ENGINE DESIGN REQUIREMENTS FOR SUPERSONIC BUSINESS JETS

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ABSTRACT
Business jets represent a significant market segment in civil aviation. The development of supersonic business jets is a logical extension of this market segment. Typical supersonic and subsonic mission profiles for a potential supersonic business jet design are discussed. They result in distinct engine thrust requirements. Operating points of maximum dimensional and non-dimensional parameters are chosen for the engine cycle choice. It turns out that these differ significantly from engines for subsonic applications. An engine design featuring a two stage fan, moderate overall pressure ratio and a mixed exhaust nozzle of variable geometry has been found to be a suitable starting point for further engine design studies.

KEYWORDS
SUPERSONIC BUSINESS JET, AIRCRAFT ENGINE, PRELIMINARY DESIGN, DESIGN REQUIREMENTS

NOMENCLATURE

Abbreviations
CAS calibrated air speed
HPC high-pressure compressor
ISA International Standard Atmosphere
NASA National Aeronautics and Space Administration
ROC rate of climb
SSBJ supersonic business jet
TAS true air speed

Greek
\( \eta \) efficiency
\( \kappa \) heat capacity ratio
\( \Pi \) pressure ratio

Latin
\( A \) area
\( D \) aircraft drag
\( f_{acc} \) acceleration factor
\( F_G \) gross thrust
\( F_N \) net thrust
\( G \) aircraft weight
\( g \) gravitational constant
\( H \) altitude
\( M_a \) Mach number
\( n \) number of engines
\( P \) pressure
\( T \) temperature

Subscripts
0 ambient
15 mixer entry, bypass
2 fan inlet plane
3 compressor exit plane
51 mixer entry, core
9 nozzle exit plane
t stagnation value
INTRODUCTION

With worldwide billings having totalled 21 billion US $ in 2019 (GAMA, 2020) business jets represent an important aircraft market segment. For this market segment, the time saved when travelling is the unique value proposition (Henne, 2005; Liebhardt and Lütjens, 2011; NBAA, 2015). Consequently, flight speed is a key design requirement for business jets. To date, business jets’ flight speeds do not exceed the speed of sound. This opens the possibility for product innovations in the field of supersonic business jet (SSBJ) (Henne, 2005; Welge et al., 2010). Therefore, it is not surprising that supersonic business jets have been the subject of extensive research and development, as in the European HISAC (Environmentally friendly high speed aircraft) and RUMBLE (RegUlation and norM for low sonic Boom LEvels) projects (Sun and H. Smith, 2017).

Supersonic business jet designs pay tribute to the unique flight conditions and resulting aerodynamics. A prominent example for this is the sonic boom generation. Furthermore, the occurring wave drag and high stagnation temperatures need to be taken care of. The complexity of the design task gives leeway for the application of seemingly conflicting design philosophies. Hence, one particular design approach is selected to generally derive the engine design requirements for future supersonic business jets.

MISSION SELECTION

The selected flight missions, the aircraft design, the envisaged aircraft performance and the assumed level of technology form the basis for the derivation of the engine design requirements. The mission capabilities offered in the business jet segment are shown in figure 1. The flight missions of long range business jets reflect the needs of so-called premium passengers. Flight missions between 3000 nm and 4000 nm as well as between 5000 nm and 7000 nm are most important to this class of passengers (Welge et al., 2010). These cover, besides many continental routes, most routes across the North Atlantic and the Pacific. The highest corresponding maximum range Mach number currently offered by business jets is $Ma_{0.85}$. The highest flight Mach number currently offered is $Ma_{0.935}$. The latter serves as reference to discuss the savings in flight time offered by supersonic business jets.

Figure 1: Maximum range and cruise Mach number capabilities of business jets
The currently offered capabilities leave opportunities in terms of range and flight speed. At the upper end of the range spectrum, there is still potential for business jets to catch up with the most capable airliners, but only for specific routes such as the so-called Kangaroo Routes, e.g. Perth to London. Hence, increasing flight speed might be deemed to be a more attractive value proposition. This option is shown in figure 1 for the investigated business jet design. With the reduction of flight time being the main goal, refuelling the aircraft is acceptable as long as a time advantage is realized. Refuelling intermissions are represented by a step change in time advantage. The prohibition of supersonic flights over land in most countries due to sonic booms (Liebhardt and Lütjens, 2011) suggests that the aircraft should also be operable at subsonic speeds and still outperform current business jets in terms of speed. It becomes obvious that the investigated business jet design offers significant savings in flight time at cruise times of $Ma_{1.4}$ and $Ma_{1.1}$ even though refuelling is needed to achieve the respective maximum range. At a subsonic flight Mach number of $Ma_{0.95}$ it slightly outperforms current competition until a distance of 5400 nm. Refuelling is needed beyond this range which makes subsonic long range flight with this type of aircraft unattractive.

AIRCRAFT DESIGN

The aircraft design on the basis of which figure 1 was derived is oriented towards the Aerion AS2 concept (Aerion Supersonic, 2017). Aircraft design and performance are derived using an aircraft pre-design model which has been created in the software environment Pacelab APD. The derived aircraft geometry and main aircraft parameters are shown in figure 2.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>maximum take-off mass</td>
<td>55 t</td>
</tr>
<tr>
<td>fuel fraction</td>
<td>49 %</td>
</tr>
<tr>
<td>maximum cross section</td>
<td>9.6 m$^2$</td>
</tr>
<tr>
<td>wing area</td>
<td>180 m$^2$</td>
</tr>
<tr>
<td>length</td>
<td>52 m</td>
</tr>
<tr>
<td>span</td>
<td>22 m</td>
</tr>
<tr>
<td>time to climb to ceiling</td>
<td>15 min</td>
</tr>
<tr>
<td>number of engines</td>
<td>3</td>
</tr>
</tbody>
</table>

![Aircraft Design](image)

**Figure 2: Aircraft design geometry and key parameters**

It features a design cruise Mach number of $Ma_{1.4}$ and a subsonic cruise at $Ma_{0.95}$ which is faster than any business jet in operation. A third potential cruise Mach number of $Ma_{1.1}$ is taken into account. It represents a conservative estimation for the weather and altitude dependent cutoff Mach number, for which the shock wave responsible for the sonic boom does not reach the ground (Plotkin et al., 2008). Under these circumstances, the flight prohibition does not apply in some countries and could be relaxed in others (Sun and H. Smith, 2017) if NASA flight tests concerning the matter (see for example Kamlet, 2019) are successful. The time advantage gained over the $Ma_{0.935}$ threshold is displayed in figure 1 for all three mentioned cruise Mach numbers. It sums up to 1.8 to 2.6 hours for the North Atlantic regime when cruising with $Ma_{1.4}$ throughout the mission. For longer missions, 1 hour is assumed for the entire refueling intermission.
As shown in figure 3, the supersonic business jet is assumed to climb at comparably high flight speeds to reach cruising altitude quickly to avoid traffic. A climb speed of 400 kts calibrated air speed (CAS) has been derived from the historic Concorde climb profile whilst obeying a general air traffic speed limit of 250 kts calibrated air speed below 10 000 ft. A constant altitude acceleration at 10 000 ft is assumed, since any other transition would depend on flight operation and air traffic control directions. At crossover altitude the calibrated air speed equals the same true air speed as the applicable cruise Mach number, which is kept constant from this point on. A ceiling of 51 000 ft is selected, oriented towards existing top tier business jets considering cabin depressurisation safety concerns and high altitude emissions effects such as depletion of stratospheric ozone (Sun and H. Smith, 2017). In order to allow for a response to air traffic control instructions at any time, a residual climbing ability of at least 300 fpm rate of climb (ROC) is specified.

![Figure 3: Climb speed schedules for selected supersonic business jet missions](image)

Ground performance is defined via required field length and noise limitations. The targeted maximum field length is set to 1580 m (5200 ft) to serve at least as many important general aviation airports as current top tier business jets. This is a more challenging target than the maximum field length of 1980 m (6500 ft) which is proposed in Liebhardt and Lütjens (2011). Jet noise is considered the dominant form of community noise (Berton et al., 2005). It is key to the local acceptance of air traffic and therefore as important for operation and certification as sonic boom generation. It is assumed that the aircraft has to meet the latest International Civil Aviation Organization Annex 16 standards.

**ENGINE DESIGN REQUIREMENTS**

The described take-off, climb and cruise performance of the aircraft is translated into engine design requirements. These are expressed in terms of required thrust and maximum acceptable fuel consumption. A maximum jet velocity at take-off of 350 m/s is chosen to fulfill the noise requirements (Lighthill, 1952; M. J. T. Smith, 1989).
The engine net thrust required to achieve the climb schedules is derived using equation 1 (Blake, 2009). The envisaged speed schedule shown in figure 3 as well as the required rate of climb are input to it. Top of climb thrust is calculated at ceiling altitude ensuring the minimum rate of climb of 300 fpm.

\[ n \cdot F_N = D + \frac{\text{ROC}}{\text{TAS}} \cdot G \cdot \left( 1 + \frac{\text{TAS}}{g} \cdot \frac{d\text{TAS}}{dH} \right) = D + \frac{\text{ROC}}{\text{TAS}} \cdot G \cdot f_{\text{acc}} \]  

The net thrust required to achieve a given rate of climb during the climb phase of the design mission with \( Ma_{1.4} \) cruise is shown in figure 4a. The lines of constant rate of climb feature a distinct shape. The step change in required thrust at the tropopause is caused by the corresponding step change in \( d\text{TAS}/dH \). Between \( Ma_{1.0} \) and \( Ma_{1.1} \), the isolines show a peak in required net thrust that is caused by breaking through the sound barrier. The drop in required thrust when reaching the cruise Mach number is caused by the transition to flight at constant true air speed (see figure 3).

The actual available net thrust of an engine that meets the thrust requirements of all regarded missions is also shown in figure 4a. The first kink of the available net thrust line is caused by the change from take-off to the first climb segment. The second kink is caused by the change from the first climb segment to a constant altitude acceleration at 10,000 ft. It becomes obvious that the designed supersonic business jet is able to pass through the sound barrier with a rate of climb higher than 2000 fpm whilst a rate of climb of 4000 fpm cannot be achieved. The demanded minimum rate of climb of 300 fpm is exceeded during the climb. It is only relevant at the ceiling altitude. The resulting gross thrust is shown for all regarded missions in figure 4b. It is derived using the engine model described below. The inlet momentum exaggerates the shape of the net thrust requirement.

![Figure 4: Supersonic business jet thrust requirement](image-url)
The available static thrust shown in figure 4a results in a jet velocity of 393 m/s. With the thrust reduced to meet the jet velocity limit, roughly 66 kN of sea level static thrust are achievable. Such a reduction allows the field length target to be maintained up to a field elevation of 1200 m above sea level at hot day conditions. At sea level and International Standard Atmosphere (ISA) conditions, 43 kN are required.

The engine fuel consumption requirements are derived from aircraft mission fuel burn. Full tanks must be sufficient to cover the full North Atlantic route regime without refuelling, as depicted in figure 1. 5% contingency and fuel for a diversion and a holding pattern according to European Union Aviation Safety Agency regulations have been taken into account.

ENGINE CYCLE DESIGN

The engine design requirements have been used to select a suitable engine cycle. Engine architectures with variable bypass ratio have been excluded from the engine study, although they are attributed considerable potential (Morgenstern et al., 2010; Whurr, 2016). A conventional two spool, mixed turbofan of moderate bypass ratio has been selected as advantageous starting point of the cycle selection (Walsh and Fletcher, 2008). Engine component efficiencies are adopted from Grieb (2004), Grieb (2009), and Mattingly et al. (2004) without additional technology factors.

There is a conical shock generated at the aircraft nose at relevant Mach numbers and angles of attack. The entropy increase caused by the conical shocks is assumed to be small (Sims, 1964). This shock is neglected for the engine cycle computations (see also Brear et al., 2006). Hence, the full deceleration from free stream flight Mach number to the Mach number level required by the fan has to be achieved by the inlet. This increases the shock intensity at the inlet which results in increased inlet losses (Wyatt, 1958). The inlet performance is modeled according to MIL-E-5008 (Mattingly et al., 2004).

The design point of the performance model is set at the operating condition featuring maximum values of the non-dimensional performance parameters. This point is found using the non-dimensional gross thrust parameter as a reference. This parameter is defined in equation 2 assuming full expansion to ambient pressure. The maximum engine pressure ratio does not occur during the high Mach number design mission, but rather at top of climb with Ma 0.95.

\[
\frac{F_G}{A_9 \cdot P_0} = \frac{2 \kappa_9}{\kappa_9 - 1} \cdot \left[ \left( \frac{P_{t9}}{P_{t0}} \right) \frac{\kappa_9 - 1}{\kappa_9} - 1 \right] = f \left( \frac{P_{t9}}{P_{t0}}, Ma_0, \kappa_9 \right)
\]  

(2)

Nozzle pressure ratio \(P_{t9}/P_0\) and engine pressure ratio \(P_{t9}/P_{t0}\) as well as ram pressure ratio \(P_{t0}/P_0\) are depicted for the investigated missions in figure 5. Representative cruise conditions are included as discrete points for comparison. It becomes obvious that the observed increase in nozzle pressure ratio with Mach number is dominated by the increase of ram pressure ratio. The engine pressure ratio does not show such a distinct increase. The maximum engine pressure ratio of 2.32 is found at the top of climb condition of the \(Ma_0 0.95\) mission. It is this point at which the engine is sized.

Consequently, the required overall pressure ratio and maximum engine temperature ratio is defined at this condition. The required overall pressure ratio of 39.3 leaves room to choose the split of pressure ratios between fan root and high-pressure compressor (HPC). A boosterless architecture is assumed as a design starting point since it represents a favourable cost-performance-compromise (Richter, 2000). A maximum high-pressure compressor pressure ratio of 22 is
assumed as design limit. This represents a state of the art 10 stage high-pressure compressor. The resulting design space is shown in figure 6. Maximum fan root pressure ratio per stage is assumed as 1.42 based on an average tip pressure ratio of 1.6 and pressure ratio over blade height distributions (Grieb, 2009).

The required engine overall pressure ratio further reduces the available design space if equal stagnation pressures at mixer entry $P_{15}/P_{51} = 1.0$ are assumed. Hence the pressure ratio of the high-pressure compressor is limited to a maximum of 19.5. This is not exploited completely to achieve an engine design featuring a two stage fan. This design choice implies a distinct engine overall temperature ratio to achieve the required thermodynamic boundary conditions at mixer entry (Guha, 2001).
The design of the secondary air system is carried out at the operating conditions of maximum stagnation temperatures. Typically this operating condition is not identical to the one of maximum non-dimensionals. This is also found for the engine of the supersonic business jet. This is exemplified in figure 7 using compressor exit temperature during climb. It is found that the highest cruise Mach number yields the highest temperature. The increase of stagnation temperature at high Mach numbers is the underlying reason. The life expectancy of the engine components is intended to match current business jets. Compressor exit temperatures and turbine inlet temperatures are therefore checked for compliance with short-term and long-term metal temperature limits for materials and corrosion protection coatings (Bürgel et al., 2011). State of the art cooling technology and thermal barrier coatings are taken into account.

![Figure 7: Compressor exit temperature](image.png)

The nozzle pressure ratio range shown in figure 5 raises the question about the application of a variable geometry nozzle. A nozzle of a fixed geometry which is designed for the required maximum pressure ratio of 5.94 would feature a significant divergent part. Operating such a nozzle at the pressure ratios required at take off would lead to a drop in the nozzle thrust coefficient of about 10% (Fleming, 1953; Krull and Steffen, 1952). This effect even is exaggerated since the engine needs to be derated at take-off in order to meet the noise requirements. Hence, a nozzle featuring constant throat area but variable exit area is chosen.

A first estimate of the resulting engine architecture is shown in figure 8. The size of the engine and of its individual components is subject to further cycle optimisation and design considerations.

**CONCLUSIONS**

The design requirements for engines of future supersonic business jets differ from the requirements of subsonic aircraft. Supersonic business jets climb at comparably high flight speeds to maximise their value proposition of reducing flight time. Nevertheless the engines experience the highest values of the non-dimensional performance parameters at missions featuring high subsonic mach numbers. Highest temperatures are not experienced at take-off conditions but at top speed, top of climb conditions due to the raise in stagnation temperature at supersonic conditions. The optimum pressure ratio of the high-pressure compressor is limited due to the required high fan pressure ratios. The exhaust nozzle is subjected to a range of...
operating conditions which exceeds those of subsonic aircraft by far. Therefore, nozzles featuring constant throat area but variable exit area are required for supersonic business jets to avoid severe reductions in thrust coefficients. Yet, the resulting engine architecture can be based on available technology of civil transport aircraft engines.

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REFERENCES


