Optimum Turbofan Engine Performance Through Variation of Bypass Ratio

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Abstract

The desire for higher engine efficiency has resulted in the evolution of aircraft gas turbine engines from turbojets, to low bypass ratio, first generation turbofans, to today's high bypass ratio turbofans. It is possible that future designs will continue this trend, leading to very-high or ultra-high bypass ratio engines . The most significant impact of the design changes was a reduction in the aircraft weight and block fuel penalties incurred with low fan pressure ratio, ultra-high bypass ratio designs. This enables lower noise levels to be pursued (through lower fan pressure ratio) with minor negative impacts on aircraft weight and fuel efficiency. Regardless of the engine design selected, the results of this study indicate the potential for the advanced aircraft to realize substantial improvements in fuel efficiency, emissions, and noise compared to the current engines in this size class.

Keywords: turbofan engines, bypass ratio, noise reduction, specific thrust, Specific fuel consumption

الخلاصة

إن الحاجة للحصول على محركات ذات كفاءة عالية أدت إلى تطور محركات الطائرة التوربينية من محركات تور بينية نفاثة إلى الجيل ألأول من المحركات التوربينية المروحية ذات نسبة المرور الجانبي القليل إلى محركات اليوم ذات نسبة المرور الجانبي الكبير. من الممكن أن التصاميم المستقبلية سوف تستمر في هذا الاتجاه مؤدية إلى محركات ذات نسبة مرور جانبي كبير جدا أو كبير جدا جدا. إن التأثير ألأهم في تغيير تصميم المحركات التوربينية المروحية التي تتمتع بنسبة مرور جانبي هو في تقليل وزن الطائرة وكذلك التغلب على ظاهرة إنسداد مجاري الوقود التي تحصل في المحركات ذات نسبة المرور الجانبي الواطئة,وكذلك التمكن من خفض مستويات الضوضاء نتيجة تطبيق (نسبة ضغط مروحية واطئة) مع أحداث تأثير سلبي قليل على وزن الطائرة وكفاءة الوقود. بغض النظر عن التصميم المختار للمحرك ،بينت نتائج هذه الدراسة إلى الإمكانية للطائرة المتقدمة لإدراك تحسينات كبيرة في كفاءة الوقود، وتقليل الانبعاثات ، ومستوى الضوضاء مقارنة بنفس الحجم من المحركات المطبقة حاليا.

الكلمات الدالة: محركات توربينية مروحية,نسبة المرور الجانبي,تخفيض مستويات الضوضاء,الدفع النوعي استهلاك الوقود النوعي.

١. Introduction

The propulsion systems used on today's civil transport aircraft represent the refinement of the principle of jet propulsion based on the gas turbine, first conceived by Whittle and Von Ohain nearly ٧٠ years ago. In that period, propulsion system concepts have evolved through turbo-props, turbo-jets, low by-pass ratio (BPR) turbofans, to today's high BPR ٢-shaft and ٣-shaft turbofans. Also, this period has seen remarkable progress in the performance and reliability of these propulsion systems.

Aircraft are now three times more fuel-efficient than the early turbo-jet powered aircraft (see Fig.١،١.), and roughly two-thirds of this improvement is due to the giant strides made in reducing engine fuel consumption.
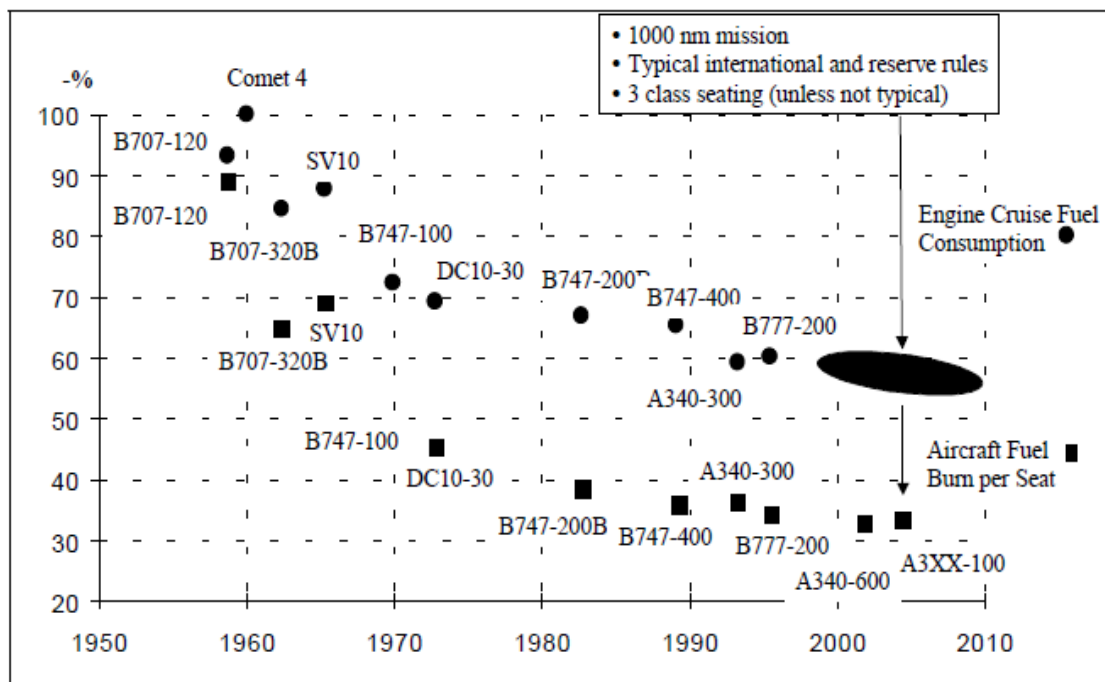

Figure ١،١. Aircraft fuel burn

Another key engine design criterion over the last ٣٠ years has been noise, driven by the rapid expansion of airport usage at major city hubs and its impact on the local resident population. Here again, the engine industry has responded by producing design that are ٧٥٪ quieter than the early turbo-jet powered aircraft (see Fig. ١،٢.). Continued development of the turbo-jet powered aircraft has resulted in an increase in bypass ratio from low values (١ to ١،٤) to moderately high values (٤ to ٨) for turbofan engines; this has brought about significant improvements in subsonic aircraft cruise performance and reductions in aircraft noise. These moderately high-bypass-ratio engines have evolved through technological advances in overall pressure ratio, turbine inlet temperature, hot-parts cooling, and materials. [٥]
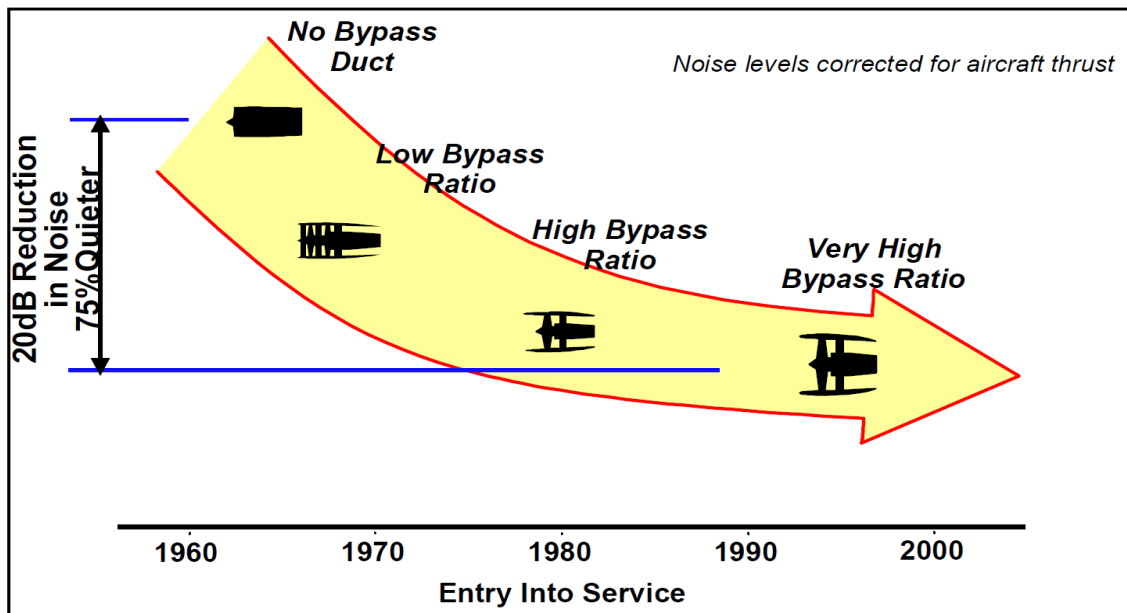
Figure ١,٢. Aircraft Noise

These engines provide (١) better cruise economy because of lower specific fuel consumption, (٢) lower noise in and around the airport community because of lower core-engine and fan-jet velocities, and (٣) shorter take-off distances and faster climb out because of the higher take-off thrust of engines that are sized for matching of cruise net thrust with cruise drag (hereinafter referred to as cruise thrust-drag matching or thrust-drag matched engines). Shorter take-off distances and faster climb out also reduce community noise.

It has been suggested that engines with bypass ratios even higher than those of present engines would provide further gains in cruise economy, shorter take-off distances, and lower noise. Lower cruise specific fuel consumption is inherent in higher bypass-ratio cycles for basic engines of a given technology level. Thrust lapse rate, the rate at which engine net thrust decays with flight speed, is also a function of bypass ratio, and engines which are sized specifically for cruise thrust-drag matching will certainly produce increases in take-off thrust with increases in bypass ratio. Furthermore, with high bypass ratios, if the exhaust flow, which is at a lower velocity, could be directed over or through wing-flap systems to increase take-off lift coefficients, shorter take-off distances, faster climb out, and still lower noise could be realized. Short take-off and landing aircraft thus could be configured to meet noise requirements expected for future aircraft without sacrifices in flight performance.

The potential improvements offered by high-bypass-ratio engines may not be fully realized, however, because of aircraft installation effects. Since thrust lapse rate increases with bypass ratio, propulsion systems sized to provide cruise thrust-drag matching will become larger and heavier as bypass ratio is increased. Increases in propulsion-system weight would require either an increase in aircraft gross take-off weight to perform the same mission requirement or a displacement of fuel or payload for aircraft having the same gross weight. Performance losses due to engine-installation effects and propulsion-system cruise drag can reduce the advantage of lower cruise specific fuel consumption provided by the high-bypass ratio engine;

the lower fan pressure ratios of high-bypass-ratio engines of a given technological level result in greater sensitivity to installation effects.

Thus, it is not clear that the advantages of lower cruise specific fuel consumption, increased take-off thrust, lower noise, and possibly lift augmentation at take-off, which are attributable to increases in bypass ratio, can be attained without important influences on overall aircraft flight efficiency and cruise range. The weight of the engine and propulsion package and the specific fuel consumption are of great importance to short-haul aircraft, for which the total fuel is a relatively small fraction of gross take-off weight For long-haul aircraft, the weight of the engine and propulsion package is of lesser importance; cruise specific fuel consumption and propulsion-system drag are the more important parameters associated with aircraft performance.[٦]

An ideal concept, of course, would be a fixed-cycle engine that is quiet on takeoff and efficient at cruise. Although this idea was probably unfeasible several years ago, advances in engine technology bring it closer to reality today. A central parameter is the turbine inlet temperature (TIT). Increasing the TIT allows a supersonic engine to operate at higher bypass ratio while maintaining a reasonably small frontal area.

١،١.The turbofan engine

The turbofan engine is a propulsive mechanism to combine the high thrust of a turbojet with the high efficiency of a propeller. Basically, a turbojet engine forms the core of the turbofan; the core contains the diffuser, compressor, burner, turbine, and nozzle. However, in the turbofan engine, the turbine drives not only the compressor, but also a large fan external to the core. The fan itself is contained in a shroud that is wrapped around the core. The flow through a turbofan engine is split into two paths. One passes through the fan and flows externally over the core; this air is processed only by the fan, which is acting in the manner of a sophisticated, shrouded propeller. The propulsive thrust obtained from this flow through the fan is generated with an efficiency approaching that of a propeller. The second air path is through the core itself. The propulsive thrust is obtained from the flow through the core is generated with an efficiency associated with a turbojet.

This engine draws atmospheric air into the ducted fan ١. The fan ٢ in the duct compresses it by a small pressure ratio of ١،٢ to ١،٥. A large part of this air is expanded and discharged at ٣ to produce the main propelling jet. The balance passes through the low pressure (LP) compressor ٤ and the high pressure (HP) compressor ٥. Fuel is added in the combustion chamber ٦ to generate the hot high pressure gas. This gas is expanded in the HP turbine ٧ which drives the HP compressor and the LP turbine ٨ which drives the LP compressor and the fan. The gas emerging from the LP turbine is expanded to produce the second propelling stream of gas. ٤ to ٩ thus constitute the core engine which drives the fan ٢.

The overall propulsive efficiency of a turbofan is therefore a compromise between that of a propeller and that of a turbojet.
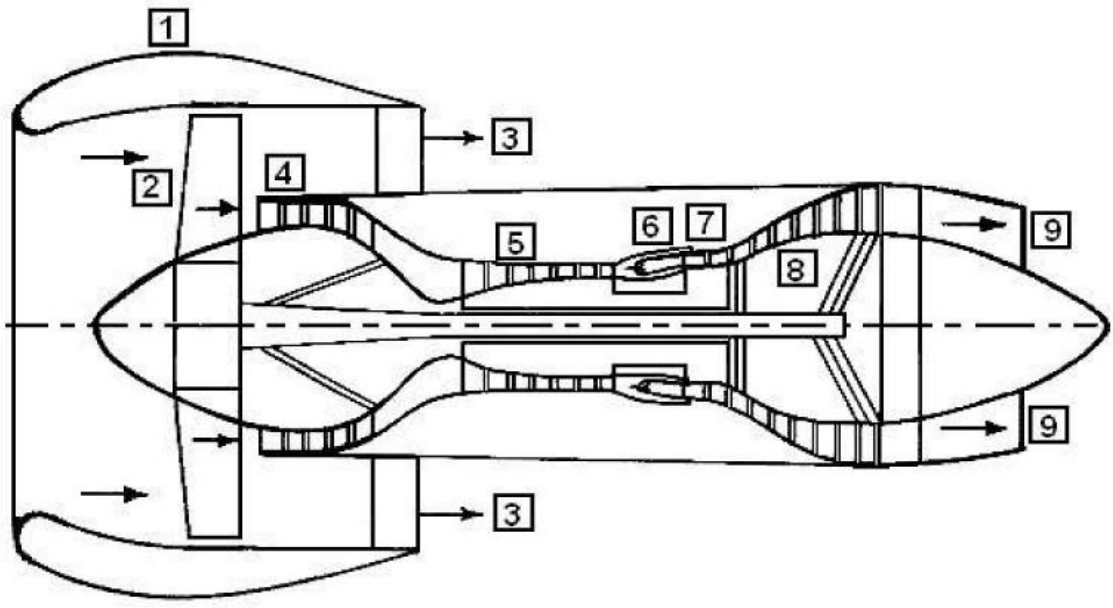
Figure ١،٣. Functional description of turbofan engine

The figure below illustrates two generic turbofan engine designs. The upper figure shows a military turbofan designed for high performance at supersonic Mach numbers in the range of ١،١ to ١،٥. The fan on this engine has three stages with an overall pressure ratio of about ٦ and a bypass ratio of only about ٠،٦.
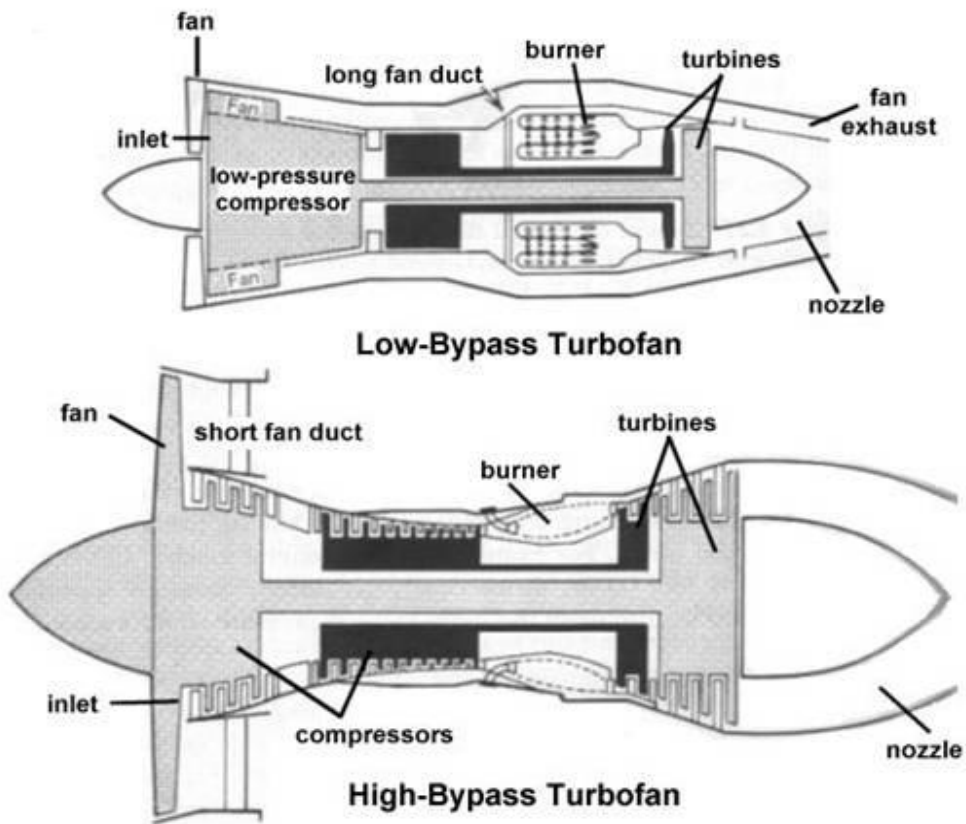

Fig ١،٤. Turbo fan engine.

The lower figure shows a modern high bypass ratio engine designed for long distance cruise at subsonic Mach numbers around ٠٫٨٣ typical of a commercial aircraft. The fan utilizes a single stage composed of a large diameter fan (rotor) with wide chord blades followed by a single nozzle stage (stator). The bypass ratio is ٥٫٨ and the fan pressure ratio is ١٫٩.

It is well known in aircraft propulsion system design that it is more efficient to generate thrust by accelerating a large mass of air a small amount than by accelerating a small mass of air a large amount; propulsive efficiency increases as the ratio of exhaust velocity to free stream velocity decreases. For a turbofan engine, this can be accomplished by reducing the fan pressure ratio (FPR), which decreases the amount of fan air stream acceleration, and increasing the fan mass flow (fan size) to maintain thrust. An increase in fan mass flow for a given core engine size leads to higher bypass ratio (BPR). The desire for higher engine efficiency has resulted in the evolution of aircraft gas turbine engines from turbojets (BPR=٠), to low bypass ratio, first generation turbofans (BPR=١-٢), to today's high bypass ratio turbofans (BPR=٥-١٠). It is possible that future designs will continue this trend, leading to very-high or ultra-high bypass ratio (UHB) engines.

Reduced FPR has complementary benefits in lower engine noise due to the strong relationship between noise and the velocity of the air exiting the engine. Low pressure ratio fans also typically require lower tip speeds which can result in lower fan noise. Although there are fundamental noise and efficiency benefits to lowering FPR, there are typically weight and drag penalties which can potentially offset those benefits. In addition, the larger fan diameter associated with lower FPR can lead to engine-airframe integration issues. Only through analysis of the complete aircraft system can the best FPR for a given aircraft design be determined.

٢. Noise Reduction

Because one of the most actual problem is noise and emissions at the aircraft level, the design tool can be used to study the impact of changing bypass ratio, engine pressure ratio, or other such high-level variables on the aircraft as a whole. As the design of the aircraft progresses, further improvements can be made via the installation of nacelle liners and chevron nozzles, for example. Typically, these modifications do not impact the aircraft configuration as a whole, and can therefore be considered separately during detailed design. Such improvements at the engine or airframe-component level are the focus of programs such as the European X-NOISE project, SILENCE(R), and NASA's Advanced Subsonic Technology Project and Quiet Aircraft Technology Program in the United States.

٢,١.Bypass Ratio variation

Jet engines produce most of the sideline and takeoff noise measured during the certification process. It follows that engine design is critical to the noise performance of the aircraft. Advances in liner materials and high-bypass ratio engines have been the largest contributors to aircraft noise reduction (Figure ٢,١.). The particular importance of bypass ratios in this respect is well known: increasing the bypass ratio can have a dramatic effect on fuel efficiency, noise, and emissions. By increasing the amount of airflow directed around the combustion chamber relative to the amount of air passing through it, mixing between the flows on exit is increased and exhaust velocities reduced. The result is a considerable decrease in jet noise and overall engine noise (Figure ٢,٢.): increasing bypass ratios from ٦ to ١٤ results in a cumulative noise reduction of ٨ dB. These results were obtained with the design tool developed as part of this research. The design tool incorporates ANOPP, a detailed noise prediction code developed at NASA Langley, and NASA Glenn's NEPP engine simulator, as well as aircraft design, analysis, and optimization modules developed at Stanford.[٢]
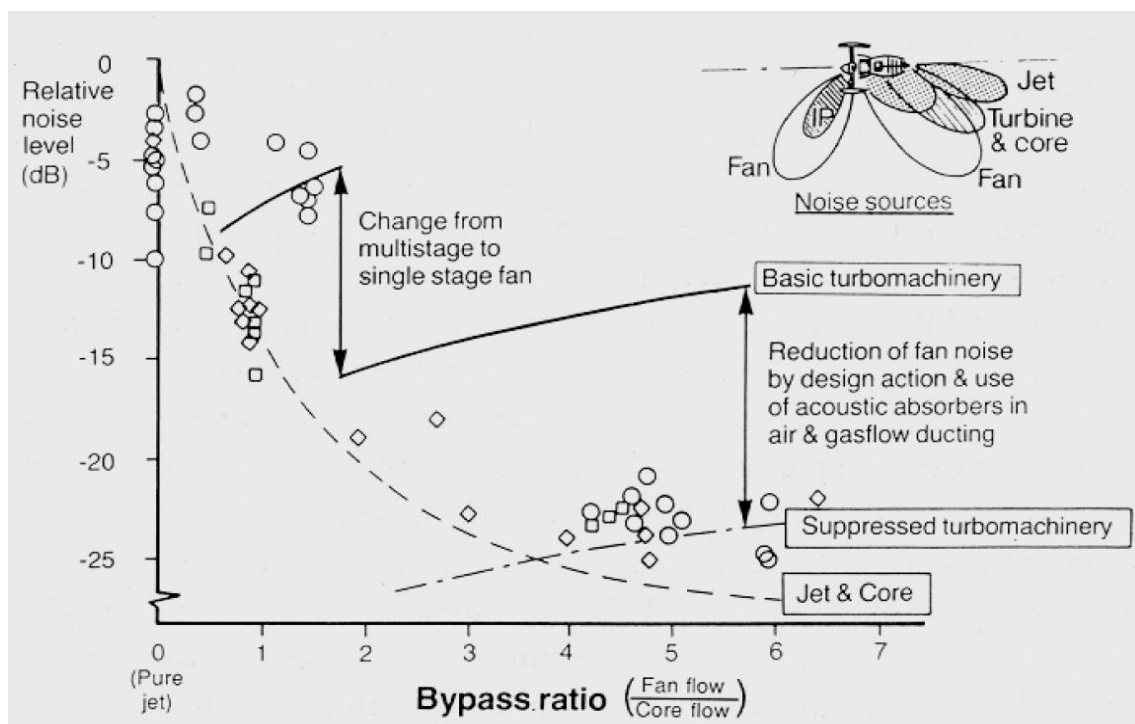

Figure ٢,١. Noise reduction technologies

The impact on noise emissions and operating costs of increasing bypass ratio is not as obvious. Figure ٢,٢. also illustrates the variations for optimized aircraft in total fuel carried (that largely determines both cost and emissions performance) at a function of the bypass ratio. While fuel consumption improves by about ٩٪ when bypass ratio increases from ٤ to ٨, it increases again when the bypass ratio exceeds ١٠. The relative deterioration of the fuel consumption for high bypass engines is caused in part by the significant parasite drag

associated with their large fans. In addition, for a given thrust requirement at cruise conditions, high bypass ratio engines will typically have excess sea-level static (SLS) thrust. For instance, an engine with a bypass ratio of ١٠ may produce about ٢٠٪ less thrust at ٣١٠٠٠ ft than a engine with a bypass ratio of ٦ having identical SLS thrust. As a result, while high bypass ratio engines have low noise emissions because of reduced exhaust velocities, some of this advantage is offset by the need to increase the SLS thrust (i.e. oversize the engines) in order to achieve the required cruising altitude thrust. The trend of improving fuel consumption (at the engine level) with increasing bypass ratio requires that the fan pressure ratio be optimized for each bypass ratio.
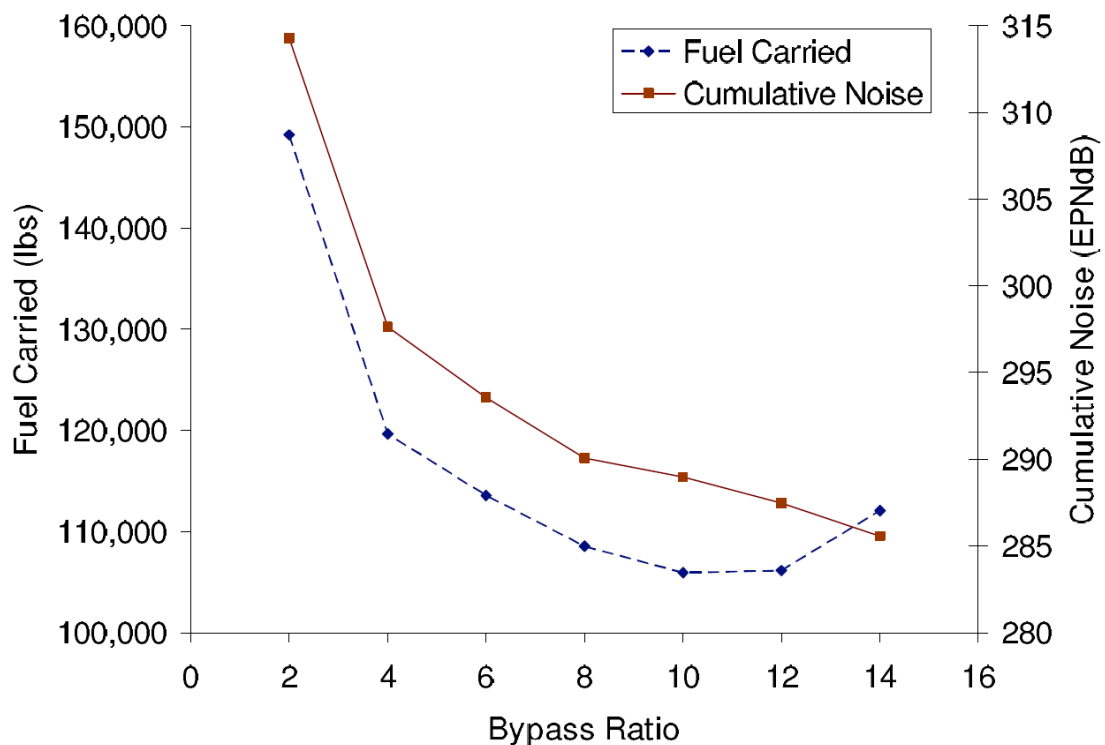

Figure ٢.٢. Impact of increasing bypass ratio on cumulative certification noise and total fuel required to complete the mission

Taking into account engine stability and fan surge margins, the variation of optimum fan pressure ratio with BPR from ٤ to ١٥ is shown in Figure ٢.٣. The noise measured at each of the certification points for the same aircraft, as a function of bypass ratio, is shown in Figure ٢.٤. Note that sideline and flyover noise both gain significantly from the decrease in jet velocities associated with increasing bypass ratios. At the reduced throttle settings required at approach, however, jet noise is not a dominating factor.

Airframe and fan noise are the most important contributors in this regime. This is illustrated by the relatively flat approach noise data shown in Figure ٢.٤. The larger fans associated with high bypass ratio engines tend to have the high tip velocities that engine manufacturers have

been able to partially mitigate by sweeping the fan blades, for example. Having achieved significant progress in reducing jet noise, the focus of most current research is on reducing fan and airframe noise, currently seen as the limiting factors in the manufacturers' present ability to improve aircraft noise performance.
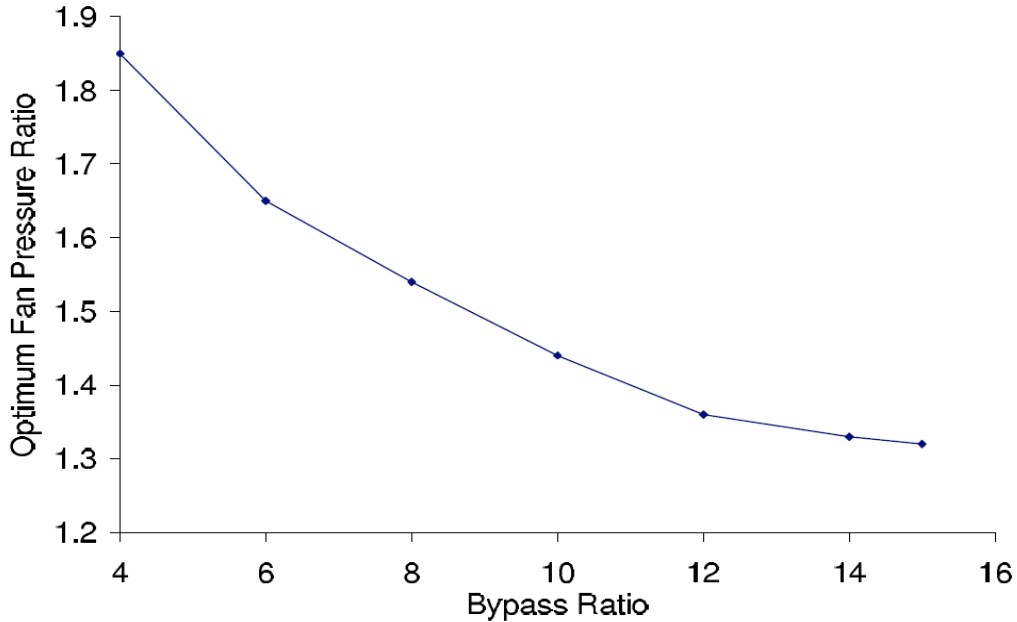

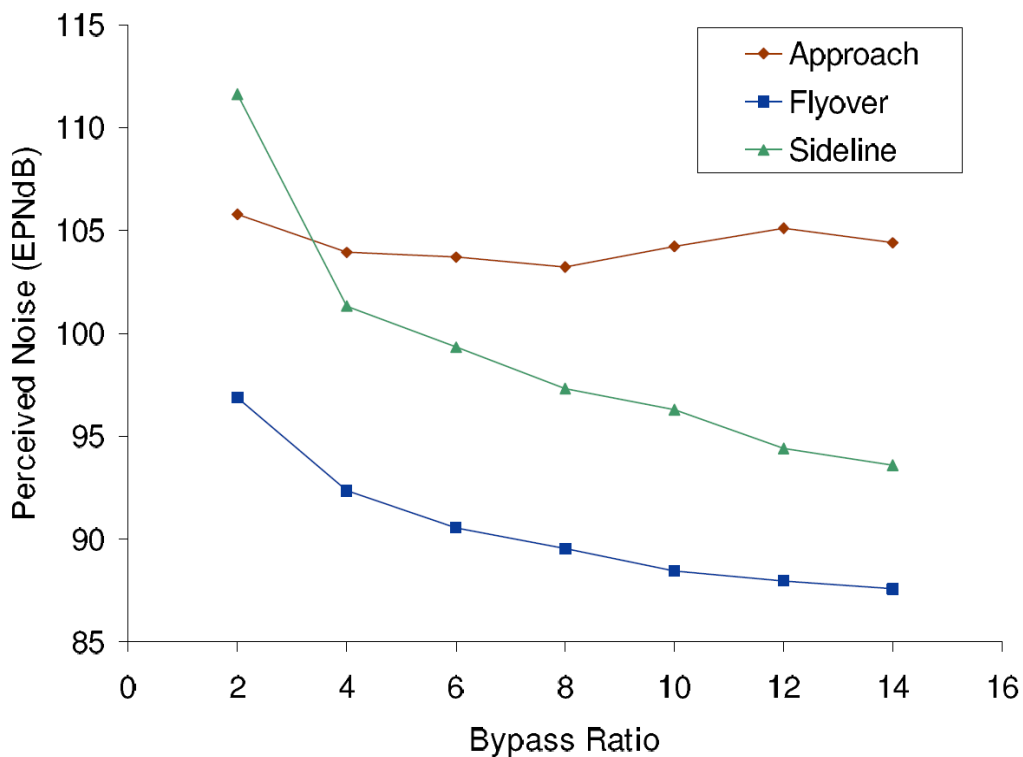**Figure ٢٠٣. Optimum fan pressure ratio as a function of bypass ratio**

Figure ٢٠٤. Noise measured at the three certification points as a function of bypass ratio.

٣. Emission level

Current combustion emissions regulation centers on the take-off and landing regimes. Limits are imposed on the emissions of nitrogen oxides (NOx), smoke, un-burned hydro-carbons and carbon monoxide. Most modern engines meet these regulations with ease, except for NOx, which is the most difficult. This is because the production of NOx in the combustion chamber is largely a function of the local temperature.

All engines in this section are two-spool, separate flow, turbofans designed with the same Aerodynamic Design Point (ADP) and same over pressure ratio (OPR) at the ADP. The ADP of ٥٠٠٠٠ lb of thrust at Mach ٠,٨ and ٣٥٠٠٠ ft was selected to represent a nominal top-of-climb (TOC) condition for the advanced technology airframe.

The ADP engine OPR of ٤٢ is the same for all the engines, two different compressor work splits were considered. The "low work" engines have a lower pressure rise across the Low Pressure Compressor (LPC) and a higher pressure rise across the High Pressure Compressor (HPC) compared to the "high work" engines. Inlet mass flow for each engine was selected to achieve the net thrust requirement at ADP.

Results of the aircraft sizing analysis are summarized in Table ٣,١. for the low work engines and Table ٣,٢ for the high work engines.

For the low work, direct drive engines, block fuel consumption is minimized with a design of BPR~١٣ (engine FPR is ١,٦) at ADP conditions.

Although the minimum fuel consumption case is at BPR~١٣, the minimum gross weight occurs at BPR~١١. In other words, the decrease in engine weight for that configuration is sufficient to offset the increase in fuel weight to arrive at a lower total gross weight. Lowest total NOx emissions (referred to as "block NOx" in the table) also occur with a BPR~١١ design. Landing-takeoff cycle (LTO) NOx emissions are lowest for the BPR~١٩ engine; but, the variation in LTO NOx is relatively small among all the cases. Clearly, identifying a "best" engine design depends on the metric of interest. Ultimately the primary metric is life cycle cost, and historically gross weight has been used as a surrogate for life cycle cost in aircraft design and optimization. However, recent increases in fuel cost have made

fuel consumption a more important factor in life cycle cost. It may no longer be valid to assume the lowest gross weight configuration has the lowest life cycle cost.

Sizing results for the high work engine cases are given in Table ٣,٢. Both geared and direct drive fan approaches were considered for the high work engines. The lowest block fuel consumption occurs for the geared, FPR~١,٥ engine case. The BPR of this engine is ١٥ at ADP conditions. As with the low work engines, there is a trade-off between the efficiency associated with lower FPR and the increase in engine weight. The geared, FPR=١,٦ (BPR~١٢) case provides the lowest total NOx emissions and lowest ramp weight. The lowest LTO NOx emissions occur at the opposite end of the fan pressure ratio spectrum, at FPR=١,٣ (BPR~٢٤). The geared fan system is able to mitigate to some extent the penalties associated with decreasing FPR and increasing BPR.

Table 3.1. Aircraft Sizing Results for Low Pressure Rise
(162 Passenger, 3250 nm Design Mission)

	Lo-dd-1.4 (BPR ~ 19)	Lo-dd-1.5 (BPR ~ 15)	Lo-dd-1.6 (BPR ~ 13)	Lo-dd-1.7 (BPR ~ 11)
Ramp Weight, lb	168600	156400	151600	150800
Thrust(SLS), lb	26100	23600	22900	22650
T/W (takeoff)	0.310	0.302	0.303	0.300
Block Fuel, lb	32900	31100	30800	31250
Block NOx, lb	245	226	218	216
LTO NOx, lb per cycle	10.7	11.0	11.1	11.8

Lo-dd (Low pressure rise – direct drive fan)

This benefit can be seen by comparing the BPR~18 (FPR=1.4) results in Table 3.2 for the two different fan drive approaches. The aircraft with the geared fan engine has a lower empty weight, lower ramp weight, lower block fuel consumption, lower total NOx and lower LTO (Landing-Takeoff Cycle) NOx emissions. But, even in the case of geared designs, minimum block fuel occurs at a BPR~15 (FPR of 1.5), not at lower FPR where cruise efficiency is higher. [1]

Table 3.2. Aircraft Sizing Results for High Pressure Rise
(162 Passenger, 3250 nm Design Mission)

	Hi-g-1.3* (BPR ~ 24)	Hi-g-1.4 (BPR ~ 18)	Hi-dd-1.4* (BPR ~ 18)	Hi-g-1.5 (BPR ~ 15)	Hi-dd-1.5 (BPR ~ 15)	Hi-g-1.6 (BPR ~ 12)	Hi-dd-1.6 (BPR ~ 12)	Hi-dd-1.7 (BPR ~ 11)
Ramp Weight, lb	158950	153800	174200	151200	161000	151000	154800	152700
Thrust(SLS), lb	27650	24800	28350	23200	24400	22900	23100	22600
T/W (takeoff)	0.348	0.323	0.325	0.306	0.303	0.303	0.298	0.296
Block Fuel, lb	30900	30600	34550	30400	32200	31000	31600	31800
Block NOx, lb	226	215	242	210	224	209	215	210
LTO NOx, lb per cycle	9.3	10.0	11.3	10.0	10.4	10.6	10.6	11.2

Hi-dd (High pressure rise – direct drive fan)
Hi-g   (High pressure rise– geared drive fan)

٤. Specific thrust characteristics and specific fuel consumption

In following section we compare engine performances for a number of engine configurations, including the conventional base-engine configuration with or without an afterburner, the ١-ITB (introduce inter-stage turbine burners) engine, the ٢-ITB engine, and the CTB (continuous turbine-burn cycle) engine configurations. The turbine power ratios are fixed at ٤٠ : ٦٠ and ٣٣ : ٣٣ : ٣٤ for the ١-ITB and ٢-ITB engines, respectively. We argued that it is best to maximize the propulsion efficiency in order to make use of the high energy gas produced at high thermal efficiency by the core gas generator. It is then useful to see the effect of bypass ratio of a turbofan engine as a design parameter in more detail. Figure ٤,١. and ٤,٢. Shows the performance parameters vs. the bypass ratios at a compression ratio of ٤٠. Although these curves now take different shapes from curves in the preceding section on the variation of pressure ratios, they still show the same relative standing of the various engines. To be noticed, however, is that the specific thrust gain by the turbine-burner engines over the base engine widens significantly as the bypass ratio increases (Fig. ٤,١.), while the specific fuel consumption rate decreases to approach the level of the base engine (Fig. ٤,٢.) [٤]
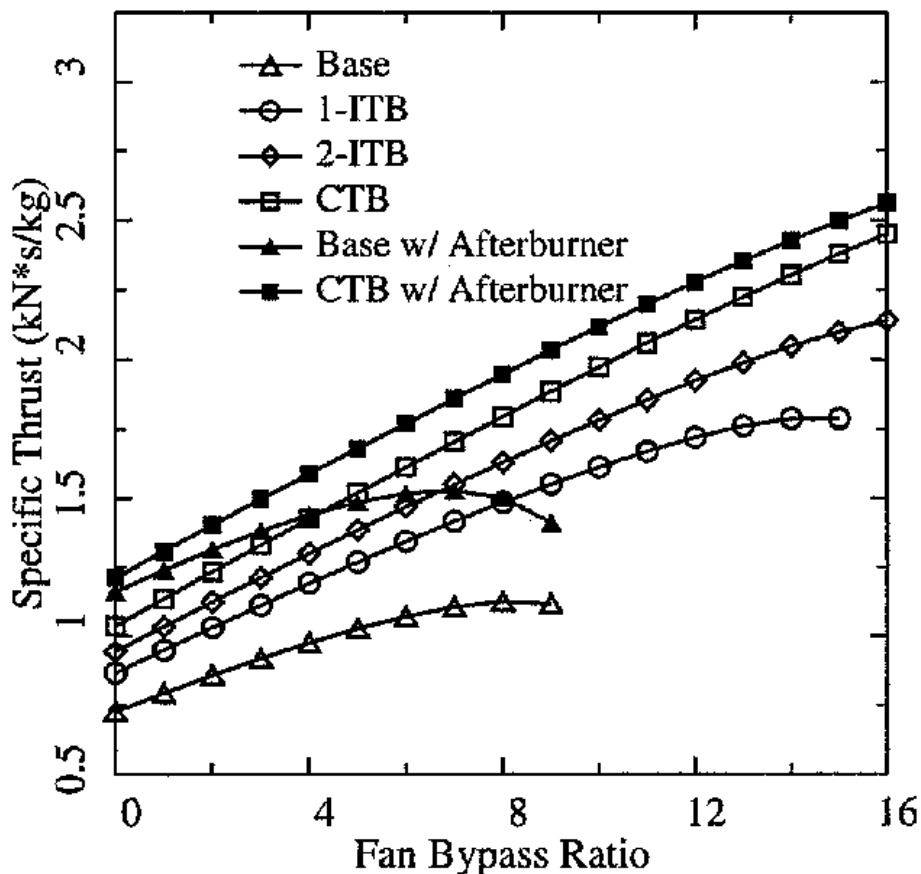

Fig. ٤,١. Specific thrust characteristics of turbofan engines vs. fan bypass ratio at M١ = ٠,٨٧. T٠٤ = ١٥٠٠ K, T٠٦ = ١٩٠٠ K, □f = ٤٠, and □f = ١,٦٥

This is a clear indication that the turbine-burner engines benefit more from the increased bypass ratio than the base engine, conforming our preceding discussions. In addition, we

notice that the base engines stop producing positive thrust for bypass ratios over ١٠. The large-bypass flow drains all of the power from the core engine in such situations.
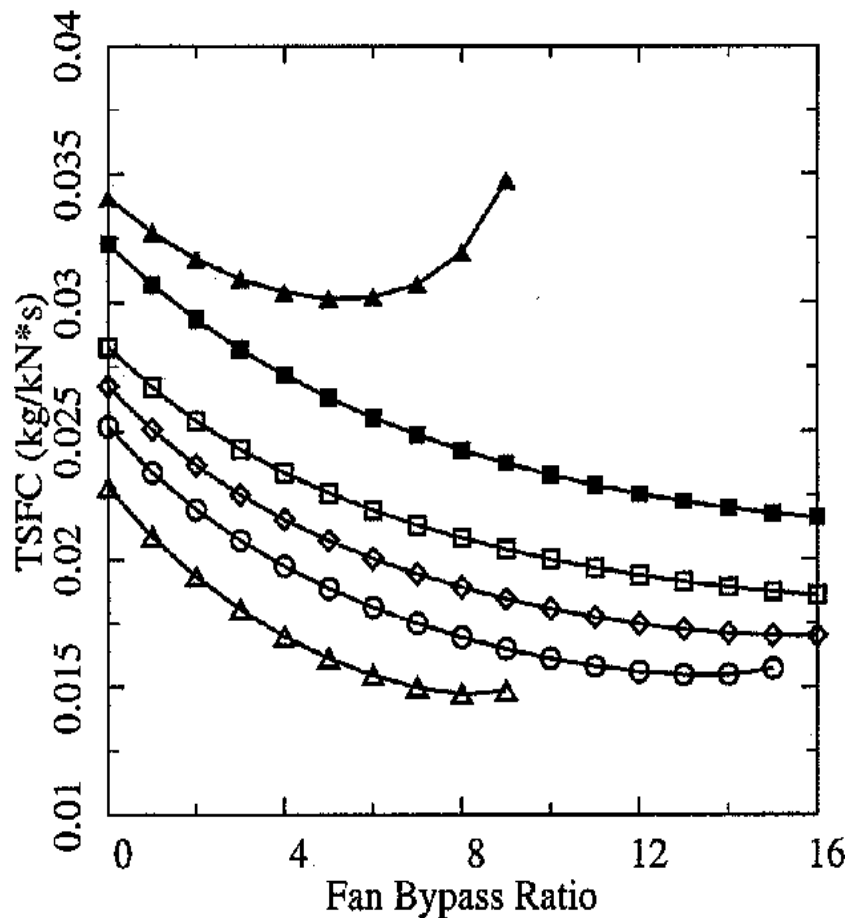

Fig. ٤,٢. TSFC characteristics of turbofan engines vs. fan bypass ratio at M١ = ٠,٨٧. T٠٤ = ١٥٠٠ K, T٠٦ = ١٩٠٠ K, ☐c = ٤٠, and ☐f = ١,٦٥

The turbine-burner type of engines is capable of operating with a much larger-bypass ratio with decreasing fuel consumption rate and no sign of decreased specific thrust. In fact, the ١-ITB engine appears to operate optimally with a bypass ratio of ١٣. With that bypass ratio the ١-ITB engine produces more than ٥٠٪ thrust with no more than ١٠٪ increase in fuel consumption rate than the base engine with its optimal bypass ratio around eight.

The effects of BPR and FPR are shown in Fig. ٤,٣., which plots isocontours of TSFC on the BPR–FPR plane. Given a turbine inlet temperature in the neighborhood of ١٨٠٠ K, it is important to know what conditions minimize fuel consumption. The overall pressure ratio (OPR), which, for a supersonic engine, should be in the range ١٥–٢٥, has very slight effect on TSFC. The minimum TSFC occurs at BPR=٢,٢ and FPR=٢,٥. What is optimal for cruise, however, may not be the best choice for takeoff. A BPR of ٢,٢ may be too small for quiet operation. In addition, FPRs above ٢,٤ will likely require a two-stage fan, which complicates engine design. The selection here is an engine with BPR=٣,٠ and FPR=٢,٢٥. As seen in Fig.

٤,٣., this condition is very close to the optimum point of minimal specific fuel consumption, yet it increases significantly the chances for meeting noise regulations and affords the simplicity of a single-stage fan.[٣]
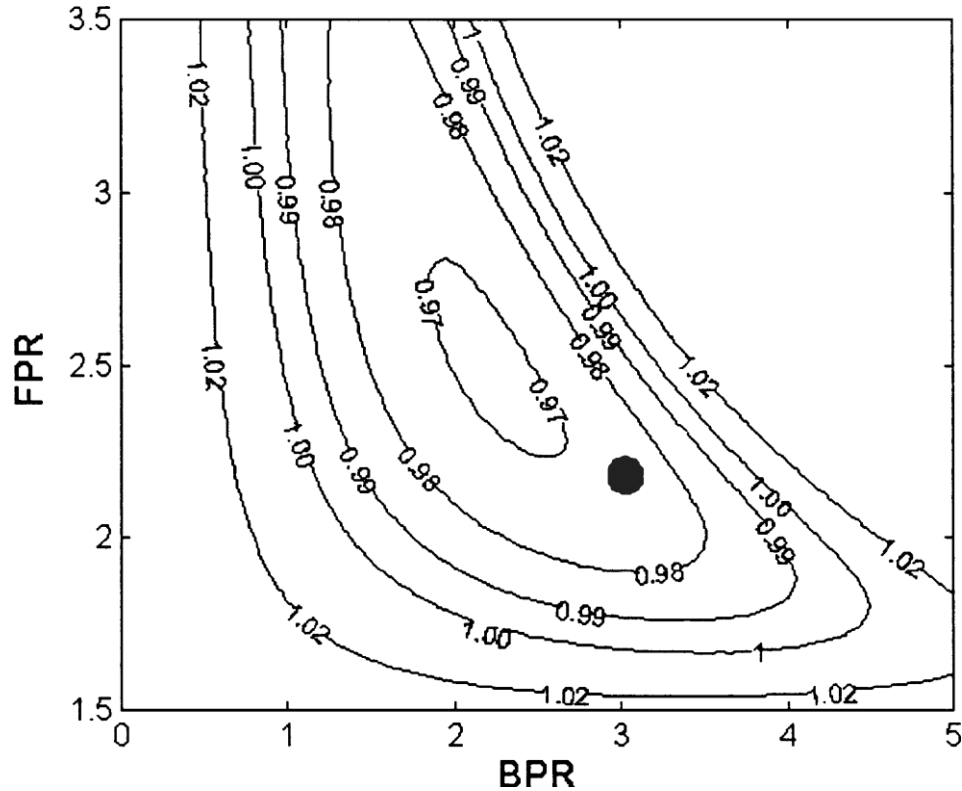

Fig. ٤,٣.Isocontours of TSFC on the BPR–FPR plane for $M∞ = ١,٦$; TIT = ١٨٠٠ K and OPR = ٢٠

٥. Installation drag

Since several years aerodynamic engine/airframe integration (EAI) for civil transport aircraft has been determined by two major aspects. The first one is the need to integrate engines with increasing bypass ratio and thus nacelle diameter on the aircraft wing and the second one is a trend towards a closer coupling between wing and propulsion unit. The concern about engines with higher bypass ratio is based on the fact that increasing the bypass ratio leads directly to an improvement of the propulsion efficiency, which is among others an appropriate means to achieve a reduction of the specific fuel consumption of jet engine. Consequently new engine concepts are considered, such as the 'Very High Bypass Ratio' engines (VHBR) with a bypass ratio of about ١٠, or 'Ultra High Bypass Ratio' engines (UHBR) with a bypass ratio up to ١٥ or even beyond. The request on EAI is to ensure that the benefit of advanced engine concepts is retained for the complete system with the engine mounted on the aircraft. An important parameter to assess the aerodynamic performance of the engine integration is the so called installation drag. The installation drag covers the

external drag of nacelle (N,e) and pylon (P,e), and the interference drag. The latter characterizes the additional drag, which origins from the change in aerodynamics of the single components due to the installation:

$$CD,inst = CD (N,e) + CD (P,e) + CD,interf$$

The installation drag is evaluated, e.g. in wind tunnel tests, as the total drag of the configuration including the propulsion system (WBEP: Wing, Body, Engine, Pylon) reduced by the drag of the wing/body (WB) configuration and the internal drag of the nacelle (N,i):

$$CD,inst = CD (WBEP) – CD (WB) – CD (N,i)$$

As Figure ٤,٤. illustrates, the installation drag rises with increasing bypass ratio, mainly due to the higher interference drag and a larger wetted surface of the nacelle, CD (N,e), and thereby tends to spoil the efficiency benefit of the isolated engine. Thus, the primary task of engine/airframe integration in connection with engines of increasing bypass ratio is to minimize the interference drag.
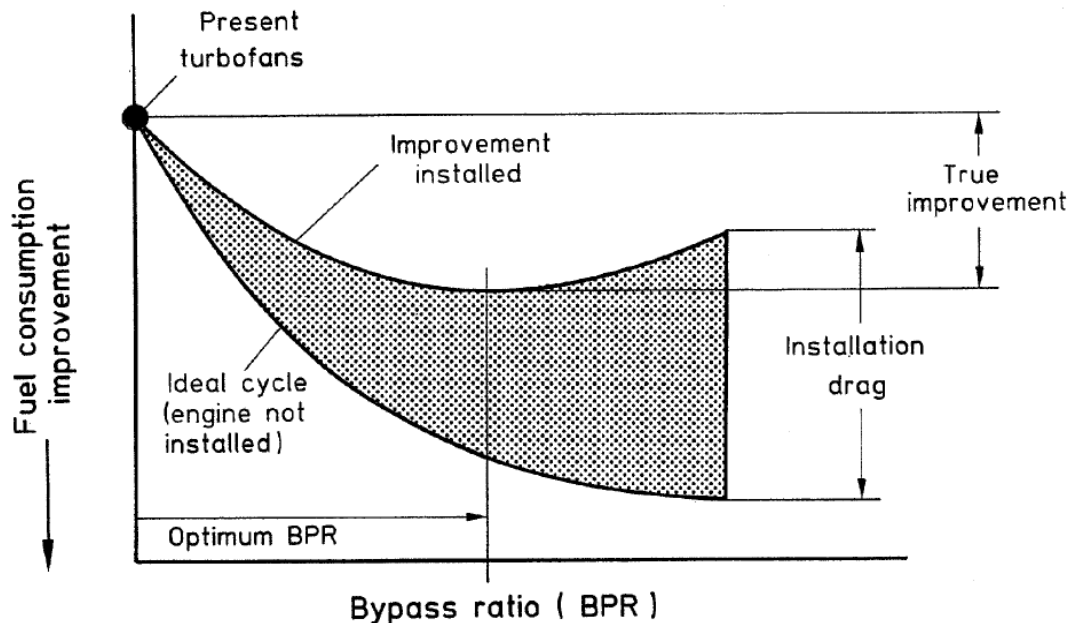

Figure ٤.٤. Dependency of fuel consumption improvement on installation drag

٦. Conclusion

Results of the present study indicate that the engines with bypass ratios over ۱۲ provide increases in take-off thrust and significant lower jet noise, they result in higher propulsion-system weight and would require aircraft oversizing to attain the same cruise range. With technology advances, the propulsion-system thrust-weight ratio with bypass-ratio

over ١٢ is higher, and specific fuel consumption is lower. This study also showed that aircraft designed for long cruise ranges would not suffer significant range penalties with high-bypass-ratio engines. The advantage in specific fuel consumption at high bypass ratios would compensate for the oversizing and higher propulsion. Improvement in propulsion-system thrust-weight ratio and drag of the high-bypass-ratio engine would provide significant increases in cruise range. The take-off thrust advantage of high-bypass-ratio engines will also allow take-off distance to be reduced significantly from that for low-bypass-ratio engines. Increasing the BPR above ١٢, also have some positive influence in concentration of toxic NOx component in exhaust gases.

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