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Propulsion System of Jet-Flapped Subsonic Civil Transport Aircraft Design

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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. To accomplish this objective, a number of alternative concepts have been proposed, one of which is based on the jet flap. In this paper, the propulsion system of a jet-flapped subsonic civil transport aircraft design is evaluated. The jet engines of this design are embedded in the wings and exhaust through fishtail diffuser ducts, from high-aspect-ratio nozzles located at a small control flap at the trailing edge. The aim is to match jet engine, fishtail duct geometry and jet momentum coefficient requirements. It is found that it is possible to achieve the exceptional lift-to-drag ratios of the jet flap using very high bypass ratio geared turbofans operating at a lower temperature. The resulting jet-flapped design exhibits lift-to-drag ratios of over 60 without any significant effects on specific fuel consumption or weight. The jet-flapped design is then compared with other advanced technology designs and comes first on fuel consumption per $\mathrm{seat} \cdot \mathrm{km}$, as well as in other areas of interest such as safety, emissions, and noise.

Nomenclature

AR	=	aspect ratio
C_{DON}	=	drag coefficient with jet flap in operation
C_{DONMIN}	=	minimum drag coefficient with jet flap in operation
C_{D0ON}	=	zero-lift drag coefficient with jet flap in operation
C_{LON}	=	lift coefficient with jet flap in operation
c_j	=	jet momentum coefficient
D_{ON}	=	drag with jet flap in operation, N
e	=	Oswald factor
J	=	jet momentum, N
k_1	=	jet-flap-type factor
L_{ON}	=	lift with jet flap in operation, N
m	=	mass flow, kg/s
T	=	thrust, N
S_W	=	wing reference area, m^2
V_j	=	jet velocity, m/s
V_∞	=	aircraft speed, m/s
η	=	propulsive efficiency
θ	=	jet deflection angle, °
ρ	=	air density, kg/m^3

Introduction

SINCE the late 1950s, subsonic civil transport aircraft technology has advanced substantially. This advance has been evolutionary and, consequently, the basic aircraft configuration has remained 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 (BWB) nonplanar wings, laminar flow control, unducted fan, and powered lift. Among them, a powered lift design based on the jet flap concept has been proposed [2]. A review of aeronautical technology for future subsonic civil transport aircraft [3] reached the conclusion that the jet flap is the most promising technology. In a jet-flapped design, the exhaust jet of the engines emerges, through ducts, at the trailing edge of the wing. Jet-flapped wings exhibit very high-lift coefficients, at high values of jet momentum coefficient and jet deflection angle, and exceptional zero-lift drag, leading to exceptional lift-to-drag ratios at low values of jet momentum coefficient and deflection angle [2]. At the same time, they provide the thrust, which is required to propel the aircraft. In addition, up to relatively low values of jet momentum coefficient and deflection angle, very high thrust recovery is observed [4,5]. Thus, jet-flapped wings offer superior performance in cruising conditions as well as in takeoff and landing. In this paper, the propulsion system of a jet-flapped subsonic civil transport aircraft design is evaluated with the objective, as indicated in a first attempt on the subject [2], to match jet engine characteristics, fishtail duct geometry and jet momentum coefficient requirements, and estimate thrust losses and added weight. Subsequently, the resulting design is compared with other advanced technology and unconventional configuration subsonic civil transport aircraft designs.

Propulsion System Evaluation

The configuration of a jet-flapped subsonic civil transport aircraft is similar to that of conventional designs, as far as the fuselage, the tail, and the undercarriage are concerned. The main difference lies

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with the wings and the engines. The proposed design incorporates a number of jet engines embedded in the wings, exhausting through fishtail ducts, from high-aspect-ratio two-dimensional nozzles located at a small control flap at the trailing edge. The engines are positioned chordwise between the two wing spars. Their intakes are situated in the upper surface of the wing, and they are connected to the engines by an s-shaped inlet duct. The jet engines provide for the required thrust and for the jet of the jet flap.

Possible schematic representations of the embedded jet engines, the fishtail ducts, and the small control flap are shown in Figs. 1 and 2.

The problems associated with a jet-flapped design are many. However, the development and entry into service of the Northrop Grumman B-2 shows that many of the engineering problems of the installation and operation of jet engines embedded in the wings, such as materials, insulation, and proximity to fuel tanks, have been solved. It should also be noted that, not only the engineering problems of B-2's wing–engine configuration have been solved, but judging from B-2's range and weights [6], this configuration has not compromised its performance.

The Northrop Grumman B-2 differs from the jet-flapped design put forward here in not having a jet engine exhaust duct and small control flap. But the feasibility of the jet flap concept, with the use of jet engines and ducts providing, at least partially, thrust and additional lift, has been demonstrated in the past by research aircraft such as the Hunting H 126 [7].

Therefore, the objective here is to match jet engine characteristics, fishtail duct geometry, and jet momentum coefficient requirements only in terms of performance. That is, to evaluate a propulsion system configuration suitable for the jet flap concept and then verify that the exceptional characteristics of the jet flap concept are not compromised by thrust losses, added weight or otherwise.

Analysis

The jet engines and the corresponding ducts are required to achieve a jet having a velocity that will provide toward the thrust needed to propel the aircraft, satisfy the condition for maximum lift-to-drag ratio [2], and be close to the aircraft speed for high propulsive efficiency. These conditions are subject to restrictions relating to the size (diameter) of the engines and the semi-angle of the fishtail diffuser. For aerodynamic purposes, the engine diameter must be such that it will allow the engines to be completely embedded in a wing of typical relative thickness. The semi-angle of the fishtail diffusers must cater for a jet along the whole span, with the smaller possible number of engines, and assure that flow separation within the diffusers is avoided.

In cruising conditions, the thrust produced by the jet engines must equal drag:

$$T = D_{ON} \tag{1}$$

$$m(V_j - V_\infty) = C_{DON}\tfrac{1}{2}\rho V_\infty^2 S_W \tag{2}$$

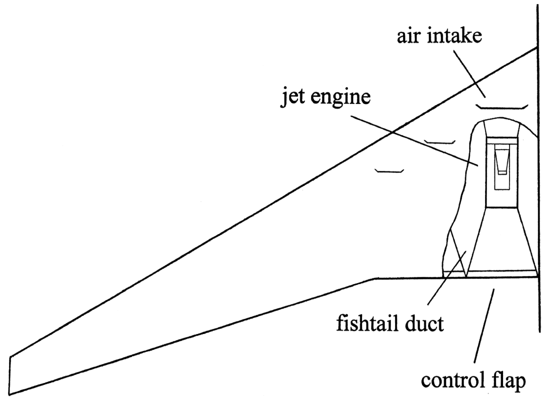

Fig. 1 Schematic representation of jet engines embedded in the wings.

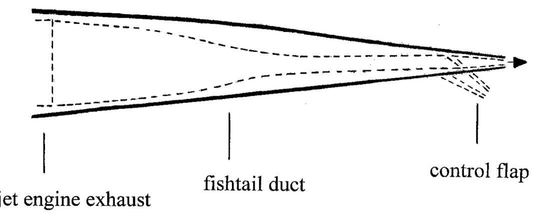

Fig. 2 Schematic representation of jet engine exhaust, fishtail duct, and control flap.

$$m = \frac{D_{ON}}{(V_j - V_\infty)} \tag{3}$$

The same mass flow m is used by the jet flap:

$$J = mV_j = c_j\tfrac{1}{2}\rho V_\infty^2 S_W \tag{4}$$

$$m = \frac{J}{V_j} \tag{5}$$

Thus,

$$\frac{C_{DON}}{(V_j - V_\infty)} = \frac{c_j}{V_j} \tag{6}$$

$$V_j = V_\infty\left(\frac{c_j}{c_j - C_{DON}}\right) \tag{7}$$

According to the theory of the jet flap by Maskell and Spence [8], we have for the lift C_{LON} and drag C_{DON} coefficients,

$$C_{LON} = k_1 \sin\theta\, c_j^{\frac{1}{2}} \tag{8}$$

$$C_{DON} = C_{D0ON} + \frac{k_1^2 \sin^2\theta\, c_j}{(e\pi\,\mathrm{AR} + 2c_j)} \tag{9}$$

$$\frac{C_{DON}}{C_{LON}} = \frac{C_{D0ON}}{k_1 \sin\theta\, c_j^{\frac{1}{2}}} + \frac{k_1 \sin\theta\, c_j^{\frac{1}{2}}}{(e\pi\,\mathrm{AR} + 2c_j)} \tag{10}$$

For low values of c_j, which are dictated by the mass flow requirements of the jet engines, the effect of c_j on the C_{LON}/C_{DON}, ratio is insignificant. The factor k_1 depends on the type of the small control flap and, consequently, is irrelevant to this analysis. Therefore, we have to find the C_{DON} that corresponds to the maximum C_{LON}/C_{DON} ratio condition with respect to the jet deflection angle θ. For maximum C_{LON}/C_{DON}:,

$$\sin\theta = \frac{1}{k_1}\left\{\frac{C_{D0ON}(e\pi\,\mathrm{AR} + 2c_j)}{c_j}\right\}^{1/2} \tag{11}$$

Thus,

$$C_{DONMIN} = 2C_{D0ON} \tag{12}$$

$$\left.\frac{C_{LON}}{C_{DON}}\right|_{MAX} = \frac{1}{2}\left\{\frac{(e\pi\mathrm{AR} + 2c_j)}{C_{D0ON}}\right\}^{1/2} \tag{13}$$

The propulsive efficiency η is given by

$$\eta = \frac{2}{1 + (V_j/V_\infty)} \tag{14}$$

Jet Momentum Coefficient, Jet Engine, and Fishtail Duct Geometry Calculations

A jet that will provide the thrust needed to propel the aircraft, satisfy the condition for maximum lift-to-drag ratio, and be as close to the aircraft speed for high propulsive efficiency must have a velocity much lower than the velocity of the exhaust jet of typical turbofans. As a result, jet engines with very low exhaust jet velocity and, consequently, very high mass flow rate are required. Up to relatively recently, a very low exhaust jet velocity could only be achieved by a highly derated jet engine, a supersonic diffuser, or a purpose-built engine. In every case, the loss in efficiency of the propulsion system would substantially reduce the benefits of the jet flap concept. However, with the development of geared turbofan engines [9], it is possible to satisfy the very low exhaust jet velocity and very high mass flow rate requirements without any significant effects on the efficiency. The very low exhaust jet velocity is achieved because the jet engine nozzle is not working in choked conditions. Decoupling the fan from the low-speed turbine, selecting a very high bypass ratio, and lowering the combustion temperature make possible nearly equal values of total pressure for the cold and the hot streams, a nozzle pressure ratio less than the critical and, in turn, exhaust jet Mach numbers less than one.

The jet engine, for which the specifications are presented in Table 1, running at 75% in cruising conditions can achieve exhaust jet Mach numbers less than one. This is due to the fact that the nozzle pressure ratio is less than the critical pressure ratio, and the nozzle is not choked. This jet velocity is around 300 m/s due to the low jet temperature arising from the mixing of the very high bypass cold flow with the hot core flow. Hence, the jet velocity can be further reduced with a subsonic diffuser in the form of a fishtail duct.

The starting points for the calculations are the specifications for the subsonic civil transport aircraft that are to be used as an example. These are presented in Table 2. Next, a judgment has to be made as to the value of the jet momentum coefficient c_j. The jet momentum coefficient in conjunction with the drag coefficient must lead, according to Eq. (7), to a value for the jet velocity V_j, which is a compromise between the condition for maximum propulsion efficiency [Eq. (14)] and the mass flow rate, which reflects on the size (diameter) of the embedded jet engines. A value of 0.03 for c_j has been chosen. In [2], the conclusion has been reached that the zero-lift drag coefficient of a jet-flapped design is of the order of one-tenth of the zero-lift drag coefficient of a conventional design. This means that a typical value for the zero-lift drag coefficient for a conventional design of 0.018 corresponds to a value of 0.0018 for the jet-flapped design. The value of the drag coefficient C_{DON} is then 0.0036, which is the minimum drag coefficient, and it is twice the zero-lift drag coefficient [Eq. (12)]. Taken together, they give a jet velocity 1.136 times the value of the aircraft speed [Eq. (7)] and a propulsive efficiency of 0.936 [Eq. (14)]. The lift-to-drag ratio L_{ON}/D_{ON}, the lift coefficient C_{LON}, and the jet deflection angle θ corresponding to the c_j and C_{DON} are 63, 0.227, and 11.6°, respectively.

To proceed with the calculation of the thrust and the mass flow, the wing reference area is required. To find it, the wing loading is needed. At Mach 0.85 and 30,000 ft, and with $C_{LON} = 0.227$, the wing loading is 3450 N/m^2. At takeoff, the wing loading is 3 555 N/m^2, and with a takeoff mass of 235,200 kg (Table 3), a wing reference area of 650 m^2 is obtained. At Mach 0.85 and 35,000 ft, a wing reference area of 650 m^2 with a $C_{DON} = 0.0036$ results in around 28,000 N of drag. The thrust to balance this drag will be provided by a number of scaled versions of the geared turbofan jet engine presented in Table 1. The jet deflection angle at 11.6° is well below the 30°, up to which over 95% thrust recovery is attained [5]. In cruising conditions, the engines operate at 75% of their maximum thrust. At Mach 0.85 and 35,000 ft, a lapse rate of 0.17, assumed to be typical of very high bypass ratio geared turbofans, leads to a static thrust of about 220,000 N (49,400 lbf). This amount of thrust covers climb and airworthiness requirements.

The last step in the jet momentum coefficient, jet engine, and fishtail duct geometry calculations is to establish the number of jet engines that will produce the necessary thrust. In doing that, the relative thickness of the wing and the semi-angle of the fishtail ducts are to be taken into account. The wing specifications of the example aircraft (Table 2) dictate the fan diameter of the embedded jet engines at each station along the span. Fishtail ducts have similar performance to conical ducts [10]. Hence, to avoid separation and the subsequent losses, a semi-angle of 16° was chosen. Consideration of the preceding information can lead to the conclusion that 18 jet engines, nine on each side, are needed to provide a jet over a whole span. The jet engines come in different sizes in order to match lift requirements and wing thickness at various positions along the wingspan.

Table 1 Specifications of very high bypass ratio geared turbofan running at 75% of maximum thrust at sea level

Parameter	Value
Overall pressure ratio	31.75
Fan pressure ratio	1.20
Bypass ratio	11.00
Turbine inlet temperature, K	1075.00
Mass flow rate, kg/s	280.00

Table 2 Specifications of subsonic civil transport aircraft

Parameter	Value
Range, km	13,000
Number of passengers	800
Cruise Mach	0.85
Cruise altitude, ft	35,000

Results

The first criterion, to be used in the comparison of the jet-flapped to other advanced technology and unconventional configuration designs, is fuel consumption. Using the specifications for the example of subsonic civil transport aircraft of Table 2 and the Breguet equation, suitably modified, the fuel consumed per seat · km is derived. The results are shown in Table 3. With the exception of the jet flap case, the results are those found in [3], with a few minor differences. These differences are due to the alternative approach to fuel reserves and payload mass calculation. Instead of using Torenbeek's formula [11], which seems to be unsuitable for flying-wing designs, fuel reserves of 7% of block fuel are assumed. As for the payload, the mass of a passenger plus luggage is taken to be 95 kg and not 200 lb. In addition, two typing errors in the manufacturer's weight empty (MWE)/[takeoff weight (TOW)-MWE] values for the all laminar and propfan-based designs have been corrected. MWE, instead of operating weight empty, has been retained, because it provides a better criterion of structural efficiency through the MWE/(TOW-MWE) ratio.

The jet-flapped design results presented in Table 3 are, obviously, quite different from those of [3]. As already described, the difference lies in the propulsion system. As a result, the specific fuel consumption (SFC) of the present jet flap design is much lower. The SFC of the present jet flap design at 0.54 kg/h · kg has been derived from the baseline SFC of 0.55 kg/h · kg by subtracting 12% due to the geared very high bypass ratio turbofan-type of engines used [9], by adding 5% due to duct losses [12], and by adding 5% due to the fact that some of the 18 turbofans, required to provide the thrust needed, are very small; hence, Reynolds number and other effects increase their SFC. Other factors affecting SFC are the lower combustion temperature, which has been specified, and the lower exhaust gas (jet) velocity of the very high ratio geared turbofan. However, data on geared turbofan operating temperatures and exhaust velocities are not readily available. It has been assumed that the lower exhaust jet velocity more than compensates for the lower operating temperature.

Table 3 Results of the comparison of various unconventional configuration or advanced technology designs

	Baseline (1993)	Projected technology (2005)	Pure flying wing (spanloader)	Liebeck et al. [13]	All laminar	Propfan (unducted fan) based on An-70	Jet flapped
Range, km	13,000	13,000	13,000	13,000	13,000	13,000	13,000
Number of passengers	800	800	1 600	800	800	800	800
Cruise Mach at altitude, ft	0.85	0.85	0.75	0.85	0.85	0.73	0.85
	35,000	35,000	39 000	35,000	35,000	35,000	35,000
Maximum L/D	19.5	27.0	25.2	29.3	55.7	19.5	63.0
Cruise SFC, kg/h · kg	0.550	0.435	0.678	0.439	0.605	0.357	0.540
Change in structural weight based on MWE/(TOW-MWE), %	——	−40.8	−71.5	+2.8	+5.0	+3.2	0.0
Payload × 10^{-3}, kg	76.0	76.0	152.0	76.0	76.0	76.0	76.0
OWE × 10^{-3}, kg	355.7	93.0	132.5	167.8	123.8	235.2	125.3
Fuel × 10^{-3}, kg	278.0	54.7	205.1	72.7	40.1	142.0	32.2
Fuel reserves × 10^{-3}, kg	19.4	3.8	14.4	5.1	2.8	9.9	2.2
TOW × 10^{-3}, kg	729.0	227.5	504.0	321.6	242.7	463.1	235.2
Grams of fuel consumed per seat · km	26.70	5.26	9.86	7.00	3.86	13.60	3.09

Discussion

The results of a comparison of a number of case studies of advanced technology and unconventional configuration designs presented in Table 3, with a few differences and the exception of the jet flap, have been extensively discussed in [3]. These designs include a baseline at 1993 technology level for reference purposes, a projected to 2005 technology level, the Liebeck et al. [13] BWB, an all-laminar flow, a propfan (unducted fan)-powered based on the An-70, and the jet flapped. The differences, already described, are of very minor importance and do not in any way change the conclusions of [3]. However, the present jet-flapped design, which is quite different from the one of [3] due to the much lower SFC, alters the conclusions that can be drawn from the comparison. The present jet-flapped design, when compared with the other designs with the amount of fuel consumed per seat · km as criterion, comes first. The rest retain the same relative places, with the all-laminar being second, followed by the projected to 2005 technology level, the Liebeck et al. [13] BWB, the pure flying-wing spanloader, and the propfan (unducted fan)-based. It is remarkable that the jet-flapped design is better than both the design that provides laminar flow over the entire aircraft and the design that possesses all the technology advances envisaged in the late 1980s and early 1990s.

The advantages of the jet-flapped design are presented in Table 4. Its superior performance is mainly based on its exceptional L/D ratio. This exceptional ratio is over 60, and it is a consequence of the exceptionally low zero-lift drag of the jet flap observed at certain values of jet momentum coefficient and deflection angle. Although, the jet flap seems to have been initially conceived as a drag-reducing concept, its low drag attributes were soon forgotten, and all the interest has been focused on its very high-lift capabilities. It is most interesting how much one of the earlier publications on the subject, by Davidson [14], is devoted to the low drag and propulsive aspects of the jet flap, albeit in the wrong way. Later, in the 1960s and 1970s, a very substantial research effort was undertaken, but this was solely on the very high-lift characteristics of the jet flap. Drag reduction was rarely mentioned, and only in an indirect or secondary capacity. One of these rare instances was mentioned by Capone [15], where thrust vectoring, in addition to increasing maneuverability, was proposed as a means of improving cruise performance of fighter aircraft. Work on the jet flap died out, the most probable reason being its complexity and weight compared with mechanical high-lift systems. A high cruise lift-to-drag ratio jet-flapped-type design was put forward by Kehayas [16] in the mid-1980s. Recently, the jet flap was reconsidered, in the context of distributed propulsion, by Ko et al. [12] and others but without any acknowledgment of its exceptional low zero-lift drag attributes. Again, there are rare cases, as with Kim and Saunders [17], where massive zero-lift drag reduction is indicated but not acknowledged as far as its implication on the lift-to-drag ratio is concerned. Actually, Kim and Saunders report negative zero-lift drag, something that can also be deduced from an earlier publication by Chin et al. [18]. It should be noted that in the evaluation of a jet-flapped design by Kehayas [2], although the negative zero-lift drag in Chin et al. [18] had been noticed, a much more conservative, positive value for the zero-lift drag coefficient, at 10% of a typical value for conventional subsonic transport aircraft, was adopted.

Table 4 Advantages and disadvantages of the jet-flapped subsonic civil transport aircraft design

Advantages	Disadvantages
Exceptional L/D ratio without any significant effects on SFC or weight	Risk associated with new technology
Very high propulsive efficiency	High development cost
No need for flaps	Higher maintenance costs
No need to change altitude during flight	
Optimum wing loading	
Enhanced safety	
Passenger acceptability	
Airport compatibility	
Support of the case of electric propulsion	
Comparable manufacturing costs	
Very low CO2 emissions	
Reduced NOX emissions	
Reduced noise	

The exceptional lift-to-drag ratio of over 60 of the present jet-flapped design is not marred by increased structural weight or higher SFC. A first attempt on structural weight estimation of a jet-flapped design by Kehayas [2] showed no significant change. The weight increase associated with the jet flap configuration was counter-balanced by the elimination of the need for flaps. The SFC is 10% higher when compared with the SFC of a typical geared turbofan, as a result of duct losses, small turbofan size, Reynolds number, and other effects. However, this is just an assumption made for calculation purposes. The geared turbofan is connected to a diffuser duct and is operating at a lower combustion temperature. The data of Table 1 indicate that this is around 200 K lower than combustion temperatures of typical geared turbofans. The geared turbofan–diffuser duct combination has a propulsion efficiency of 0.936, which must be higher than the propulsive efficiency of typical geared turbofans. The higher propulsion efficiency is expected to compensate for the diffuser duct and turbofan size losses and for the lower operating temperature. Unfortunately, data on very high bypass ratio geared turbofans are scarce and, consequently, the effect of higher propulsive efficiency could not be quantified and, in turn, accounted for. Hence, the actual SFC is not expected to be significantly higher when compared with the SFC of typical geared turbofans.

Another advantage of the jet-flapped design is the absence of flaps. The role of the flaps is covered by the small control flap, for which the function is to alter the jet deflection angle. By changing the jet deflection angle and the jet momentum coefficient, high-lift coefficients are attained. The high-lift system of a subsonic civil transport aircraft, comprising flaps, slats, and their mechanisms, represents something of the order of 1% of TOW. It is used for a few tens of kilometers, and it is carried for thousands of kilometers, depending on the aircraft range. Furthermore, additional fuel must be carried aboard to be burned in order to ferry the high-lift system all the way. The small control flap of the jet-flapped design is a fraction of the weight of a typical high-lift system. Although a first attempt on structural weight estimation of a jet-flapped design by Kehayas [2] indicated no significant change, a more detailed study may even show a weight reduction. When it is compared with the other designs of Table 3, the jet flapped is the only one that does not require flaps.

The flexibility of the jet flap operation and the small percentage of block fuel in relation to TOW eliminate the need to significantly change aircraft altitude during the flight in order to maintain optimum L/D ratio. By altering the jet momentum and, hence, jet deflection angle for optimum L/D ratio, the small change in weight during flight can be accommodated without change in altitude. The jet-flapped design is the only design among the ones presented in Table 3 that can achieve this.

In support of the superior performance of the jet-flapped design is the possibility to establish the optimum wing loading. This is not the case for two of the other designs: the pure flying-wing spanloader and the BWB. It is difficult to control the wing loading of the BWB and impossible to control the wing loading of the pure flying-wing spanloader.

The jet-flapped design compared with the flying-wing spanloader and the BWB has an additional advantage. It can be applied to aircraft of any size.

Safety is enhanced by the jet-flapped design because of the multitude of its engines. In this sense, the design is safer than the rest of the designs shown in Table 3. When compared with the pure flying-wing spanloader and the BWB, its safety levels are relatively higher due to the unconventional seating arrangement of these designs. When compared with the projected to 2005 technology level design, which encompasses all the technology advances envisaged in the late 1980s and early 1990s, its safety levels are relatively higher due to the complexity of this design.

Passenger acceptability of a novel design is a factor not to be ignored. The shape and the seating arrangement of the pure flying-wing spanloader and the BWB are not going to place them high on the passenger's list of preference. Some concerns have also been raised over the shape of the propfans, something that covers the propfan and the projected to 2005 technology design. Having the jet engines embedded in the wing is not considered to be a problem, since a similar arrangement in the de Havillant Comet jet transport aircraft of the 1950s gained the public's acceptance. Therefore, the jet-flapped and the all-laminar designs are thought to be the most acceptable from the passenger's point of view.

Airport compatibility is an important issue affecting, in particular, unconventional designs. Among the designs presented in Table 3, the pure flying-wing spanloader is incompatible with present airports. The main reason is its enormous wingspan. BWB's compatibility is also questionable for a number of reasons relating to runway width, passengers embarking and disembarking, and wingspan size in the case of very large aircraft. The jet-flapped and the rest of the designs do not pose any airport compatibility problems because of their conventional fuselage–wing configuration.

Electric propulsion is an alternative technology envisaged for future subsonic civil transport aircraft. Conventional electric machines do not have the power density necessary for aircraft applications. Toward this end, the feasibility of superconducting machines is being investigated. The exceptional performance of the jet flap concept may accelerate this effort and bring it forward in time.

The manufacturing costs of a jet-flapped design are not expected to be much higher than those of a conventional configuration. The only difference is in the wings, where a number of jet engines are embedded. The cost of a larger number of jet engines of the same thrust, instead of two, may eventually, according to Ameyugo et al. [19], be lower. The wing structure will retain its basic form of a box. The embedded jet engines will be situated between the two beams. The rear beam will have to be castellated in order to accommodate an opening for the fishtail duct. The inlet and the fishtail exhaust ducts and the small control flap represent added complication, but this is balanced by the lack of a high-lift system and engine nacelles. The manufacturing costs of the jet-flapped design are clearly lower than those of the pure flying-wing spanloader and the BWB due to the unconventional configuration of the latter. The all-laminar design may have manufacturing costs that are too high.

Last, but most important, is the positive effect of the jet-flapped design on the environment. Since CO2 emissions are directly related to fuel consumption, it is evident that CO2 emissions of the jet-flapped design will be around one-ninth of the emissions of the baseline, 1993 technology, design. NOX emissions are roughly halved for every 100 deg of combustion temperature reduction [20]. Judging from the turbine entry temperature of the example geared turbofan used (Table 1), the NOX emissions of the jet-flapped design, regardless of NOX-reducing technology, will be one-fourth of the emissions of a conventional design. Furthermore, although the jet-flapped design was not conceived as a silent aircraft [21], it seems (from an entirely qualitative point of view) to exhibit a very low noise footprint. This is attributed to the propulsion system and the absence of flaps and slats. Noise sources on conventional subsonic civil transport aircraft are the fan inlet, the fan exhaust, the combustion, the turbine, the jet exhaust, the flaps and slats, and the undercarriage [21]. The jet-flapped design does not have flaps and slats. Its small control flap is much smaller, and very different in the way it works, than the typical flaps of subsonic civil transport aircraft. As a result, airframe noise is confined to the undercarriage. The jet engines of the jet-flapped design are embedded in the wing. The propulsion system, in addition to the jet engine, includes an s-shaped inlet and a fishtail exhaust duct. Consequently, the wing structure and the inlet and exhaust ducts will considerably shield the noise originating from the fan inlet, the combustion, and the turbine. The fan and core flow of the geared turbofan jet engine of the jet-flapped design are being mixed and then exhausted through the fishtail diffuser duct. They mix at the same total pressure and, combined, they exhaust at a velocity that is close to the aircraft speed. Thus, the shear stresses between the exhaust jet and the external flow are very small, generating substantially lower noise compared with a conventional design. The jet-flapped design when compared with the other designs of Table 3 comes way ahead in relation to their impact on the environment. The jet-flapped design exceeds the Advisory Council for Aeronautics Research in Europe and NASA N + 1, N + 2, and N + 3 targets for emissions and, most probably, noise. As far as the CO2 emissions are concerned, a comparison of the jet-flapped design to the designs presented in Table 3 follows the classification of the fuel consumption. The jet-flapped design also takes the first place in the NOX emissions comparison, because its geared turbofan jet engines are set to operate at a lower temperature. In noise terms, the jet-flapped design comes first due to its embedded jet engines, lack of slats and flaps, and jet flap configuration, while the propfan (unducted fan)-based design is last due to its open rotor.

The main disadvantages of the jet-flapped design are the ones associated with the introduction of new technology: namely, high development cost and risk. Nevertheless, it should be pointed out that some of the cost and risk has already been credited. The jet-flapped design is focused on the jet flap concept, an appropriate jet engine, and the engineering aspects of jet engines embedded in the wings. The jet flap concept has been, albeit in a different context, thoroughly investigated in the past. An appropriate jet engine, the very high bypass ratio geared turbofan, is being developed. As exemplified by the Northrop Grumman B-2, the engineering aspects of jet engines embedded in the wings have been solved. Therefore, development cost and risk, although they remain as disadvantages, might not be as great as would be expected.

Also, a question arises in relation to maintenance costs. The large number of embedded jet engines and the associated ducts should lead to increased maintenance costs. However, the absence of flaps will, to some degree, lower this increase. In any case, the disadvantage of higher maintenance costs is very small compared with the advantages of the jet-flapped design.

Conclusions

A subsonic civil transport aircraft design using the jet flap concept in combination with the geared turbofan has been proposed. The design provides an integration of lift and propulsion [22]. The exceptionally low zero-lift drag of the jet flap concept, which leads to exceptionally high lift-to-drag ratio, has been recognized. The suitability of a very high bypass ratio geared turbofan (operating at a lower temperature) as the propulsion plant of the jet-flapped design has also been recognized. The problems associated with jet engines embedded in the wings and exhausting through fishtail ducts have been considered. When compared with other advanced technology or unconventional configuration designs, the jet-flapped design takes first place in terms of fuel consumption, safety, emissions, noise, and passenger acceptability, and it is compatible with existing airports. In relation to a 1993 technology level design, the jet-flapped design exhibits a reduction in fuel consumption per seat · km, CO2 and NOX emissions, and, probably, noise of over 75%. It remains to be verified, by means of a series of experimental investigations, the exceptional zero-lift drag characteristics of the jet flap concept.

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