Propfan, an alternative for turbofan engines

Tackling the technical design characteristics of a propfan
Propfan, an alternative for turbofan engines

Introduction
The Aviation industry grows with an annual average of 2.5% until 2022, at the same time the fuel prices are expected to increase (FAA, 2017). On a global scale, aviation is responsible for 2.5% of the CO₂ emissions from worldwide fossil fuel consumption (Brueckner & Abreu, 2017). For this reason, an innovative propulsive concept is required which offers great improvements in terms of emissions and fuel usage.

A designed concept to fulfill this need is the propfan concept, which goes under different names. These names include “open rotor”, “unducted fan”, “ultra-high bypass ratio engine” and “propfan”, which is the term used throughout this fact sheet. Propfans are characterized by two very large diameter fans that are not covered by a nacelle. The ultra-high bypass ratio of the propfan increases propulsive efficiency. This in turn creates the potential of significant reductions in fuel consumption and emissions relative to turbofan engines (Rolls Royce, ) (Safran, 2017).

The propfan concept was introduced in the 1970s in NASA’s Aircraft Energy Efficiency program (Guynn et al., 2011; Van Zante, 2015) as a response to the oil crisis. However, the development of the propfan was put on hold after the oil prices went down. This reduced the demand for a more fuel efficient engine (Sweetman, 2005). Today, propfans are being developed by several major organizations, including General Electric, Rolls Royce, NASA, Boeing and the FAA. In Europe the concept is being supported by the Clean Sky Program (Lecompte-Boinet, 2017; Rolls Royce, ; Van Zante, 2015). SAFRAN started demonstrator tests with their open rotor aircraft engine together with their partners from the Clean Sky program in October 2017, but the concept is not expected to be commercially introduced until 2030 (Safran, 2017).

The mentioned characteristics also introduce challenges for the designers in order to introduce it to the commercial aviation industry. One aspect is the absence of the nacelle which creates noise implications. This fact sheet will discuss the concept and the design characteristics together with a short description of the technical and performance related advantages compared to a turbofan. To conclude this fact sheet, the challenges that need to be overcome will be discussed.
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Propfan concept compared to conventional commercial aircraft engines

51% of the passenger and cargo aircraft in service in 2017 are from the Boeing 737 and Airbus A320 family. These aircraft, as well as other Boeing and Airbus aircraft families, are equipped with turbofan engines. This shows that turbofans are the most commonly used engine type (Morris, 2017). Scientists focus on the propfan as an alternative for turbofan engines on narrow body aircraft as the Boeing 737 family (Larsson, Grönstedt, & Kyprianidis, 2011). For this reason, this fact sheet mainly focuses on the propfan as an alternative for the turbofan. The turboprop is shortly discussed in the next subchapter because the propfan also shows similarities in design with this engine type.

Turboprop

Turboprop engines consist of a core which is connected by means of shafts and/or a gearbox to the propeller (Figure 1). Another possible configuration is the use of a free stream turbine stage behind the turbine that is connected to the propeller by means of a separate shaft (Hall, 2015). The thrust of turboprop engines is generated by the propeller (Aviation-History, 2013; Helba, 2004).

Turbofan

Turbofans consist of a core and a fan which guides part of the airflow through the bypass (Figure 2). The amount of air flowing through the bypass depends on the bypass ratio (BPR). This fan is connected to the turbine by means of shafts and/or a gearbox. Turbofans have two or three stages, low and high pressure, for the compressor and the turbine in order to increase engine efficiency. Shafts with different rotational speeds are used to achieve this (Aviation-History, 2013; Helba, 2004).

Propfan

The first main difference between turbofans and propfans is the absence of the nacelle, which is the housing of the engine and it damps engine noise. The other main difference is the two counter-rotating fans of the propfan, where the turbofan has only one fan. These two fan stages are used in order to reduce swirl losses that are caused by the pressure differences around the

Figure 1: Turboprop engine.

Figure 2: Turbofan engine.
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fan blade tips. The two fans reduce these pressure differences which increases cruise efficiency by 8% (Larsson et al., 2011).

The propfan engine shows similarities in design with both turboprops and turbofans. The propfan turbine is used to drive two unshielded fans, just like the turboprop powers an unshielded propeller. Compared to turbofans, the fans of the propfan concept use highly twisted blades as well. Propfans also consist of a core with similar modules as the cores of both turboprops and turbofans (Figure 1, 2 and 3). Therefore, this engine is called the propfan: “prop” from turboprop, and “fan” from the turbofan engine (Aviation-History, 2013; Definitions.net, ; Larsson et al., 2011).

Technological design characteristics

Propfan engine weight
The removal of the nacelle brings a weight reduction of 88% to the propfan concept compared to turbofan engines. But the mass of the larger fan outweighs this weight advantage. With turbofans, the nacelle is limiting the fan size and the bypass ratio of the engine. The absence of the nacelle in propfan engines makes it possible to install fans with twice as large diameters compared to turbofans. Typically, one third of the propfan weight comes from the fans as a result (Table 1). This leads to the total mass of propfans being higher compared to turbofans of similar thrust capabilities (Larsson et al., 2011) Hendricks & Tong, 2012).

Weight estimations also show differences for the propfan configurations as geared propfans are slightly lighter than direct drive propfans. This benefit is likely to increase as propfans grow to higher thrust capabilities (Hendricks & Tong, 2012).

<table>
<thead>
<tr>
<th>Engine parameter</th>
<th>Geared Turbofan</th>
<th>Direct Drive Turbofan</th>
<th>Propfan</th>
</tr>
</thead>
<tbody>
<tr>
<td>Top of Climb (M0,80; 35000ft)</td>
<td>OPR</td>
<td>42</td>
<td>42</td>
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<tr>
<td></td>
<td>Thrust (lbf)</td>
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<td>5000</td>
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<td></td>
<td>TSFC (lbf/hr/lbf)</td>
<td>0,502</td>
<td>0,525</td>
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<td>Sea Level Static (M0,0; 0ft; ISA-2,8°C)</td>
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<td></td>
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<td></td>
<td>TSFC (lbf/hr/lbf)</td>
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<td>Fan/Propeller diameter (ft)</td>
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<td>13,8</td>
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<tr>
<td>Nacelle maximum diameter (ft)</td>
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<td>6,7</td>
<td>5,6</td>
</tr>
<tr>
<td>Total engine pod weight (lbf)</td>
<td>6630</td>
<td>6100</td>
<td>9220</td>
</tr>
</tbody>
</table>

Figure 3: Open rotor engine architectures.
**Direct drive and geared propfan configuration**

Propfans can be either geared or ungeared. The latter configuration is also called direct drive. A direct drive configuration, used by General Electric, eliminates the need for a heavy and complex gearbox, but the additional weight of shafts eliminates this advantage for a direct drive propfan. The weight difference between the direct drive and geared propfan results in the thrust to weight ratio of a geared propfan being 2% higher compared to the direct drive configuration (Guynn et al., 2011). Direct drive configurations also introduce tip speed constraints due to the linked rotation speeds. This is because the fans rotate at the same rotational speed as the core, which is typically less than 1100RPM. At the tip of the fan blades, the blades have a higher tangential speed because of the larger radius (Hendricks & Tong, 2012).

The geared configuration uses a gearbox (Figure 4) and allows for higher rotational speeds of the turbine, because the fans can rotate at lower speeds compared to the core. Modern propfans use a geared configuration because of the more favourable thrust to weight ratio. This also allows for smaller diameter blades and fewer stages in the turbine. Pratt and Whitney uses a gearbox to connect the fans to the turbine. A gear ratio of 13 to 1 was needed to prevent the fans from rotating too fast (Larsson et al., 2011; Guynn et al., 2011).

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**Figure 4**: Gear propfan engine components.

**Figure 5**: Specific fuel consumption for a geared propfan powered aircraft during cruise conditions.

**Figure 6**: Specific fuel consumption for a geared turbofan powered aircraft during cruise conditions.
Propfan size versus efficiency
During propfan design it is important not to oversize the fans as it influences fan efficiency. Fan efficiency is the effectiveness at which a fan performs the conversion of power into thrust by accelerating air (EPI Inc., 2017). The fan efficiency is a function of fan diameter, true airspeed and the RPM. A larger fan diameter results in a lower RPM to achieve the same thrust. This means that a reduction in RPM also results in a lower fan efficiency.

Figure 5 shows that the optimal specific fuel consumption for a geared propfan during cruise conditions is lower than the achieved specific fuel consumption during cruise. During cruise, the propfan is throttled down to reduce the amount of generated thrust. This causes a higher specific fuel consumption and results in a lower fan efficiency. This reduction in fan efficiency can be tackled by sizing the fans correctly for their expected mission. Turbofans do not show this behaviour, as seen in Figure 6 (Larsson et al., 2011).

Propfan power management strategies
Two degrees of freedom exist to vary the generated thrust and the fuel burn of a propfan. The first freedom is the combustor fuel flow and the second is the propeller blade pitch angle. During initial concept development, a control strategy was created which varies the blade pitch angle with the Mach number according to a fixed schedule. The downside of this strategy is that the rotational speed varies greatly with the thrust setting. The second power management strategy that has been developed makes use of a constant fan blade tip speed. In this power management strategy, the pitch angle increases with Mach number while the strategy also captures the influence of different altitudes (Hendricks & Tong, 2012).

Technical and performance related improvements
Fuel consumption and CO₂
Propfan engines are designed to combine turboprop efficiency with turbofanairspeed. As a result, propfans can achieve low thrust specific fuel consumption (TSFC) values (Table 1). Despite the higher weight of propfans compared to turbofans, these engines do have a 36% lower fuel consumption compared to a 1990s aircraft turbofan for a specific flight. Relative to a geared turbofan with entry into service in 2020, propfans show a 15% reduction in both fuel consumption and CO₂ emissions since this is directly related to the fuel flow. Part of the reduction in fuel flow is caused by the absence of the nacelle which can no longer cause drag, which increases the propulsive efficiency. This results in propfan powered aircraft requiring less fuel compared to turbofan powered aircraft for a given flight (Hendricks & Tong, 2012; Larsson et al., 2011).

NOₓ Emissions
As discussed, the noise levels of propfans have shown to be a challenge which needs to be overcome. Propfans show different characteristics during take-off and landing, which can also be influenced to adjust noise levels and NOₓ emissions. Because noise levels are related to rotational speeds, the noise levels can be reduced by lowering the rotational speeds during both take-off and landing. During take-off, this results in 9% higher NOₓ emissions, while for approach there is a 5% reduction in NOₓ emissions (Bellocq et al., 2015). The propfan also shows a 5% reduction in cruise EINOx figures compared to turbofan concepts with comparable thrust characteristics and entry into service in 2020 (Larsson et al., 2011).

Reduced maintenance cost
Table 1 shows that the propfan has an excess thrust relative to the compared turbofans. This means that operators can choose to throttle the engines down during take-off. Derated thrust causes less wear to engine components resulting in lower maintenance cost (Hendricks & Tong, 2012).

Challenges related to the technical design characteristics
Propfan integration on aircraft
The fan diameter influences engine integration on aircraft as it gets more difficult. The airframe integration of the propulsion system is fundamental...
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for the aircraft design as it influences structural, aerodynamic, aircraft stability and control effects, wake/fan interaction and maintenance aspects. Turbofans are usually mounted under the wings, whereas a tail mounted configuration is preferred for propfans. In wing mounted configurations the fans will be exposed to significant angle of attacks due to the wing wash up. The angle of attack (AoA) and the absence of an inlet have a strong influence on the noise produced by the fans. A tail mounted fan experiences less disrupted airflow but the design is a bigger task for the aircraft manufacturer in case of stretched aircraft type within aircraft families, e.g. the Boeing 737-700 and the 737-800. This is because with a shorter fuselage, the airflow coming off the main wings has a downward direction. This means that the airflow will reach the fans of the tail mounted propfan at an angle for which the engine designer needs to adjust the fan blades. For aircraft with a longer fuselage this is less of an issue (Ricouard et al., 2010; Van Zante, 2015).

**Acoustic characteristics and effects of propfans**

Integration also has its effect on the net radiated noise and the acoustics of the aircraft. However, modern propfans are showing EPNdB margins in the range of 15 dB cumulative margin which is acceptable to meet current certification requirements of Annex 16, Volume I, Part II, Chapter 1 of the Chicago Convention (EASA, 2012).

The absence of the nacelle means that less damping material is present between the propfan and the cabin. Acoustic damping materials are required in the fuselage to minimise interior noise, but this does add extra weight to the aircraft, reducing the payload capabilities. Previous studies show that the noise of propfan engines is lower than conventional aircraft engines. Recent analysis by ICAO showed an increased net radiated noise with increasing aircraft maximum take-off weight (MTOW). This is an aspect which is yet to be solved (Van Zante, 2015).

The forward fan of the propfan engine induces fan wake and tip vortices which are caused by pressure differences around the fan blade. This creates a turbulent airflow that does not match the pitch angle of the afterward fans blades. The airflow in turn collides with the aft fan blades, creating interaction noise. This can be prevented if the pitch angle of the afterward fan blades is controlled in such a way that the turbulent airflow flows along the surface of the afterward fan blades.

Larger fan-to-fan spacing is also a possible solution which reduces interaction tone noise, although this has a negative effect on engine length and weight (Van Zante, 2015). Other solutions include aft fan blade clipping to reduce the acoustic impact of the forward fan tip vortex on the aft fan blades. This is done by reducing the fan blade chord by adjusting the trailing edge. Blade count can account for noise reduction as well because an increase in the number of blades increases the total blade surface area and gives both better load distribution and a higher Reynolds number which in turn increases blade efficiency. It also results in less turbulence due to the smaller space and time between the individual fan blades (Bellocq et al., 2015; NASA, 2014; Oosterveld & Oossanen, 1975). Another possibility is the use of a larger diameter fan which increases the total blade surface area and thus the amount of air that is accelerated. This in turn results in a higher thrust as well, but it allows for lower rotational speeds if the thrust is to remain the same. This lower speed results in lower induced drag due to the fan blades.
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Other noise reduction strategies include blade pitch angle, low disk loading, pylon blowing system and pylon-fan spacing. It was found that the pylon affects the tone levels in different ways for different azimuthal angle (Figure 7). The figure shows that, from a front view of the propfan, the tone levels towards the fuselage (270°) and towards the environment (90°) during flight are higher relative to the tone levels in other directions (Ricouard et al., 2010).

**Pylon influence on acoustic characteristics**

Pylon-fan airflow interaction is an important aspect because it dominates the fan noise. This is the sound produced directly by the fan blade interaction with the airflow, independent from the pylon. Only at high thrust and high rotational speeds, the fan tones become more present. This means that during take-off and climb the propfans produce more noise possibly causing nuisance while the aircraft is close to the ground.

The fan blades are mounted behind the structure connecting the engine to the airframe, at the rear of a propfan (Figure 3). This pylon disrupts the airflow and prevents the air from flowing at a straight line to the fan blades. (Ricouard et al., 2010; Guynn et al., 2011). The disrupted airflow from the pylon has a higher speed relative to the surrounding air that is not affected by the pylon. This means that the disrupted air will reach the forward fan blades with a different velocity, while the fan is not able to adjust the pitch of individual fan blades. Installing an air blowing system in the pylon could reduce these velocity differences and thus reduce the pylon-fan interaction noise levels (Ricouard et al., 2010).

**Glossary**

- AoA: Angle of Attack
- EINOx: Nitrogen Oxides Emissions Index
- EPNdB: Effective perceived noise level or relative loudness of an individual aircraft pass by event
- HPC: High Pressure Compressor
- HPT: High Pressure Turbine
- LPC: Low Pressure Compressor
- LPT: Low Pressure Turbine
- MTOW: Maximum Take Off Weight
- Narrowbody: Single aisle aircraft
- OPR: Overall Pressure Ratio
- TSFC: Thrust Specific Fuel Consumption
- Wing wash up: The air flowing to the top surface of the wing’s leading edge

**References**


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Image References

Figure 1

Figure 2

Figure 3
http://s2.smu.edu/propulsion/Pages/Images/propfandiagram.gif

Figure 4

Figure 5

Figure 6

Figure 7

Dutch Summary

In de commerciële luchtvaart wordt de turbofan het meest gebruikt. Een andere optie om een vliegtuig van stuwkracht te voorzien is de propfan, wat een combinatie is van zowel de turboprop en de turbofan. Deze motor komt in een geared en in een direct drive configuratie voor. Kenmerken van de propfan zijn de afwezige nacelle en de twee contra roterende fans.

Voordat de propfan geïntroduceerd kan worden in de commerciële luchtvaart zijn er op verschillende aspecten nog uitdagingen die overwonnen moeten worden. Deze uitdagingen zijn gerelateerd aan de vliegtuig integratie, aan de akoustische eigenschappen en aan de interactie van de pylon, fan en luchtstroom. Er worden door verschillende organisaties oplossingen onderzocht om de invloed hiervan de minimaliseren.

De propfan is 15% zuiniger in brandstofverbruik vergeleken met turbofans motoren en brengt een reductie op het gebied van CO₂ en NOₓ-uitstoot met zich mee.