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MISSION OPTIMIZATION OF THE GEARED TURBOFAN ENGINE

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Abstract

This paper carries out an optimization study for a conventional and a geared turbofan engine by minimizing CO_2 emissions for a given aircraft mission. Aircraft performance and nacelle design data have been generated with a preliminary design and analysis tool for aircraft. Engine gas path design, mechanical layout and weight estimation as well as performance were modeled using a generic tool for gas turbine design, analysis and optimization.

Although earlier studies have been made where the specific fuel consumption for the different engine configurations have been compared [1] there is a need for a study where the relative merits of a geared and a conventional turbofan are compared for a given mission.

Results show that the geared turbofan can reach a 3% lower fuel consumption for the calculated mission.

Nomenclature

BPR	Bypass Ratio
CO_2	Carbon Dioxide
$DDTF$	Direct Drive Turbofan
FPR	Fan Pressure ratio
GTF	Geared Turbofan engine
HPC	High Pressure Compressor
HPT	High Pressure Turbine
IPC	Intermediate Pressure Compressor
LPT	Low Pressure Turbine
OPR	Overall Pressure Ratio
RPM	Revolutions Per Minute
SFC	Specific fuel consumption

Introduction

One of the main drivers in the development of aircraft engines is to minimize the environmental impact of air transportation. It is commonly acknowledged that combustion of hydrocarbons, leading to production of carbon dioxide contributes to global warming. A relevant question is therefore which engine configuration for a given application has the lowest fuel consumption. Two of the main contenders to power the next generation short to mid range narrow body aircraft are the geared and the direct drive turbo fan. These configurations are also two of the alternatives that have come furthest in their technology maturation process.

Earlier attempts at comparing these two engine configurations has been made. Kurzke has in [1] compared the two different engine configurations in a design point study. The differences and challenges with the engine designs were highlighted. He notes that there is a need for a mission analysis and more detailed weight analysis in order to come to definite conclusion on which configuration is more fuel efficient.

In this paper the direct drive turbofan (DDTF) engine and the geared turbofan (GTF) engine are optimized for a given mission and a given aircraft. A mechanical design analysis is included in the optimization. This enables the effect of engine weight and nacelle drag to be included. Estimations on the difference in component efficiencies due to differently loaded components are also included in this study.

Methodology

To evaluate the relative benefits of the two engine configurations a multidisciplinary preliminary design process has been utilized. The design process includes preliminary design and evaluation of the aircraft in the in house code GISMO [2]. Aircraft performance and nacelle design data are the outputs. Engine performance is modeled using GESTPAN [3], a generic tool for gas turbine design and analysis. Preliminary design of the engine resulting in dimensions and weight is performed with a preliminary design tool called WEICO [4]. The resulting aircraft and engine is evaluated for a given mission. To optimize the design of the engine the commercially available integration and optimization environment ISIGHT [5] is used.

Component technologies

Both engines in this comparison are turbofan engines, thus they are in many ways similar. The importance lies in capturing the inherent differences between the two types of engines. These main differences are in the booster or intermediate pressure compressor (IPC), the low pressure turbine and of course the gear system.

Since the fan tip speed limits the rotational speed of the low pressure shaft the rotational speed of the low pressure turbine and booster are often lower than desired for a conventional turbofan. The geared configuration enables the LPT and IPC to rotate at a higher rotational speed than otherwise possible. Increased turbine RPM leads to a design with fewer stages, lower blade loading and higher efficiencies.

Based on Grieb [6] the difference in LPT efficiency is approximated to be 1.5%. The increased rotational speed of the IPC makes it possible to increase stage pressure ratio compared to the direct drive configuration despite lower stage loading and therefore distribute the pressure ratios differently between the IPC and high pressure compressor (HPC). The efficiency of the booster in the DDTF is approximated to be 0.2% lower than the IPC in the GTF [6]. The higher HPC pressure ratio in the DDTF leads to a more highly loaded high pressure turbine (HPT). This leads to a 0.4% lower efficeny for the DDTF HPT [6].

In Table 1 chosen efficiencies for each of the components are shown.

Limitations

In the optimization of the engines several technical limitations exists. Such limitations include maximum blade metal temperature in the turbine. In this study a 5th generation single crystal high temperature alloy is assumed. The assumption is that the allowable blade metal temperature

Table 1: Polytropic component efficiencies in take off

	DDTF	GTF
Fan eff [%]	92.4	92.4
Booster/IPC eff [%]	91.8	92.0
HPC eff [%]	92.5	92.5
HPT eff [%]	90.6	91.0
LPT eff [%]	91.0	92.5

is 1225 K in hot day take off. The maximum combustor outlet temperature is 1850 K.

For the compressor outlet the maximum allowable temperature is assumed to be around 970 K. Another limitation is the minimum compressor blade height. If the blades of the compressor reaches below approximately 12 mm the tip clearance losses will begin to affect the efficiency of the engine. What minimum blade height and allowable compressor outlet temperature that is chosen affects the permissible maximum overall pressure ratio (OPR) significantly.

Optimization

Three main parameters are varied when optimizing the engines. The bypass ratio (BPR), the fan pressure ratio (FPR) and the overall pressure ratio. For a range of OPR the variation of BPR with corresponding optimal FPR has been studied. When BPR increases the fan diameter also increases. This leads to increased drag and weight. Thus it is not possible to just look at the specific fuel consumption (SFC) in cruise to judge the merits of the engine. In this mission optimization the weight and nacelle drag are accounted for. Because of the installation effects the optimum fuel burn curve differs from, and is flatter than, the cruise SFC-curve.

In Figure 1 it can be seen that when moving from BPR 13.5 to 12.5 the fuel burn increases by 0.3 %. There is a discontinuity in the fuel burn curve.

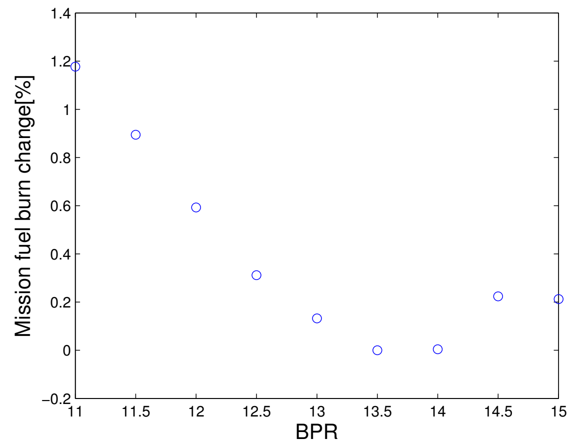

Figure 1: Mission fuel burn for varying bypass ratio with corresponding optimal fan pressure ratio for a constant take off OPR for the GTF engine

This is because the limit in stage loading for the LPT is reached and another stage is added at BPR 14.5 thus adding weight to the engine.

In Figure 2 the SFC for varying bypass ratio is shown. When moving from 13.5 to 12.5 in BPR the cruise SCF increases by 0.6 percent, around twice the variation of fuel burn. The SFC also continues to improve with a higher BPR.

For the DDTF engine the fuel burn curve with varying BPR is more discontinuous than for the GTF as can be seen in Figure 3. This is due to higher stage loading of the low pressure turbine. The number of LPT stages varies more, resulting in step changes in weight. When moving from 13.5 in bypass ratio to 12.5 the fuel burn is increased by 0.2 % for the DDTF.

Even though the mission optimization gives an optimum BPR and FPR it is worth considering going to a slightly lower BPR than the optimum if the part count can be reduced. This is the case for the DDTF engine. When

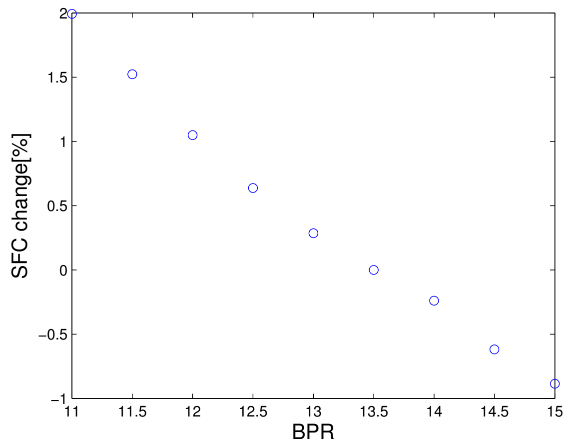

Figure 2: Cruise SFC for varying bypass ratio with corresponding optimal fan pressure ratio for a constant take off OPR for the GTF engine

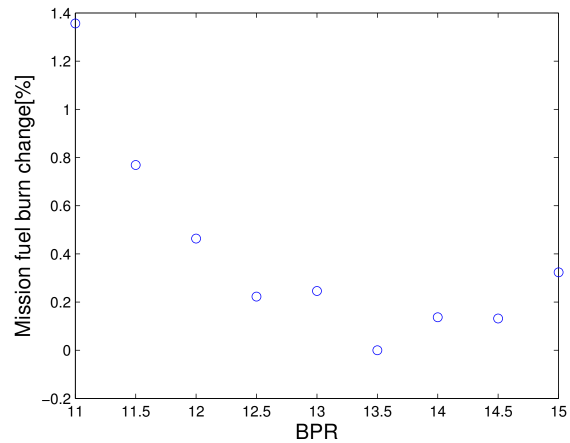

Figure 3: Mission fuel burn for varying bypass ratio with corresponding optimal fan pressure ratio for a constant take off OPR for the DDTF engine

choosing a BPR of 12.5 instead of the fuel optimal 13.5 the number of LPT-stages is reduced from 9 to 8 stages.

Figure 4 shows the optimal combination of BPR and FPR for a range of OPR. It can be seen that the fuel burn decreases with increasing OPR. There is a practical limit to how much the pressure ratio can be increased. Higher pressure ratio gives decreasing blade height of the last stage HPC. In this comparison the same overall pressure ratio is chosen for both engine configurations in take off. Although in practice it may be possible for the GTF to reach a higher OPR. Since the rotational speed of the GTF IPC is significantly higher than for the conventional engine, the stage pressure ratio is higher. Thus a greater part of the over all pressure ratio can be obtained in the IPC. This leads to a lower HPT loading. Because of this the maximum HPC pressure ratio for a 2 stage turbine is reached at a lower OPR for the DDTF.

Optimization Results

In Table 2 the performance parameters for the chosen engine designs are presented. To be noted is that the chosen engine design for the DDTF engine differs slightly from the fuel optimal configuration seen in Figure 3. This is due to fewer turbine stages in the chosen design. Results show the SFC is 2.2% better for the GTF. This translates for this mission into 3% lower fuel burn.

It can be seen that the optimal bypass ratio does not differ significantly between the two engines. In the DDTF configuration the booster does not contribute significantly to the OPR. This results in a higher pressure ratio for the DDTF HPC. The number of HPC stages is therefore higher. The HPT cooling flow does not differ significantly between the two engines since they operate at the same OPR. The cooling flow temperatures are therefore not very different. If different pressure ratios for the two engines were to be chosen the cooling flow requirements would differ.

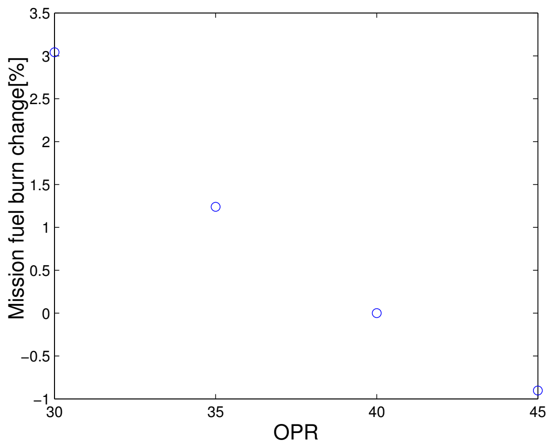

Figure 4: Mission fuel burn optimal BPR and FPR for a range of OPR for the GTF engine

The chosen engine configuration for the DDTF engine has 4 booster stages, 9 HPC stages, 2 HPT stages and 8 LPT stages. The GTF design consists of 3 IPC stages, 6 HPC stages, 2 HPT stages and 3 LPT stages.

As is shown in Table 3 the optimization results in a 220 kg lighter GTF engine. The main difference between the two engines is the LPT weight. The average weight per stage is higher for the GTF LPT despite the 16 % lower radius

Table 2: Performance of final engine configurations. The values given for take off unless stated otherwise

	DDTF	GTF
BPR	12.5	13.5
T3 [K]	902	905
T4 [K]	1850	1850
FPR	1.47	1.45
IPC PR	1.45	2.5
HPC PR	18.76	11.03
OPR	40	40
HPT cooling % of W25	14.4	14.6
SFC mid cruise	base	-2.2 %
Mission fuel burn	base	-3.0 %

Table 3: Dimensions and weight of the two different engine configurations

	DDTF	GTF
Total engine weight [kg]	3100	2880
Fan weight [kg]	888	906
Booster/IPC weight [kg]	66	55
HPC weight [kg]	87	48
HPT weight [kg]	66	78
LPT weight [kg]	555	221
Gearbox weight [kg]	-	170
LP-shaft weight [kg]	44	18
Fan diameter [m]	1.84	1.87
Nacelle length [m]	3.8	3.4
Blade height last stage HPC [mm]	12.3	13.5

of the last stage. This is due to heavier discs in the geared turbofan engine. The discs are on average 50% heavier than the discs in the low speed turbine. Despite the heavier discs the effect of stage count on the turbine weight is a larger contributor to weight.

The difference in fan weight is due to the slightly smaller diameter of the direct drive engine. The DDTF booster is somewhat heavier than the IPC for the GTF. This is due to the additional fourth stage. The HPC is almost 40 kg heavier for the DDTF, this is mainly due to the difference in stage count.

Because of the higher rotational speed of the LP-shaft in the geared configuration the torque is less. This makes it possible to design a slimmer and thus a much lighter shaft. This also means that the inner diameter of the HPC may be decreased further for a GTF since less space need to be available for the shaft. The bore radius in the HPT disc may be decreased as well.

The reason for the lower blade height of the last stage in the HPC compressor for the DDTF is that the smallest possible radius and thus highest possible hub tip ratio is limited by the HPT stage loading.

Uncertainties

In order to check the sensitivity of the fuel burn due to weight the GTF the fuel burn was calculated for the same mission, but with an increased initial aircraft weight corresponding to the difference in engine mass. This naturally resulted in a somewhat higher fuel consumption than for the original take off weight. Still the fuel burn is 2.8% better than for the DDTF.

In this paper the mission optimization has been carried out with the same take off weight regardless of engine efficiency. In reality a more fuel efficient engine would need less fuel on board. This results in decreased vehicle take off mass which reduces the mission fuel burn. If this effect had been taken into account the difference in mission fuel burn would have been even larger.

In this study the efficiencies, particular the difference of efficiency between the two engines, are approximated and assigned in the design point. The resulting stage loadings have in this paper been compared to the initial assumptions of efficiencies and was found to be valid. Still the optimum might shift if the efficiency is varied with varying component stage loading in the optimization process.

One of the issues that has not been addressed in this paper is the limitations and possibility of an advanced nacelle design thus reducing nacelle length. If the nacelle length with resulting drag and weight can be reduced the optimal bypass ratio might be allowed to increase.

Diameter

In this study no limitation to the fan diameter and engine diameter has been assumed. In practice this might be an important consideration to be made. A larger fan requires higher under the wing clearance. Depending on if it is a design of a new airplane or a redesign of an existing airplane this might either result in an absolute maximum engine diameter or larger and heavier landing gear. Figure 5 shows the variation in engine diameter with varying BPR for the GTF.

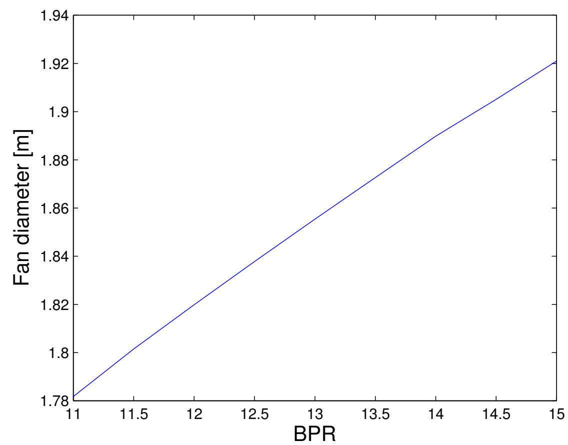

Figure 5: Variation in fan diameter with varying BPR for the GTF

Overall pressure ratio

As can be seen in Figure 4 the calculations show that the fuel burn continues to decrease with increasing OPR. Mainly three parameters limits the possible OPR. One of the limitations is the HPC exit temperature. When moving from 40 to 45 in pressure ratio the temperature increases approximately 30 K. Also the effects of hot day take off and component deterioration affects the temperature. Even if the compressor outlet temperature is not near the material limit at design point the off design conditions must also be accounted for in order to evaluate if the metal temperature limit is reached.The second limitation is the last stage compressor blade height. The efficiency will at some point begin to drop rapidly due to increased tip clearance losses. Exactly when this loss begins to affect the efficiency is not evaluated in this paper. For this study a fixed blade height limit is assumed and not exceeded. The third limitation is the maximum stage loading of the HPT. Especially in the DDTF configuration where the HPC pressure ratio is high this might be a limiting factor. If any conclusions about the optimal OPR are to be made and if it differs between the two engine types more detailed studies of these effects need to be made.

Conclusions

As was also concluded by Kurzke [1] one benefit of the geared configuration compared to the direct drive configuration for a high bypass ratio engine is the lower part count for the GTF. The number of low pressure turbine stages increases more rapidly with increasing BPR in the DDTF than in the GTF. If the direct operating cost had been taken into account in the optimization, the DDTF configuration could have ended up at a lower bypass ratio and overall pressure ratio. Although the fuel consumption would have increased this would have been outweighed by the reduction of maintenance cost and manufacturing cost due to lower part count.

A mission optimization was performed, including effects of engine weight, nacelle drag and differences in component efficiencies. It is concluded that there is a potential fuel benefit for the geared turbofan engine. A part of the reason for this benefit is that the GTF is a less heavy engine. The largest contributor to the difference is the possibility of higher component efficiencies due to lower stage loading in the GTF. This also means that the fuel consumption benefits are highly dependent on reaching the envisioned component efficiencies.

Acknowledgment

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