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DISTRIBUTED PROPULSION AND TURBOFAN SCALE EFFECTS

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ABSTRACT

A coupled aircraft and engine model is used to evaluate the fuel consumption and mission weight of distributed propulsion aircraft. The engine cycle is optimized for the installation to show the ultimate performance of each propulsion alternative. The effect of higher specific fuel consumption for smaller engines is weighed against the potentially lower installation weight and higher integration efficiency of distributed propulsion.

Nomenclature

V	Velocity relative to the aircraft
T	Total propulsive thrust
P	Propulsive power
D	Drag
FHV	Fuel Heating Value
W	Mass flow
W*	Normalized Mass Flow
TOW	Take off weight
PSW	Propulsion System Weight incl. nacelle
OPR	Overall Pressure Ratio
FPR	Fan Pressure Ratio
BPR	ByPass Ratio
SFC	Specific Fuel Consumption
Re	Reynolds number
η	Efficiency

Subscripts

0	Free stream
j	Jet
t	Turbine
c	Compressor
pol	Polytropic
i	Immediately upstream of intake
in	Component inlet
out	Component outlet
p	Propulsive
th	Thermal
F	Fuel
ing	Ingested part
ps	Propulsion System, i.e. exclusive of airframe drag effect on intake pressure recovery

INTRODUCTION

A conventional subsonic transport aircraft is equipped with two to four turbofan engines. The trend from the fifties until now has favored the twin underwing engine configuration. An alternative is to use a large number of engines. This concept can broadly be described as distributed propulsion.

More than four engines have been used in the past for reasons of reliability and unavailability of sufficiently large engines (compare e.g. the "Spruce Goose" and the B-52). Reliability concerns also led to the requirement that an ocean crossing aircraft must have at least three engines, although the number of routes affected by this has decreased due to ETOPS qualification of twin engine aircraft.

However, in the future the possible advantage of using more than four engines on an aircraft relies on weak "scale effects" simultaneously affecting many parameters. Lowered structural load by distributing propulsion units is one such engine scale effect used to some advantage on e.g. the Helios solar powered aircraft. Positive scale effects for distributed propulsion may also include lower engine installation drag, the potential to increase propulsive efficiency, decreased noise, lower aircraft and engine structure weight, better material properties of small components, increased aircraft configurational freedom and mass production cost advantages. A smaller engine may also find a wider application for transport aircraft of various sizes as well as business jets and UAVs, which would increase production efficiency and spread development cost.

There are, however, also definite disadvantages from using engines of smaller size, the main ones being increased pressure and heat losses due to a decreased Reynolds number and leakages, as well as increased maintenance cost. It can be noted that it is primarily this negative impact on efficiency and cost which has driven configurations to the ubiquitous twin engine transport aircraft, and which has increased the market share for single engine military fighters compared to twins.

The presented technology study attempts to identify relevant engine scale effects for turbofan propulsion and to quantify their size. The scale effects are applied in a coupled engine cycle, component efficiency and weight estimation model. The application effect is then evaluated in a simple aircraft weight and mission performance estimation for a conventional and a flying wing/Blended Wing Body (BWB) configuration.

PROPULSION MODELING

Turbofan scale effects modeling

Today's large aircraft engines show an unprecedented level of efficiency caused by refined aerodynamics, materials and cooling which allow extreme cycle temperatures. This in turn has allowed a high pressure ratio which is the chief parameter behind high thermal efficiency. The size of these engines helps keeping flow losses small. Smaller engines are less fuel efficient for a number of reasons. When comparing engines of different size for one application, limitations of physics and technology must be kept apart from the difference in current applications and previous limited availability of development resources for small engines, scarcity of new designs for smaller engines etc.

In this study we have chosen to concentrate on the efficiency variation of the turbomachinery with size.

Compressor efficiency has been correlated to a Reynolds number of the high pressure compressor exit. Expecting a power law to give a good fit it was found that the compressor efficiencies of state of the art compressors can be found as:

$$\eta_{c,pol} = 1 - C_c \operatorname{Re}_{c,out}^{-0.4}$$

$$\operatorname{Re}_{c,out} = \sqrt{W_c^*} P_{c,out} / T_{c,out}^{1.7}$$

Note that this is a stronger relationship than the $\operatorname{Re}^{-0.2}$ expected from turbulent skin friction only. The Reynolds number definition is consistent with a blade velocity independent of compressor size and that the hub tip ratio and blade aspect ratio does not have a significant trend with size.

For the turbines limited data suggests that:

$$\eta_{t,pol} = 1 - C_t \operatorname{Re}_{t,in}^{-0.2}$$

$$\operatorname{Re}_{t,in} = \sqrt{W_t^*} P_{t,in} / T_{t,in}^{1.7}$$

give a satisfactory correlation. The constants C_c and C_t were chosen to set the efficiency to the level of state of the art turbomachinery.

It is clear that losses other than turbulent skin friction contribute in turbomachinery components, but most of them are related to viscous effects either directly or indirectly through the design process. Newer designs have also succeeded in reducing secondary flow losses. The fit of the above relations with data also means that other effects are taken into account at least approximately.

Fan flow is dominated by transonic and shock losses and available data did not suggest a strong correlation with size. Combustor flow losses are designed in for combustion stability and do not vary with engine size. Other flow losses are small and their dependence on size should be largely insignificant. Weight models (described below) based on cycle data correlate well without scale corrections.

Wing beam weight may vary with number of engines but gains using smaller engines should be small for a typical jet transport where the wing is gauged to carry the larger weights of the fuselage and fuel, and these gains may be offset by requirements for local strengthening at many points.

In summary, for the relatively large engines the primary scale effects are found to be compressor and turbine efficiencies. Inclusion of other, weaker scale effect can refine the results given here, but will most likely not change the main trends.

Installation efficiency modeling

Several critical issues in assessing the performance of the distributed propulsion concept relate to the engine installation efficiency [1,2]. Embedding the engine in the wing or fuselage may, depending on engine size and aircraft design, completely or at least to a large extent eliminate nacelle drag. Another opportunity related to distributed propulsion is its potential to efficiently ingest large parts of the aircraft wakes, thereby increasing the propulsive efficiency. Quantitative models for assessing the impact on the aircraft system performance of both engine embedding and wake ingestion are developed below.

Wake ingestion modeling

The common definitions of propulsive and thermal efficiency are the quotients

$$\eta_p = \frac{V_0 T}{P_j - P_0}$$

$$\eta_{th} = \frac{P_j - P_0}{W_F FHV}$$

That is the propulsion efficiency is the quotient of "useful" propulsive power divided by the increase in gas flow kinetic power provided by the engine.

For the definitions to be meaningful the velocities of the inflow and jet must be measured where the static pressure is the same, i.e. upstream of the aircraft and downstream of the engine. Since in practice the kinetic energy decreases downstream due to viscous effects, an ideal non-viscous velocity must be used to find P_j. It is easily verified that this propulsive efficiency is less than or equal to one.

By this definition intake losses will cause P_j to decrease and the thermal efficiency of the power plant will decrease. However, if the intake is located downstream of a part of the aircraft not belonging to the power plant, this means that the drag of this part is then included in the thermal efficiency as a loss of intake pressure, and should then not be included in the drag. This division is also consistent with the standard drag accounting procedure [3,4]. It is somewhat counterintuitive that a downstream power plant affects the drag of an upstream surface, even if the pressure and flow field around the latter is unchanged.

To solve this paradox we propose that in the manner of Smith [5], for the special case that the static pressure immediately upstream of the intake is the same as the free stream value, to define the propulsive and thermal efficiency as:

$$\eta_{p,ps} = \frac{V_0 T}{P_j - P_i}$$

$$\eta_{th,ps} = \frac{P_j - P_i}{W_F FHV}$$

$$P_i = W_i V_i^2 / 2$$

and similarly the net thrust from

$$F = W_j V_j - W_i V_i$$

with V_i being the velocity of the intake gas stream immediately upstream of the intake. For the general case V_i, here labeled the equivalent intake velocity, should be taken as the velocity which at the freestream static pressure gives the same total pressure as that at the station i.

With these definitions the engine efficiency and thrust depends only on what happens from intake to exhaust, and the drag of any item in the upstream path of the intake should be attributed to the airframe. The definitions above collapses to the standard expression when there is no airframe effect on the pressure recovery.

Note that the above propulsive efficiency as well as the one used by Smith, can be increased beyond one in some cases and thus as he suggested should properly be termed the "propulsive coefficient".

The procedure for calculating the engine cycle is then simply to calculate the total pressure at the air intake, and then to calculate the engine cycle with this lower intake pressure and he corresponding equivalent intake velocity. In fact it can be performed by finding the equivalent flight velocity of the propulsion system. It has to be kept in mind, however, that while the total pressure is decreased, the total temperature stays constant, if there is no heat exchanged with the airframe.

When estimating the equivalent velocity decrease, the concept of D_{ing}/T introduced by Smith is useful. D_{ing} is the momentum deficit in the air ingested by the propulsion system corresponding to part of the viscous drag of the vehicle. From momentum balance it follows:

$$V_0 - V_i = T(D_{ing}/T)/W_i \ .$$

Because the wake momentum loss is distributed over a considerable airflow, the attainable D_{ing}/T is limited by a function of the engine airflow and the shape factor of the wake as shown by Smith.

It should be clear from the above description that increased propulsive efficiency comes from ingesting the wake rather than injecting the jet in the wake as suggested by Ko [6] and Dippold [7]. Any mixing of jet and wake which occurs downstream of the aircraft will not contribute to engine thrust.

Engine embedding

As shown by the Comet airframe, which in its Nimrod configuration recently has been re-engined with BR710 engines, integration of engines in the wing is possible provided the engine diameter is small enough. The avoidance of nacelle skin saves drag and weight. The assumptions for embedded (buried) engines are shown in the results section below.

Installation weight modeling

The weights of nacelles were correlated to engine airflow which in turn correlates excellently to the square of the fan diameter. Results show that a linear relationship between maximum airflow and nacelle weight is reasonable. For a constant length to diameter nacelle this is equivalent to a constant weight per nacelle skin area.

SYSTEM EVALUATION MODEL

The engine performance was evaluated for a fully loaded 250 passenger, 15000 km range, twin-jet with a cruise speed of M=0.85. The engines and aircraft were evaluated at the mean cruise weight at an altitude of 41000 ft when 54% of max fuel was computed to remain.

Based on existing aircraft a correlation was devised which shows that max take-off weight can be approximated by 1.61 times the sum of 148 kg per passenger, fuel, engine and nacelle weight. The 148 kg can be interpreted as the sum of passenger, luggage, seat, interior and passenger cabin (including pressure vessel). The 1.61 snowball factor includes the wing and the fuselage load bearing structure, the empennage and landing gear etc. Required fuel load was calculated to be 18.7 hours of mid-cruise consumption, including take-off, climb and reserves.

An aircraft model was set up to give drag estimates. It was assumed that the wing loading at take off would be 650 kg/m^2, and the wing aspect ratio10. The drag model determined the fuselage drag to 25.7 kN, the drag of wing and empennage to 3.54% of cruise weight and installation drag was estimated at 1.9 N per kg normalized mass flow the reference twin engine configuration. The resulting lift to drag ratio is about 19, with a higher ratio for higher flying weights as the drag of the fuselage does not scale with weight.

The above system model corresponds to a new design aircraft of conventional configuration with current (2005) technology.

A blended wing body (BWB) aircraft seating 600 passengers was also modeled. The BWB has the same 15000 km range, flying M=0.85 at 37000 ft. The span loading was set at 70 kg/m^2. From design studies of BWB it was assumed that the wing would have a wing area corresponding to an aspect ratio of 10 plus a central wing/body chord extension with an area of 700 m^2.

The drag model determined the drag to be 30.9 kN + 3.35% of cruise weight and installation drag was estimated at 2.2 N per kg normalized mass flow with nacelle mounted engines. The resulting lift to drag ratio was about 22 for the reference four-engine configuration.

To estimate direct operational cost (DOC) it was assumed that, for the take-off weight optimized reference aircraft and engine, 11% of DOC is proportional to engine weight, 15% is proportional to aircraft max take-off weight and 20% is proportional to fuel burn. The remaining 54% includes crew costs and passenger cabin costs etc.

A similar model was used by Lundbladh and Sjunnesson [8] to evaluate system performance of heat exchanged engines.

ENGINE MODEL

The engine cycles were evaluated in the Gasturb engine simulation program[9]. Although a two shaft unmixed exhaust configuration was used for all engines, a similar results can be expected for a three-shaft and/or mixed exhaust engine.

Typical polytropic efficiencies and pressure losses for components in current engines were assumed and installation effects like bleed, power off-take, intake total pressure loss, and nacelle drag were included. Design speeds for components were chosen to avoid large efficiency losses at off-design conditions.

The engine model also included a weight model, which estimates low pressure system and core weight from airflows, fan pressure ratio and high pressure compressor temperature rise. The model has been correlated to modern transport engines.

The engine model was optimized with a constraint of a fixed high pressure turbine metal temperature at mid-cruise. This was done to make the different engines comparable with regard to technology. The technology level will be defined by the highest temperatures at take-off but the constraint of equal temperatures at mid cruise simplifies the calculation procedure and yields almost the same result.

The primary engine parameters for optimization are BPR, high pressure compressor pressure ratio, outer fan pressure ratio. The engine was scaled by changing the airflow until thrust equals drag. In general three types of optimizations can be performed for all engine cycles while satisfying the installed thrust requirement:

- minimization of fuel burn,
- minimization of operational cost
- minimization of aircraft mission take-off weight

The results below are given for the case of minimum take-off weight only, as this is a reasonable trade between cost and fuel consumption. Previous studies [8] have shown that cost optimized aircraft have smaller engines with lower bypass and pressure ratios.

The optimization does not take engine noise into account, and it is expected that results will be driven towards somewhat higher airflows and bypass ratios if noise is included in the goal function. However, neither the take-off weight nor the relative merits of the various engine installations are expected to change significantly.

Similarly if NOx emissions would be included in the goal function the optimum pressure ratio would be decreased and the fuel consumption would increase, but the relations between the various engine installations would change only slightly.

RESULTS

For the conventional twin engine aircraft the take-off weight optimized engine cycle has the parameters shown in the first column in Table 1 below.

The turbine metal temperature was fixed to 1030 K as representative for new design large twin engine aircraft application taking into account the technology trend. Notable is that the pressure ratio in cruise at 38 and the BPR at 8.4 corresponds well to published data on recently designed engines for twin engine aircraft. At take-off the pressure ratio would be 30-40% higher and the bypass ratio slightly lower. This set of data will serve as our reference for comparison.

When attempting to model performance for an engines say 100 times smaller than those on today's twins it is found that they give a too high fuel consumption, especially for a long distance aircraft. As a compromise, eight engines of roughly the size of General Electric's CF34 appears possible to integrate in a wing, and will yield nearly all the benefit of having a large number of engines, while not losing too much internal efficiency. However, as can be seen below, these engines, when designed for a long distance application, would have a cycle much closer to a large engine than to a CF34 optimized for regional aircraft.

For the distributed propulsion with eight pod-mounted engines, and the same turbine metal temperature as for the two engine aircraft, the optimal pressure ratio is about 5 units lower because of the lower component efficiencies.

However, for a multi-engine aircraft the engines can be downsized for take-off. Based on current twin- and four-engine aircraft at a fixed wing and span loading, the thrust required in a twin-engine aircraft was assumed to be 20% higher, (e.g. T/TOW=0.25 for four or more engines and 0.3 for two engines.) No further decrease was expected to be possible for an eight engine aircraft as climb and noise considerations would set thrust requirements.

The 20% thrust difference was found to correspond to a 7% difference in metal temperature for a modern engine cycle. Thus the metal temperature in the smaller engines was set to 1100K. Similarly the smaller sizing of the engines leads to lower nacelle drag and propulsion system weight for the multi-engine case, a fact which has been integrated in the engine and drag models. Again optimizing the cycle and aircraft for these parameters yields a cycle shown in column two of Table 1. When comparing cycle data to the reference it should be remembered that the engines in the distributed propulsion case is running at a higher relative thrust setting. Thus the take-off and maximum pressure ratio will be lower in this case although the cruise pressure ratio is higher.

An important result is that the fuel consumption is 1.8% higher and the weight of the aircraft 0.3% higher than for the twin-engine one. The propulsion system is on the other hand 9% lighter due mainly to the smaller thrust needed at take-off.

For the engines buried in the wing a 1% higher pressure loss in the air intakes due to internal flow friction was estimated from experience with military engine installations. Some of the nacelle weight should be possible to remove as the wing surface replaces the nacelle outer fairing, but this is partly offset by the need to confine the engine to a sealed bay. It was here assumed a reduction of 50% of the installation weight and 70% of the installation drag would be possible, the remaining drag coming from the "humps" needed to house the engine in the wing. If these assumptions can be realized column 4 in the table shows that the take-off weight is 4% lower than the twin-engine case and the propulsion system is 17% lighter. The fuel consumption is 4% lower than the reference aircraft. The buried engines increase lift to drag ratio for the aircraft by 1.9%.

It can be noted that optimal embedded engines have a higher bypass ratio and 7% higher airflow than for eight engines in nacelles, due to the lower installation weight which enables larger engines to be accommodated. The high pressure system parameters are hardly changed.

For the wake ingestion case the engines are spread out along the trailing edge of the wing. Of the reference configuration drag 48% was calculated to be lift-dependent, 19% zero-lift drag from the wing and 33% is fuselage and empennage drag. About 10% of the lift-dependent drag (or 5% of the total drag) is viscous drag, for a total 24% of drag to be wing viscous drag.

For the size of the fans used with a conventional propulsive coefficient of around 0.8 it is not possible to absorb the wake corresponding to more than about 25% of the drag even if the engine intake is optimally located and shaped to pick up the part of the wake which is slowed down the most, see [5]. Considering this and that the wing viscous drag is 24% and that the engine intake cannot pick up the wake from the wing tips and all the way down to the trailing edge, a realistic goal is to pick up the wake corresponding to 15% of the drag, i.e. $D_{ing}/T=0.15$.

The wing wake ingestion configuration cannot be accomplished with the same reduction in installation drag as for the buried configuration with a conventional leading edge intake. The engines will extend rearward from the trailing edge. The installation drag and weight will then only be reduced by 10% due to the omission of the pylon.

The resulting optimal engine and aircraft is given in the rightmost column of Table 1. In this case, compared to the reference aircraft, the fuel consumption is 4% lower; the take-off weight is 4% lower, the propulsion system 13% lighter, and the operating cost is reduced by more than 3%. However this is only slightly better than what is achieved by the buried engine configuration.

Moreover, this configuration implies eight engines of about 1.3 m diameter spread out along a 60 m long wing. To pick up enough of the boundary layer air to yield $D_{ing}/T=0.15$, the intakes would need to be flattened to take in air in a slit along the wing. Additional calculations show that if this is accompanied by an increased intake pressure loss of 2%, the fuel consumption is increased by 7% and any advantage of wake ingestion is lost.

As can be expected and is explained in [5], the boost in propulsive efficiency from ingesting the wake leads to the optimum changing to a higher delta velocity over the engine, a higher fan pressure ratio and to a lower airflow.

Table 1 optimized engines for various comparison installations in a conventional aircraft. Fuel flow is the total for all engines, air flow and thrust for each engine.

No of engines	2	8	8	8
Installation	pod	pod	buried	pod
Intake	std	std	std	wake
SFC mg/Ns	15.04	15.37	15.44	14.95
W_F kg/s	1.528	1.556	1.467	1.460
PSW kg	16113	14661	13434	14056
TOW kg	251085	251804	240193	240455
W_i kg/s	397	102.9	110.1	84.7
T kN	50.8	12.65	11.88	12.21
OPR	38.7	41.5	41.2	40.9
BPR	8.42	9.72	11.17	9.19
FPR	1.64	1.61	1.52	1.63
$\eta_{pol,c}$	92.0%	89.0%	88.8%	88.6%
$\eta_{P,ps}$	79.7%	80.4%	82.5%	84.5%
DOC	1	0.990	0.973	0.968

The blended wing body reference configuration has four engines. This simplifies the comparison as no difference in take-off thrust to weight needs to be accounted for. However, because the cruise drag is about 15% lower, with a lift over drag ratio of about 22, the metal temperature was set lower, at 1050 K, for all engines, to allow for a thrust to weight of about 0.25 at take off.

For this configuration it is reasonable to use a combination of embedding and wake ingestion as the large root chord allows most of the boundary layer to be picked up well ahead of the trailing edge. Because the wing-body viscous drag is about 56% of the total in this case, it was assumed that $D_{ing}/T=0.2$ would be achievable. Table 2 shows the main results.

As can be expected, in absence of any sizing advantage, the lower component efficiencies cause higher fuel consumption, weight and cost for distributed, nacelle mounted engines. The effect of simultaneously reducing drag and improving propulsion efficiency by embedding the engines reduces fuel consumption to almost 9% and take off weight by 6% below the reference. As the rightmost column shows, however, a not unreasonable increase of intake pressure loss absorbs most of the advantage. Some of the advantages of embedding the engines can also be gained for a (non-distributed propulsion) four-engine configuration.

Table 2 optimized engines for studied installations in a blended wing body. Fuel flow is the total for all engines, air flow and thrust for each engine.

No of engines	4	16	16	16
Installation	pod	pod	buried	buried
Intake	std	std	wake	wake
Intake loss	std	std	std	+2%
SFC mg/Ns	14.94	15.75	15.08	15.82
W_F kg/s	2.339	2.579	2.168	2.339
PSW kg	21042	22320	18844	18896
TOW kg	430560	458404	408473	426894
W_i kg/s	324	85.7	78.2	65.7
T kN	39.1	10.23	8.98	9.24
OPR	41.6	35.5	33.5	34.0
BPR	9.18	9.15	10.29	7.84
FPR	1.61	1.58	1.51	1.64
$\eta_{pol,c}$	91.8%	89.1%	88.3%	88.4%
$\eta_{P,ps}$	80.6%	80.8%	88.0%	86.3%
DOC	1	1.047	0.971	0.999

It is interesting to note that the pressure recovery for wake ingesting propulsion consists of two parts, the one caused by the unavoidable drag of the upstream airframe and the other one caused by engine intake and channel. While the previous can be taken advantage of, the latter is detrimental. In fact, for the above BWB the loss of pressure due to wake ingestion is 8.4%, but the advantage of this is cancelled by an additional 2% loss in the intake. It is thus clear that intake optimization must take the effect on the engine into account. Rodriguez [2] shows optimized intake shapes for a BWB which gives a pressure recovery of 0.93, but because of the lack of the split into to the two effects his results are hard to compare to this study, except to say that with such a low loss of pressure his D_{ing}/T value must be below about 0.16 and probably significantly smaller.

CONCLUSIONS

Two aircraft configurations were studied to show the effect of increasing the number of engines and distributing them over the airframe.

It was found that a four percentage gain in fuel consumption can be achieved by embedding the engines into the wing for a conventional 250 passenger long range aircraft. Wake ingestion for this configuration showed little advantage and great dependence on the intake pressure ratio.

For a 600 passenger blended wing aircraft the advantage of embedded engines with wake ingestion was greater, but the large dependence on intake pressure ratio means more detailed studies of intake performance is needed to show the viability of the technology.

High efficiency was found to require the pressure ratio of smaller engines to be over 40 and BPR over 8. Very high pressure, high efficiency compressors, advanced cooling and multistage low pressure turbines needs to be developed in smaller sizes than available today, all at cost which should decrease proportionally with the smaller size of the components.

It is clear that distributed propulsion, if of any advantage at all, relies on a weak dominance of beneficial effects over negative effects of a similar magnitude. The lack of alternative ways to reduce propulsion drag and increase propulsive efficiency for aircraft flying at high subsonic speeds still makes the field worthy of detailed studies. In particular calculations which would provide better estimates of D_{ing}/T values and pressure recovery for wake ingestion intakes would be valuable. Full mission calculations would also help clarify the engine sizing effects. In any case, it is likely that distributed propulsion will have to be combined with technologies which avoid some of the efficiency losses of smaller engines for it to be a competitive solution.

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