]. Usable volume is an additional factor in the evaluation of the flying wing as a transport aircraft[13]. The overall performance of the flying wing as is still a matter of some debate[7,8,9,11,12,13,14].

In this paper a powered lift-jet flap concept is put forward as an alternative to the flying wing and current aircraft technology such as: laminar flow, composite structures, very-high-bypass ratio engines and advanced control systems.

Powered lift is not a new technology [15]. 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[15,16,17]. The application of powered lift has already been considered for cruising flight conditions [18,19,20].

In this paper, by means of a case study, three subsonic civil passenger aircraft concepts- the flying wing, the jet flap and one based on projected developments in current technology- are evaluated and then compared.

Methodology

Comparison Approach

The usual approach to civil transport aircraft technology assessment is to estimate the effect of technology on Direct Operating Costs (DOC).

However, a comparison of the three concepts in terms of DOC is beyond the scope of this paper. A simpler approach will therefore be adopted; choosing fuel costs as the criterion. The choice of fuel costs, and hence fuel consumption per passenger and distance travelled (kg of fuel/seat-km), presupposes that all DOC, other than fuel costs, are similar for the three concepts. This is not an unreasonable assumption if the three concepts are the same size; provided their development costs are also comparable.

In order to evaluate the three concepts, and then compare them according to the adopted criterion, the Breguet formula will be used. For this evaluation the various parameters of the Breguet formula have to be estimated or, in cases where this is not possible, chosen from the available sources for each of the three concepts.

For the evaluation and the comparison of the three concepts range, speed and payload have to be specified. A first estimation of payload as 72500 kg is based on an 800 passenger UHCA. Range and speed are set at 13000 km and 470 kt (M 0.81, 35000 ft) respectively; typical of very long-range subsonic civil transport aircraft.

Concept Technology Definition

Another problem facing a comparison of three very different concepts is the definition of the technology of each concept.

The objective of this study is to weigh each concept against the others. Consequently, technology features that characterize any one concept must not be present in the other two. For example, laminar flow is a current technology concept feature not present in the flying wing and the jet flap concepts.

The development period of each concept is difficult to predict; a situation well known in aerospace projects. It is equally difficult to assess the technology level that can be achieved over this period. For the present comparison study a nominal development period of 10 years is proposed and a corresponding technology reference date of 2005 is set for all three concepts.

Current Technology Concept Evaluation

In a brief comparison study it is not possible to do more than assess available data on current technology. From the available data on current technology, lift-to-drag (L/D) ratio, specific fuel consumption (SFC) and structural weight reduction, are projected into the 2005 technology reference date. Then, using the Breguet formula and the specified range, speed and payload, the performance of the Current Technology Concept will be evaluated.

Data on current technology is scarce. Therefore, it is necessary to make a number of assumptions in the course of processing, and then projecting, the available data into the year 2005.

Lift-to-Drag (L/D) Ratio

The principal sources of information on L/D ratio are references 1, 11, 21, 22, 23 and 24. With the exception of reference 11 from 1978, these references were published between 1989 and 1993 and hence provide recent appraisals of the aerodynamic potential of subsonic civil transport aircraft.

References 1 and 11 give actual values of L/D ratios for past, present and proposed future designs. L/D ratio values of references 21, 22 and 23 are relative with respect to an unspecified datum. Actual L/D ratios from these references are derived by assigning specific values found in references 1 and 11 to the unspecified data. Reference 24 provides relative aerodynamic performance indirectly, in terms of energy consumed, and the corresponding L/D figures are found using the Breguet equation. In particular, references 21 and 22 illustrate the aerodynamic development of the Airbus family of civil transport aircraft from the A300 to a planned design for the year 2000.

L/D ratios for various subsonic civil transport aircraft designs presented in references cited above, are shown in Figure 1 against year of aircraft introduction. Figure 1 correlates well with Figure 5 of reference 1 of maximum Mx(L/D) against year of aircraft introduction; given that the speed of subsonic jet-engine civil transport aircraft has not changed dramaticaly over the last 35 years. The projected L/D ratio for 2005 is found to be around 27.

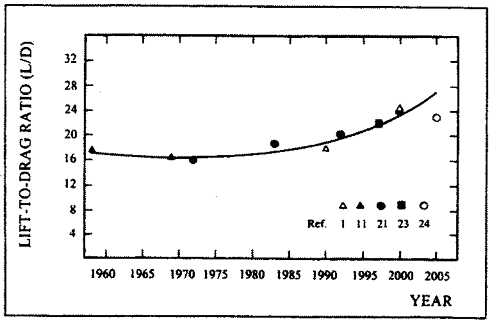

Figure 1. Current Technology L/D projection.

Specific Fuel Consumption (SFC)

Data on large commercial engine SFC trends are provided by references 1, 23, 24, 25, 26 and 27. References 25 and 26 provide actual values while other values are relative to a datum. The same procedure as used with the L/D data is followed in order to plot actual and relative SFC values against year of introduction of engine (Figure 2). As indicated in Figure 2 there is good agreement between the sets of data. The data do not represent cruise thrust SFC, therefore they have to be scaled accordingly. Assuming a 1993 technology cruise SFC of 0.55 lb/h/lb, the corresponding 2005 projected cruise SFC is found to be 0.43 lb/h/lb.

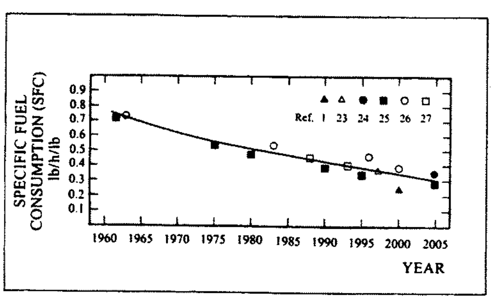

Figure 2. Current Technology SFC projection.

Reduction in Structural Weight

Structural weight reduction is, by definition, relative to a datum. To define a datum, a baseline aircraft has to be established. The baseline aircraft follows the payload, range and speed specifications that have already been set. For a better technology projection it is based on recent technology (1993).

Using the Breguet equation with L/D ratio and SFC values for 1993 extracted from Figures 1and 2, the specified payload, range and speed, and a value for the ratio of operational empty weight to takeoff weight[28]; a first estimation of the operational empty weight of the baseline aircraft is made. A final result is found after a few iterations. To find the aircraft's structural weight, the weight of the operator's items are substracted from the operational empty weight to give the manufacturer's empty weight, which is essentially structural weight. It is assumed that the operator's items weight represent 20 % of payload weight. The 1993 baseline aircraft data is shown in Table 1.

References 1, 11, 23 and 24 are used to evaluate the progression of structural weight reduction (Figure 3). The datum is the year 1976 of reference 11. Using the 1993 baseline aircraft structural weight, that has been previously defined, and, Figure 3, the structural weight of the 2005 current technology concept can be established. The structural weight reduction in relation to the 1993 baseline aircraft is found to be approximately 27.5 % (Figure 3).

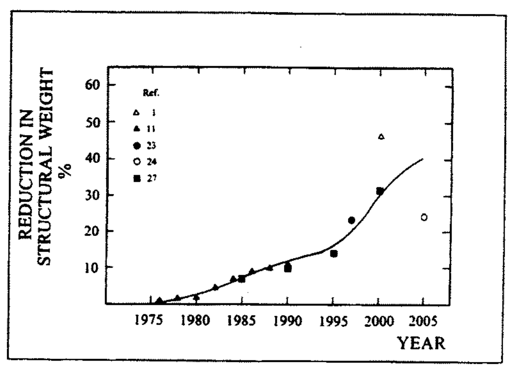

Figure 3. Current Technology structural weight reduction projection.

Flying Wing Concept Evaluation

Flying Wing Geometry

The starting point for the evaluation of a flying wing passenger aircraft concept is the thickness of the wing. To be possible to accommodate passengers, a flying wing must have a certain thickness. The value of this thickness is made of the passenger cabin height, plus the thickness of the wing's upper and lower surface structure. In this paper the flying wing thickness is set at 2.7 m. This is an arbitrary value; the reasoning behind it is that provides well over 2 m for passenger cabin height.

Another passenger flying wing parameter to be specified, is the position of the front and the rear wing spars. This is because the useful area for passenger seating lies between the two spars. The areas ahead of the front spar and after the rear spar are unsuitable fo passenger accommodation for a number of reasons, such as safety and passenger comfort. The front and rear spar positions are set at 10 and 65 % of chord respectively; typical figures for large civil transport aircraft.

Additionally, wing sweep of 35 degrees, a 15 % thickness-to-chord ratio and an aspect ratio of 6.5 are specified. The wing sweep is necessary for a high subsonic speed design. A thickness-to-chord ratio of 15 % is deemed as the maximum possible; higher ratios would demand a reduction in cruise speed due to the resulting drag rise. The aspect ratio of 6.5 is dictated by both useful seating area and optimum L/D ratio[13]. Wing taper is zero and wing thickness-to-chord ratio does not vary along the span.

The flying wing geometry follows.

$$\text{(mean) chord } c = \frac{\text{thickness}}{\text{thickness-to-chord ratio}} \quad (1)$$

$$= 2.7\ \frac{100}{15}$$

$$= 18 \text{ m}$$

$$\text{wing span } b = AR\ c \quad (2)$$

$$= 117 \text{ m}$$

$$\text{wing area } S = b\ c \quad (3)$$

$$= 2106 \text{ m}^2$$

Useful area for passenger accommodation:

$$S_{usef} = (0.65\text{-}0.10)\ c\ b \quad (4)$$

$$= 1158.3 \text{ m}^2$$

It is assumed that around 30 % of the useful area is used for aisles, galleys, etc; hence, the area available for seating is:

$$S_{seat} = 1158\ 0.70 \quad (5)$$

$$= 810 \text{ m}^2$$

At 84 cm pitch and 60 cm seat width, the seating area caters for approximately 1600 passengers. At 165 lb each passenger and 35 lb of baggage per passenger, an initial estimate of the payload is:

$$W_P = 145125 \text{ kg}$$

Weights

From this initial payload estimate the operational empty weight can be found, if the ratios of payload-to-takeoff weight and fuel consumed-to-payload are known. Reference 14 supplies these ratios for a flying wing with a range of 5560 km. If it is assumed that the operational empty weight does not vary appreciably with range, the same operational empty weight can apply to the 13000 km range flying wing concept under consideration. Therefore:

$$W_{TOW} = W_{OWE} + W_P + W_{FC} + W_{FR} \quad (6)$$

where:

W_{TOW} is takeoff weight
W_{OWE} is operational empty weight
W_P is payload weight
W_{FC} is the weight of the fuel consumed
W_{FR} is the weight of fuel reserves

$$\frac{W_{TOW}}{W_P} = \frac{W_{OWE}}{W_P} + 1 + \frac{W_{FC}}{W_P} + \frac{W_{FR}}{W_P} \quad (7)$$

From reference 14:

$$\frac{W_{TOW}}{W_P} = \frac{1}{0.45} \qquad (8)$$

and

$$\frac{W_{FC}}{W_P} = 0.3 \qquad (9)$$

Fuel reserves can be expressed as a function of takeoff weight, specific fuel consumption (SFC) and aspect ratio (AR)[29]:

$$W_{FR} = \frac{0.18\ SFC\ W_{TOW}}{\sqrt{AR}} \qquad (10)$$

with baseline SFC=0.55 and AR=6.5

$$W_{FR} = 0.038\ W_{TOW} \qquad (11)$$

Hence:

$$W_{OWE} = 0.84\ W_P \qquad (12)$$

L/D Ratio

The procedure for the calculation of the flying wing L/D ratio is given by reference 13. For the case that a specified total volume is carried inside a wing only:

$$C_L = \frac{W_{TOW}}{q\ Q_{tot}^{\frac{2}{3}}} \frac{Q_W^{\frac{2}{3}}}{S} \qquad (13)$$

where q is dynamic head

The ratio $Q_W^{\frac{2}{3}}/S$ is given as having a typical value of about 0.07 for high subsonic transport aircraft[13]. In the case of a wing only, Q_{tot} is the volume of the wing:

$$Q_{tot} = Q = S\ h \qquad (14)$$

where h is a parameter that relates wing surface area S to wing volume Q. It was found that for a number of airfoils of thickness-to-chord ratio 15 %, h has a value around 1.5. The L/D ratio is obtained from[13]:

$$\frac{C_D}{C_L} = \frac{C_{DP}}{C_L} + \beta\ C_L \qquad (15)$$

where:

C_{DP} is the wing profile drag coefficient

and

$$\beta = \frac{1.075}{\pi AR} \qquad (16)$$

with:

$q = 10700\ \ Kg/m\ s^2$ for M=0.81 at 35000 ft

$Q = 2106\ 1.5 = 3160\ m^3$

$C_{DP} = 0.0073$ (Ref.13)

$AR = 6.5$

and an initial estimate of W_{TOW}=460000 kg

$$\frac{C_L}{C_D} = 16.65$$

Considering the same flying wing at M 0.75 and at 39000 ft

$$\frac{C_L}{C_D} = 20.75$$

SFC

For the M 0.81, 35000 ft case the baseline SFC of 0.55 lb/h/lb is used. For M 0.75, 39000 ft the following relation is applied :

$$\frac{SFC_{35000}}{SFC_{39000}} = \left(\frac{p_{39000}}{p_{35000}}\right)^n \frac{T_{35000}}{T_{39000}} \qquad (17)$$

where:

p is pressure
T is temperature
n = 0.173

giving SFC_{39000} = 0.565 lb/h/lb

Jet flap Concept Evaluation

The jet flap concept can provide high lift and an integration of the aircraft lift and propulsive systems(30,31,32).

The proposed jet flap concept incorporates a number of engines buried in the wings exhausting, through fishtail ducts, from high aspect ratio two-dimensional nozzles (slits) along the trailing edge. The engines are positioned chordwise between the two wing spars. Their intakes are situated in the upper surface of the wing as exemplified in the B-2 (Figure 4).

For the evaluation of this concept the following issues have to be investigated:

- L/D ratio
- SFC
  - Duct losses
  - Jet thrust recovery
- Weight increase

As with the case of the flying wing, control aspects are not to be considered.

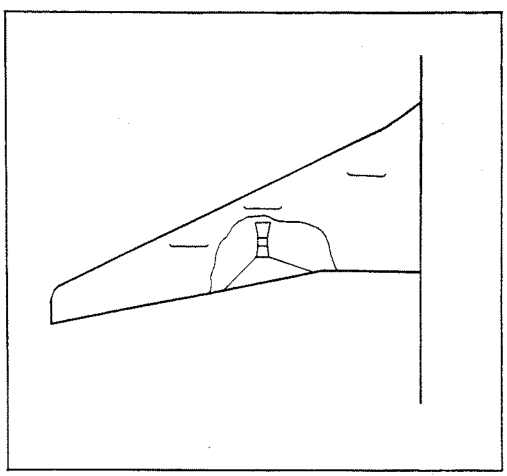

Figure 4. The Jet Flap concept.

L/D Ratio

The jet flap concept is known to achieve very high lift coefficients, which can reach values of 8 or more depending on jet flap deflection angle and jet momentum coefficient (18,30,33,34). However, the situation on the L/D ratio is not very clear with the few references available reporting L/D ratios ranging from very high to relatively low(20,30,35). Relatively low L/D ratios could be explained since, for the usual application of jet flap-powered lift, that is STOL aircraft, high lift coefficients are required but not high L/D ratios(15).

In addition, there is some uncertainty concerning the drag associated with the emerging jet. This is a change in the drag of the wing caused by the emerging jet. As noted in some studies(18,30,33), this jet drag has a negative value and is of such a magnitude that it renders the total wing drag negative. It should be made clear that this negative wing drag is not related to the thrust, or the thrust recovery of the jet.

For the purposes of our comparison study a L/D ratio of nearly 55, indicated in reference 20 and supported by reference 30, will be considered. This is not an unusual value for powered lift concepts. Similar L/D ratios are attained with circulation control wings(19,36).

SFC

Duct Losses

In Davidson's 1956 paper(18) on the jet flap, duct losses of the order of 10 % were reported. Two recent sources(31,32) suggest losses of the same magnitude. Reference 31, showing a fishtail duct, simply states that losses are low. Reference 32, describing a rather complicated internally blown jet flap scheme, gives, for a four engine arrangement, duct losses nearer 25 %. The jet flap concept put forward in this paper consists of short ducts without corners or bends, starting with a circular cross-section and ending in a fishtail shape at the trailing edge. Therefore, it would not be unacceptable to assume duct losses in the region of 15 %. Considering a jet engine of suitable size for installation within the wing of a 800 passenger transport (say, 30-40 kN), 15 % duct pressure losses result in thrust losses of around 22 % (37).

Jet Thrust Recovery

All relevant studies agree that jet thrust recovery is very high(20,32,38). Provided the jet deflection angle is less than, say, 45 degrees, and the jet momentum coefficient is not very high, jet thrust recovery can be set at 95 %.

The combined effect of duct pressure losses and thrust recovery gives:

0.78 0.95 = 0.74

a 26 % trust loss which increases the baseline SFC of 0.55 to

0.55 / 0.74 = 0.74 lb/h/lb

Weight Increase

Very little information is available on weight increase due to the use of a jet flap system. Only reference 39, in which three lift/ propulsion systems are compared, demonstrates that an externally blown flap has a lower weight than a jet flap concept. The weight difference is approximately 15 % in terms of operational empty weight. Furtermore, the difference between the wing weight, based on wing area, and that based on takeoff weight, is found to be approximately 10 %[17,29].

Consequently, taking into consideration a typical weight breakdown of a long-distance transport aircraft[29], an increase of aircraft structural weight, due to the jet flap system, of around 15 % could be assumed. However, due to the lack of reliable information, this is just a rough approximation.

Results and Discussion

The L/D ratios, the SFC and the structural weight reduction found in the evaluation of the three concepts are used in the Breguet equation to calculate the fuel consumption.

The results are presented in Table 1. In addition to the three concepts, the results include the 1993 baseline aircraft and a second version of the flying wing with lower speed at higher altitude. The flying wing concept carries almost twice the number of passengers than the other two; this is because a flying wing design of capable of carrying only 800 passengers is impossible. Taking into consideration that the aspect ratio cannot be lowered much further without an effect on L/D ratio, and that the thickness-to-chord ratio cannot be set any higher without a drag penalty, a much smaller flying wing concept is not feasible. The enormous size of the flying wing poses many and difficult problems, especially on the airport side. These problems are beyond the scope of this paper. However, it should be noted that they make the flying wing a poor choice among the three concepts, regardless of the fuel consumption performance.

	Baseline Aircraft (1993)	Projected Current Technology (2005)	Flying Wing M 0.81 35.000 ft	Flying Wing M 0.75 39.000 ft	Jet Flap Concept
Range (km)	13000	13000	13000	16250	13000
Number of Passengers	800	800	1580	1580	800
Cruise Mach (altitude ft)	0.81 (35.000)	0.81 (35.000)	0.81 (35.000)	0.75 (39.000)	0.81 (35.000)
Cruise L/D	21	27	16.65	20.75	55
Cruise SFC (lb/h/lb)	0.55	0.43	0.55	0.565	0.74
Structural Weight Reduction (%)	-	27.5	70	70	+15
OWE $(x10^{-3}kg)$	169.9	127.2	121.1	121.1	194.8
Payload $(x10^{-3}kg)$	72.6	72.6	143.5	143.5	72.6
Fuel $(x10^{-3}kg)$	123.0	55.2	180.3	180.2	62.9
Fuel Reserves $(x10^{-3}kg)$	13.2	5.1	17.0	17.1	14.3
TOW $(x10^{-3}kg)$	378.7	260.1	461.9	461.9	344.6
gr of fuel consumed/ seat-km	11.8	5.3	8.7	7.6	6.1

Table 1. Results.

With the exception of the second flying wing version, range, speed and cruising altitude are 13000 km, M 0.81 and 35000 ft. The second flying wing version flies at M 0.75 and at 39000 ft. The change in speed and altitude gives longer range and/or larger payload; because of the initial payload size, the longer range option (16250 km) was preferred.

Flying wing concept L/D ratios are calculated; consequently, they are more reliable than the estimated L/D ratios of the current technology and the jet flap concepts. Current technology and flying wing concepts display a reduction in structural weight while jet flap shows an increase. Flying wing structural weight reduction values are relative; that is, they are scaled with respect to the standard payload (72560 kg).

The results for the amount of fuel consumed per seat-km indicate superior performance by the projected current technology and the jet flap concepts over the flying wing. Jet flap fuel consumption per seat-km is a 15 % higher than projected current technology; but, for a brief study this difference cannot be considered of much significance and the results could be regarded as similar. The flying wing follows with a 65 % higher fuel consumption per seat-km. The lower speed, higher altitude flying wing version offers slightly better performance, but at the price of reduced speed. It should be noted, that in the present study the flying wing concept is investigated only as a passenger, and not as a cargo aircraft. To some extent, flying wing's poor performance stems out of its low payload density. As a passenger aircraft, due to its configuration, the flying wing has a low payload density which in turn produces a low wing loading. Furthermore, it has been assumed that the flying wing operational empty weight to payload ratios provided by some references[9,10,14], and used in this study, take into account not only distributed lift and weight, but landing loads as well.

The results of Table 1 show that the performance of the jet flap concept is wholly based on aerodynamics, the flying wing mainly, if not wholly, on structural weight and the projected current technology on a balance between aerodynamics, structural weight and specific fuel consumption.

Concluding Remarks

In the present study a powered lift-jet flap, a flying wing and projected current technology concept are evaluated and then compared in terms of fuel consumed per seat-km. This comparison produced similar results for the jet flap and the projected current technology, showing that further investigation is needed. The flying wing concept not only comes behind the jet flap and the projected current technology concepts in relation to the fuel consumed, but, due to the enormous size required for it to carry passengers, it poses a number of additional problems.

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