AFFORDABLE NACELLE TECHNOLOGIES FOR FUTURE TURBOFANS

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ABSTRACT
Costs are playing an ever increasing role in determining what the next generation of aircraft and engines will be. In addition to deciding to what extent wing/engine integration or drag reducing laminar flow technologies can be employed etc, the economic impact on both aircraft operation and engines launch and development costs must be evaluated. SFC or fuel burn advantages are no longer dominant to the extent they used to be and for some apparently promising technology concepts the cost disadvantages outweigh the aerodynamic advantages when both effects are transposed into aircraft direct operating costs. In addition, a simple metric has been evolved to rank different technology concepts and prioritize them in order to help determine the most deserving technologies for scarce development funds.

INTRODUCTION
Nacelle aerodynamic technology is a well developed science and arguably offers less opportunity for refinement than does rotating aerodynamics. Large commercial subsonic airliner speeds and the air velocities at the engine inlet have changed little in 30 years so it would seem that there is not much scope for making large improvements in nacelle technology to significantly reduce the engine installation losses. There are however numerous ideas for reducing installation losses or drag but it is important to consider all the implications of the changes which a new technology will generate. Especially cost changes, because costs have currently assumed a much more important role, influencing new aircraft sales to a much greater extent than in the past.

A number of promising nacelle technologies have been examined for their possible influences on aircraft fuel burn and direct operating costs (DOC or DOC+I where I is a term to include the interest on money borrowed to purchase the aircraft).

The investigation has been taken a step further by making an assessment of the return on investment of the technology development costs relative to savings that the technology will generate when incorporated into a future commercial airliner fleet. In addition a simple figure of merit has been derived to help apportion limited development funding to the best economic advantage of the candidate aircraft/propulsion concept.

DIRECT OPERATING COST EVALUATIONS
All the applicable changes of SFC, drag, powerplant weight, price and maintenance cost from the various nacelle concepts have been converted into aircraft direct operating costs using 'rubber' sensitivities. 'Rubber' implies that a reduction in SFC, for example, will require the aircraft to carry less fuel and hence the rubber aircraft can be downsized, with attendant and additional synergistic economies.

These sensitivities are application specific and refer to a particular aircraft flown over a specific mission. The two aircraft used in this paper were an advanced medium range twin flown over a 1000 nautical mile range and a long range quad with a 5000 nautical mile mission. It can be seen that SFC and drag exert greater influence on DOC and weight less influence on DOC at the longer range, figure 1.
not given a ranking factor and was eliminated from further consideration.

FIGURE 1. DOC + I GROUND RULES AND "RUBBER" SENSITIVITIES (1000 NM & 5000 NM MISSION)

The items that are included in DOC+I, direct operating cost + interest, fall under three headings; cash DOC - (fuel, crew, maintenance etc), depreciation and interest. These are given in more detail together with a tabulation of the economic ground rules used in Figure 1.

RANKING FACTOR

The nacelle concepts described in this paper were a few of the many technologies proposed for an advanced gas turbine in a large NASA sponsored study. A figure of merit was required that could be used to rank this very diversified list of technologies in terms of their value to the airline industry measured against the cost of developing the technology.

The figure of merit selected was

\[
\text{Value to Airline} \times \text{Probability of Success} \quad \text{See Figure 2}
\]

Development Cost

Value to the airline equates directly with aircraft DOC. Probability of success is a subjective judgment on the likely outcome of the development program relative to the target improvement value, and as such relates to the most likely realizable value rather than the maximum possible attainable value. Development cost is all the costs incurred up to the point at which an engine launch decision can be made for an advanced engine incorporating the new technology.

In some instances the new technology had a negative value to the airline not a cost reduction in which case the concept was

FIGURE 2. TECHNOLOGY RANKING FACTORS

TECHNOLOGY CONCEPTS

1. Two Position Fan Nozzle

In one of the most widely used arrangements for engine thrust reversers, the aft portion of the cowl translates rearwards exposing a cascade that redirects the bypass stream to give it a forward direction and thus generate reverse thrust. This proposal adapts this type of conventional reverser. The first part of the cowl rearward movement is designed not to expose the reverser cascade but to increase the fan nozzle area, by careful design of the nozzle and core cowl profile. Further rearward movement deploys the blocker doors and the reverser cascade is exposed.

If the larger fan nozzle is used for take off and cruise mode, then it is possible to achieve a thrust increase at top of climb, above that of a fixed nozzle engine by closing the nozzle and raising the fan operating pressure ratio. A relatively small change to a conventional thrust reverser allows the moving parts to perform a dual role and offer a useful engine thrust growth.

Figure 3 identifies the changes that must be made to the thrust reverser which include

a) lengthening the travel of the translating cowl
b) modifying the blocker door operation, to keep it stationary for the first part of cowl movement
c) designing the nozzle profile to ensure up to 5% area increase with the open nozzle and a passage that converges to the nozzle for all openings.

Considerable savings can be achieved with a variable fan nozzle because of the engine downsizing it permits. A required
top of climb thrust level can be achieved with a smaller engine. The take off thrust of this smaller engine would be

![Diagram of Variable Area Final Nozzle](image)

Restored by running the fan faster. Note that the 'smaller' engine here has the same core size but a reduced fan diameter and bypass flow.

Some 0.3% sfc increase is to be expected from these changes. It will increase by about 0.1% for each of the following reasons:

a) lower bypass ratio
b) reduced fan efficiency. It must be run faster to maintain an adequate stall margin when the nozzle is in the 'closed' position
c) bypass duct leakage at the variable nozzle

Downsizing, the engine moves the SFC/thrust bucket to the left and this may or may not improve engine/aircraft cruise thrust matching depending upon the quality of the match with the fixed nozzle configuration. Rematching the engine to exploit the advantages of the variable nozzle, would permit the fan tip diameter to be reduced by 4%. This lowers the thrust by about 10%. Reducing the nozzle area by 5% restores the top of climb thrust.

Making appropriate allowances for the extra weight and cost etc of the variable nozzle, the net percentage changes resulting from the fan diameter reduction are:

- 1.7% power plant weight
- 1.2% power plant cost
- .09% power plant maintenance cost
- 4% nacelle drag

With sensitivities derived from an advanced commercial airliner the percentage changes were all converted into direct operating cost deltas. Total DOC reduction was about 0.25%

(even after the .3% SFC increase previously noted) for a medium range airliner flying a 1000 n.m. mission. The development program will include tests to verify lockouts to prevent inadvertent reverser deployment and a computational fluid dynamics, CFD, design of the flowpath.

The estimated development program cost was modest and the predicted probability of success high, so the variable fan nozzle scored well in the technology rankings using the simple expression for ranking factor.

2. Hybrid Laminar Flow Nacelle

Drag reduction through the achievement of laminar flow has long been the aspiration of aerodynamicists. In fact considerable successes have been achieved on test flights with a hybrid laminar flow nacelle. The objective is to reduce nacelle external friction drag by 1 to 2% of aircraft total drag, a conventional nacelle represents 4-5% of aircraft drag.

![Diagram of Hybrid Laminar Flow Nacelle](image)

The source of the improvement lies in the creation of laminar flow over the leading 40% of the inlet/fan cowl in order to reduce skin friction drag. Some recontouring of the nacelle together with a limited amount of boundary layer suction is required, Figure 4. The recontouring provides an extended region of favorable pressure gradient relative to a conventional nacelle. Suction is required because laminar flow lip shapes on the forward portion of the nacelle are not compatible with low speed-high angle of attack separation free operation. In accommodating the low speed angle of attack requirements with conventional lip shapes, laminar flow is possible only with boundary layer suction. Aft of this separation constrained portion of the nacelle, it is possible to maintain natural laminar flow by curvature tailoring. A multitude of small suction holes perforate the cowl skin over...
about 24% of the fan cowl from a plane 9% aft of the highlight. A small highly reliable lightweight ejector or a small turbo compressor driven by engine fifth stage compressor bleed provides the suction.

Nacelle drag reduction is expected to be around 1.5% of the total aircraft drag but against this improvement, a 0.12% SFC increase exists to provide the engine bleed for the suction turbo compressor. Of more serious consequence is the 3.8% weight increase and 18% cost increase of the nacelle and pylon. Maintenance costs, incurred through the need to keep the perforations open and insect free, are projected to add an extra 50 cents per engine flight hour to the operating costs.

Converting all these effects into DOC using sensitivities, shows that the penalties exceed the rewards and adoption of the HFLN as it is currently configured, would result in an overall cost increase to the airline operator.

Naturally this is a disappointing conclusion after the test successes. Development must address insect coating treatments, and identification of less costly manufacture and construction technologies. Also important is the need to minimize contour mismatches, steps and gaps at the nacelle joint interfaces, to ensure the boundary layer will remain laminar. This concept was not awarded a ranking because the overall benefit was judged to be negative.

3. Shortened Intake

Additional compromises, relative to those already made on engines about to enter commercial service, can also be made by shortening the inlet, Figure 5. Reductions in nacelle drag, weight and cost are possible with a judiciously optimized design. For the shorter nacelle, great care must be taken to ensure that wave drag increases at high cruise Mach numbers is not triggered by increased nacelle curvature associated with shortening the inlet. Also inlet distortion effects in cross wind operations can not be accentuated beyond the tolerance capabilities of the fan. Wide chord fans of the type likely to be used in an advanced engine exhibit greater distortion tolerance than earlier higher aspect ratio fans, which tends to mitigate the cross wind risk. The drag of the intake alone is reduced but the overall nacelle drag remains unchanged.

The other changes for the shortened intake have a beneficial effect on aircraft DOC. Projected weight decrease is 1.7% less and cost 0.7% less. These values translate into a 0.05% DOC reduction. Intake nodding loads will be reduced with the shorter intake and thus engine carcass bending and subsequently tip rubbing on the compressors and turbines will also diminish. This improvement is not readily quantified without an extensive analysis of engine bending but it could generate as much improvement in DOC as the weight and cost changes. Development testing should include low speed high angle of attack and cross winds testing performance validation and determination of the influence on high speed drag with the engine inoperative. Ground testing of the engine will assess the acoustic impact of the shortened intake and the influence on operability with the greater pressure distortion that will be present at the fan face. Development costs are not high so this concept achieves a moderate ranking.

4. Flowline Nacelle and Pylon

Reduced installation drag of the nacelle and pylon are possible if both are recontoured to account for the local flowfield (illustrated in Figure 6). Minimizing local regions of high velocity induced by the local flowfield of the wing, nacelle and pylon will lower the overall installed propulsion system drag.
The pylon and nacelle installed losses will be lowered and the aircraft cruise lift/drag ratio raised with a properly designed non symmetrical fan cowl and nacelle which, in conjunction with the cambered pylon, improves the wing/nacelle flow field and reduces installed drag.

A drag reduction of 0.6% is expected. There will be no change of weight but the non symmetrical nacelle is estimated to increase the cost by an estimated 8.5%. As with the HLFN concept the economic disadvantage of the higher cost when converted into aircraft DOC outweighs the aerodynamic benefit of lower drag. Without improvements in either manufacturing technology to lower the cost, or dramatic outside influence on airline costs like a large increase in fuel prices; this technology cannot be justified on the aircraft.

Any development program must address manufacturing costs. To support the aerodynamic contentions, 3D Navier Stokes analysis and design must be performed. This should be followed with an installed wind tunnel test with engine model simulators.

5. Thin Pylon in Long Duct Mixed Flow (LDMF) Nacelle

In a long duct mixed flow engine configuration, the pylon fairing has to surround the rear engine mount located on the rear turbine frame. Conventionally this has been a broad structure and consequently the pylon fairing eliminates one or more of the mixer lobes. Mixer tests have shown that the mixer and nozzle internal performance can be improved by reduced pressure losses and better mixer effectiveness if the pylon can be slimmer, and shorter allowing the pylon to be finished with a slim trailing edge upstream of the mixer, see figure 7. This would permit a full circumferential compliment of mixer lobes. This provides reduced pylon scrubbing and pressure drag.

The reconfigured aft mount and pylon geometry provide a 0.5% SFC reduction but the net changes to the nozzle, mixer and pylon system weigh 3.8% heavier, with no change in cost. The resulting DOC reduction is a modest .08% though estimated development costs are also modest, so this concept has a good ranking factor.

The development program would focus on the mechanical feasibility. A detailed mechanical design, together with stiffness testing to assess front to back mount deflections and their impact on casing rubs, are necessary to verify the product feasibility of this concept.

RANKING TECHNOLOGY CONCEPTS

The five nacelle technologies are compared for a 1000 nm aircraft mission and a 5000 nm aircraft mission on figure 8. Both tables are similar but those concepts which offer the greatest improvement either SFC or drag reduction give the largest improvement with the long mission. The thin pylon

in the mixed engine is in this category as is the hybrid laminar flow nacelle. At 5000 nm the HLFN is a much more attractive concept though it still carries a small penalty.

CONCLUSIONS

- The methodology described in this paper of comparing the overall benefit to the airline economy of a new technology with the development cost incurred by that technology, is a useful procedure to help determine a cost effective distribution of limited development funds.
- The importance of including in the assessment all factors which ultimately have a bearing on airline costs has been highlighted.
- Laminar nacelles flow surprisingly do not offer an aircraft direct operating cost advantage in this study.
When increased manufacturing cost for holes, suction pump, valves, tubing, etc., a sfc penalty for operating the suction system, and increased maintenance costs, are combined, they outweigh the advantage of reduced nacelle drag.

- Low risk modest payoff concepts are attractive for implementation when they have affordable development cost (i.e. Thinned Pylon with Axisymmetrical Mixer)

- Of the concepts examined in this study, the best airline operating economy improvement is offered by the variable fan nozzle.

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